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A FORECAST OF SPACE TECHNOLOGY

Part One: THE FORECAST PLAN

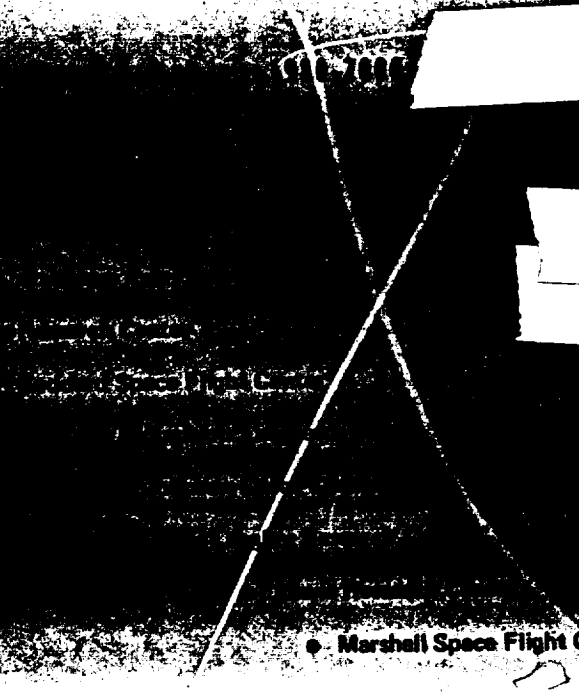
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Prepared Under the Direction of
Outlook For Space Working Group V

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SPRINGFIELD, VA. 22161

OUTLOOK FOR SPACE

A FORECAST OF SPACE TECHNOLOGY



Marshall Space Flight Center

Final Draft

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U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

GLOSSARY

AIAA	American Institute of Aeronautics and Astronautics
ARC	Ames Research Center
DOD	Department of Defense
ERDA	Energy Research and Development Administration
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
LeRC	Lewis Research Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
OA	Office of Applications, NASA
OAST	Office of Aeronautics and Space Technology, NASA
OFS	Outlook For Space
OMSF	Office of Manned Space Flight, NASA
OSS	Office of Space Science, NASA
OTDA	Office of Tracking and Data Acquisition, NASA
R & D	Research and Development
RTAC	NASA Research and Technology Advisory Council

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FOREWORD

None of us can see into the future. Yet all of us conduct our lives as if we could. We all make plans for tomorrow. So, in a sense, we are all forecasters, planning our lives around what we think the future

will be.....
could be.....
or should be.

The purpose of this document is to forecast the future of space technology in the United States during the last quarter of this century.

Through science and technology, we have the means for ennobling the life styles of humanity and answering the questions which human beings have asked throughout history. Or, we have the means for global destruction.

As ever, civilization and society are on trial, confronted with crises in population growth, natural resources, energy, pollution, and worldwide social, political, and economic unrest. With the dramatic space accomplishments of the United States during the past decade, this is an appropriate time to assess the position of the space program and its technology vis-à-vis the needs and hopes of the American and global societies during the next few decades.

The advances during the space age have rivalled the accomplishments of science and technology in all previous human history. In fact, the space effort for a time supplanted the threat of war as the ultimate stimulus in the development and exploitation of new technology.

Many are suggesting that science and technology be fixed in place -- so that the behavior of human beings can catch up. Yet science and technology will continue to be advanced, if not by the United States, then by other nations. Indeed, such advancement and its sensible utilization offer the less developed nations their only hope for improving the quality of life for their people.

In the United States, a compelling argument exists for the advancement of technology to obtain resource and energy independence and to maintain or better our standard of living and national security through more cost-effective utilization of our energy and other resources.

Technology in the United States is driven by government sponsorship, venture capital, and the intellectual curiosity of academia. For the United States to remain in a position to help itself and others, it cannot afford to lose its momentum in the creation and beneficial application of science and technology. It is equally important that the United States stay in the forefront of science and technology in order to understand and deter the adverse uses to which new knowledge may be put.

Like our problems and our challenges, space activity and its science and technology are intrinsically global and universe-oriented. Thus we are entering a new space era wherein space activities and space science and technology are key elements in the survival, the dignity, and the aspirations of the human race.

* * * * * * * * * * * *

Technology forecasting was a new and enjoyable experience for us who were members of the Outlook For Space Working Group V and its supporting task Group. It is our hope that the approach to technology structure and the actual forecasts contained in this report will be of general benefit in addition to making a useful contribution to the nation's future space activities.

This document, "A Forecast of Space Technology," serves as a reference volume in support of the Outlook For Space main report.

We gratefully acknowledge all of the participants and organizations who provided advice and assistance. They are referenced at the ends of the various sections of this volume. All of the inputs were used in some fashion. It is only natural that conflicting forecasts were made and, for that reason, as well as the need to aggregate many of the forecasts to a higher level, final accountability for the actual forecasts rests with the Coordinators of the various technological fields and myself.

J. N. James, Chairman
Working Group V

Section I. INTRODUCTION

J. N. James and R. R. McDonald

A. GENERAL

The enormity of a task encompassing comprehensive forecast of space technology for the period 1980-2000 was recognized from the outset. It also was realized that, in many of the technological fields, forecasting would be limited to those parameters judged to be most pertinent to expected space activities.

It also was understood that some technologies are more mature than others, and that in those areas, more definitive and cost-related forecasts could be accomplished. In addressing this ambitious forecasting task, two major activities were undertaken by the participants.

The first activity, exploratory forecasting, was the primary task assigned to Working Group V. It explored chains of conjecture in terms of what can or might happen and then sought to project technological parameters and/or functional element capabilities into the future, starting from a base of accumulated knowledge in relevant areas. This volume, "A Forecast of Space Technology", is devoted almost wholly to the exploratory forecasting results and is organized into six parts.

The second activity was the technological feasibility assessment of the various candidate missions and systems which were considered by the Outlook For Space Study Group. This activity, which was objective-oriented, had the character of normative forecasting. Candidate systems and missions, as identified by the Study Group, were assessed as to technological requirements. A determination was then made whether the needed technology would be available in the time frame considered. If not, the limiting technologies were identified with possible alternative approaches required to surmount these obstacles. Most of the consequence of this second activity is embodied in those parts of the OFS main report pertaining to candidate space objectives, missions, and systems.

In addition to this reference volume, all of the individual forecasts are available in microfiche form with source identification for archival purposes.

B. THE OUTLOOK FOR SPACE STUDY

1. General Approach

In June 1974, the National Aeronautics and Space Administration (NASA) announced an Outlook For Space (OFS) Study that would examine the future of civilian space activities during the period 1980-2000.

The 22-member Outlook For Space Study Group was directed by Donald P. Hearth of the Goddard Space Flight Center. The participating members were drawn from the NASA Centers and Headquarters. The Group interacted closely with as many of the Nation's communities as possible, including scientific, technological, economic, and social, through selected individuals, committees, and consultants who were recognized in their fields. Industry, the universities, and other governmental agencies supported the effort to define possible directions of space activities during the period of interest.

Objectives. The Study Director defined the objectives of the effort in a July 1974 memorandum as follows: (1) to relate the goals and objectives of possible civilian space activities in the period 1980 to the year 2000 to national goals and objectives; (2) to develop an unconstrained listing of desirable and practical U.S. civilian space activities for the period 1980 to the year 2000, and beyond; (3) to identify a grouping of activities that is consistent with specific sets of goals, objectives, and themes; (4) to define research and development tasks required to meet potential commercial and operational uses of space in the future; and (5) to identify social and economic challenges facing the Nation during the remainder of this century which can benefit from the use of space.

After studying the national and global needs which might benefit from space activities, the Study Group, through its working groups and teams, catalogued a list of candidate space activities; identified those missions that were assessed to be technologically feasible and which strongly contributed to the questions and problems of the Nation; assessed the current state of the art and the needed technology advances; and evaluated the candidate objectives as to their strength of contribution to areas of national interest.

2. Study Phasing

With the main study report due in July of 1975, the OFS effort was divided into three broad phases. Phase one, until November 1974, involved the identification of possible U.S. and world trends, questions, and problems where space might play a useful role. The second phase, extending to February 1975, involved the synthesis and ranking of the more attractive mission/system candidates which would work toward achieving

objectives through the solution of the problems or answering of questions. During the third phase, objectives were evaluated, conclusions reached, prime directions considered, and the final report produced.

The first phase employed working groups, as described later in this section. The second and third phases reformed the working groups into teams to produce the final output.

One of the major goals of the effort was to identify certain areas of national interests to which the national space program could make meaningful contributions in the 1980-2000 time period. Within each of the areas, criteria were developed to rank the relative importance of the contributions of various space activities to these needs.

The OFS Study Group divided space activities into extraterrestrial and Earth-oriented space activities. For each, various themes were developed relating, for example, to the origins and future of life, the production and management of food and forestry resources, etc.

As the working groups proceeded, a series of major problems or questions was identified as foci of candidate space activities within the various themes. Missions and systems were developed to be responsive to these major questions or problems. The missions in turn employed functional elements or "tools," based upon the technology forecast in this volume.

For a mission or system to be feasible in the 1980-2000 time frame, the Nation must have the technological capability required to implement these functional elements. Working Group V forecasted the availability of that capability.

3. Working Group Structure

The full OFS Study Group held its first meeting at Lewis Research Center on June 25 and 26, 1974. Initially, four Working Groups were established, with a fifth Group designated in early July.

Working Group I. Chaired by W. G. Stroud, Goddard Space Flight Center, this Group was chartered to examine the future political and economic environment as a background for the consideration of space activities.

Working Group II. Under the chairmanship of P. E. Culbertson, NASA Headquarters, this Group was charged with designing the output or product of the Study Group effort.

Working Group III. This Group, one of two looking at candidate future space activities, examined the terrestrial or Earth-oriented space activities, and was chaired by R. O. Piland, Johnson Space Center.

Working Group IV. S. I. Rasool, NASA Headquarters, chaired this Group, which considered extraterrestrial space activities during the period of interest.

Working Group V. J. N. James, JPL, chaired this Group, which forecasted the state of space technology during the time frame of interest and provided support to Working Groups III and IV on space activity feasibility assessments.

4. Team Structure

Around January 1975, the Working Groups were re-formed into teams to converge on the final output, and the following teams were added:

- Team led by L. G. Richard, Marshall Space Flight Center, to apply criteria and methodology to assess the relevance of various mission/system candidates for the solution and answering of problems and questions.
- Team led by J. N. Sivo, Lewis Research Center, to compare OFS results with other long-range plans and implications to space transportation.

C. FORMATION OF WORKING GROUP V

Working Group V was established in July 1974. Its charter was stated in a task order to JPL and included identifying the current state of technology as it relates to space activities being examined by the OFS Study Group, forecasting the improvements in such technology through either "normal" evolution or possible technological breakthroughs, and acting as technical advisor, as requested, to the various working groups and teams. It was to make its forecasts through a broad involvement of the NASA community and experts outside of NASA. J. N. James of JPL was appointed chairman and Colonel A. Worden, Ames Research Center, and L. Richard, Marshall Space Flight Center, were designated as members in an advisory capacity. Dr. F. E. Goddard and F. H. Felberg of JPL also performed in an advisory capacity.

Mr. James established a Task Group to execute the task order and this project-like effort was led by R. R. McDonald, JPL.

The initial approach to the entire effort was laid out by a cadre of the Task Group led by James and McDonald and consisting of V. C. Clarke, K. M. Dawson, D. F. Dipprey, N. R. Haynes, P. J. Meeks, A. Spear, and W. M. Whitney, all of JPL.

J. D. Burke of JPL was soon added to the cadre with the special assignment of interacting with both Working Groups III and IV and contributing to technological feasibility assessments. Later, N. R. Haynes, R. G. Nagler, and R. H. Steinbacher assisted in this aspect of the forecast.

Once the basic approach was adopted, the Task Group was quickly expanded to include all of the Coordinators in the respective fields of technology (R. A. Boundy, H. P. Davis, A. R. Hibbs, D. W. Lewis, R. J. Mackin, J. Maserjian, and L. D. Runkle), Contributors at the NASA Centers and JPL to perform the actual forecasting, and Consultants from many useful sources to support the forecasts.

A. Briglio, J. W. McGarrity, D. L. Vairin, and H. J. Wheelock of JPL jointed the Task Group to support documentation and general staff functions.

Working Group V remained operational to provide support through all phases of the Outlook For Space study effort until July 1975.

Section II. THE PLAN FOR SPACE TECHNOLOGY FORECASTING

A. APPROACH

The general sequence followed in getting the Working Group V operations activity underway was as follows:

(1) Description of the taks

(2) Formation of the cadre

(3) Structuring technology in the form to be used throughout the forecasting effort

(4) Identifying and enlisting the assistance of the complete group of participants

(5) Fixing upon the methodology

(6) Establishing the schedule

(7) Execution of the plan.

Once actions (1) through (6) had been accomplished, the actual exploratory forecasting process began.

Concurrently, support to Working Group III and IV activities was provided by attending their meetings and initiating feasibility assessments of selected candidate space activities that these Groups were examining.

B. STRUCTURE

1. General

A cohesive structure was needed in order to divide the entire technology forecasting task into manageable elements. The initial inclination of the Task Group was to structure the activity within the traditional technical disciplines; i.e., power, propulsion, communications, instrumentation, etc.

However, it was felt that such an organization would likely reflect the current state of technology and would not necessarily be consonant with the future time frame. A matrix morphology was needed that could function as a device for control of the entire effort -- one that could help probe a quarter-century into the future without losing touch with today.

A structure was needed, in short, that suggested logical groupings of parameters for forecasts meaningful at the functional systems level without radical departure from the predicted base of scientific resources. This structure would also have to intersect with the traditional disciplines in such a manner as not to lose the valuable body of their expertise. The structure adopted was a consequence of the recognition that civilization makes itself known by its ability to utilize energy for the transfer of information and the shaping of matter to its needs.

The basic matrix structure adopted (Fig. 1-1) strongly influenced the aggregation of parameters, forecasts, participants, and outline of the final report. Examples of the content of this matrix are shown in Fig. 1-2.

2. The Morphology

The primary matrix incorporates three vertical columns categorizing the capabilities for Management of Information, Management of Energy, and Management of Matter.

The four horizontal rows are functional processes: Acquiring, Processing, Transferring, and Storing, which operate on the vertical categories. The intersecting squares are identified as Fields: e.g., the field of Acquiring Information, or the field of Processing Information. The fields of Acquiring, Processing, and Storing Matter were also divided into animate and inanimate sectors. It was not expected that any one field in the matrix would be of scope or magnitude equal to any of the other fields.

This matrix organization of technology was intended to provide a fresh perspective which encouraged participants to think in terms of basic functions not necessarily related to today's methods, devices, or organizational interests. It was furthermore intended to expose implicit assumptions or constraints about the future contained in present organizations and approaches.

Successive examinations of the matrix have indicated that it stands the test of completeness.

The three categories of management appearing in the vertical columns of the matrix (Fig. 1-2) have been identified as Information, Energy, and Matter. Certain subdivisions of fields within the matrix have been made for convenience. They are explained below.

Management of Information. Like the other management categories, Information is subdivided functionally into Acquiring, Processing, Transferring, and Storing.

Acquiring of Information, for the purposes of this forecast, relates to science, surveillance, reconnaissance, and support of other system functions. In this study, it refers only to extrinsic information, not the intrinsic data pertinent to the performance of a functional system or its subsystems. The elements of this field include instrumentation and the apparatus and associated techniques used in the conduct of space missions.

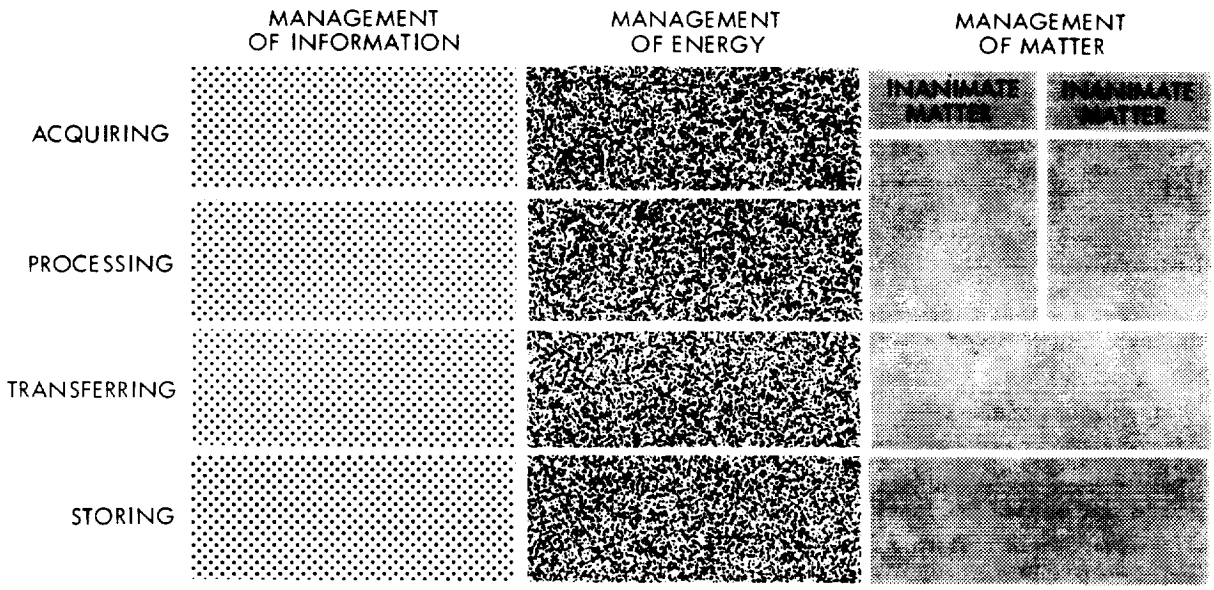


Figure 1-1. Basic matrix structure for technology forecast

	Information	Energy	Matter
Acquiring	• Instruments (1) Electromagnetic waves (2) Particles (3) Chemical properties (4) Physical properties (5) Biological properties • Apparatus	• Photons • Magnetic Flux • Indigenous materials	• Animate (1) Space medicine (2) Plants in space (3) Space processing (4) Contaminants
Processing	• Instruction and use of machines • Design and construction of machines • Automation of cognition	• Conversion of stored energy to (1) Electrical energy (2) Kinetic energy for propulsion (a) Earth-to-orbit (b) Space	• Inanimate (1) Microstructures (microelectronics) (2) Macrostructures (materials and structures) (a) On Earth (b) In space (c) On the Moon (mining)
Transferring	• Electromagnetic links (1) Spaceborne devices (2) Ground-based devices (3) Near-Earth systems (4) Deep space systems • Other links (1) Acoustic	• Beamed Photons (1) Laser (2) Microwave	• Path planning • Object location • Translation/orientation control (1) Through space (2) Through atmospheres (3) On solid surfaces
Storing	• Storage systems (1) Magnetic (2) Electro-optical (3) Solid-state	• Mechanical • Thermal • Electronic (chemical) • Nuclear • Magnetic • Antimatter	• Maintenance of state (survival) (1) Life support systems (2) Containment of pressurized fluids (3) Meteoroid protection (4) Radiation protection (5) Temperature control

Figure 1-2. Content of technology matrix

Processing covers all operations, excluding those involved in Transferring (see below), that are performed on information from the time it is received from the instruments and sensors or from the communication link until it is delivered to the next link, to a storage medium, or to the human user on a printed record, in a display, or in some other form. This category includes the interface between man and machine.

Transferring encompasses those technologies required to encode, modulate, and transmit signals over the transmission media and to receive, demodulate, decode, and reconstruct the best estimate of the signal as it existed prior to encoding for transmission.

Storing refers to the preservation of information for later retrieval and use. Since it is believed that, in the future, the devices and methods used for storing and for organizing and transforming information will be intimately related, the forecasts for this category and those for Processing are combined.

Management of Energy. In this context, Acquiring is taken to include collecting photons (electromagnetic waves), interacting with magnetic flux (near bodies with large magnetic fields), and accumulating indigenous materials from planetary atmospheres or surfaces.

Processing in this matrix refers either to conversion of various forms of energy to processed electrical energy for use in space operations, or to conversion of energy to kinetic energy of exhausted mass for propulsion.

Transferring of energy, in this forecast, will cover only the use of photon (electromagnetic) beams, further restricted to laser light and microwave techniques.

Storing of energy refers to six forms: mechanical, thermal, magnetic, electronic (chemical), nuclear, and antimatter.

Management of Matter. The functions of Acquiring and Processing are grouped together because they are closely related; they are further separated into Animate Matter and Inanimate. The inanimate category is then subdivided into microstructures and macrostructures.

Acquiring and Processing of Inanimate Microstructures considers three major categories: (1) semiconductors, (2) magnetics and optics, and (3) superconductors. Primary emphasis is given to applications in the firlds of Processing and Storing Information.

The Acquiring and Processing of Inanimate Macrostructures comprises four elements: metals, composites, ceramics (including glass), and polymers. The field also includes structures technology and space processing.

Acquiring and Processing Animate Matter includes the technologies of space medicine, closed ecological systems using plants, space processing of biological materials and biological contaminants.

The Transferring of Matter is related to path planning, object location, and translation/orientation control in various media, such as movement through space, through atmospheres, and on solid surfaces.

The Storing of Matter is principally concerned with the maintenance and survival of a given state. Environmental protection is considered for both animate and inanimate matter. The field includes life support systems, containment of pressurized fluids, meteoroid protection, radiation protection, and temperature control.

C. PARTICIPANTS

1. General

The space technology forecasting effort of Working Group V was assigned to the Jet Propulsion Laboratory for organization and execution with the intention to solicit a broad involvement in the forecasting effort from experts throughout the NASA establishment and from consultants outside the agency.

The organizational concept for the space technology forecasting effort is shown in Fig. 1-3.

Participants were designated to be Coordinators, members of Committees, Contributors, and Consultants, as follows.

2. Coordinators

Coordinators were recruited from the Jet Propulsion Laboratory. Each Coordinator headed one of the vertical categories of management capability or one of the intersecting fields appearing in the basic matrix (Fig. 1-1). These continuing members of the task activity assembled the various inputs from the several Contributors in each of their fields and prepared the final version of the Working Group V report.

Each of the coordinators headed a Committee comprising the Contributors in each of the fields. These Committees were newly formed and not related to any existing committees on science and technology.

Coordinators were appointed for the technology forecasting tasks as follows:

- Task Leader: R. R. McDonald
- Technological Feasibility Assessment: J. D. Burke
- Information: W. M. Whitney
  (1) Acquiring Information: R. J. Mackin
  (2) Processing and Storing Information: W. M. Whitney
  (3) Transferring Information: A. J. Spear
- Energy: D. F. Dipprey
  (1) Energy (all functions): D. F. Dipprey, L. D. Runkle, H. P. Davis (JSC)

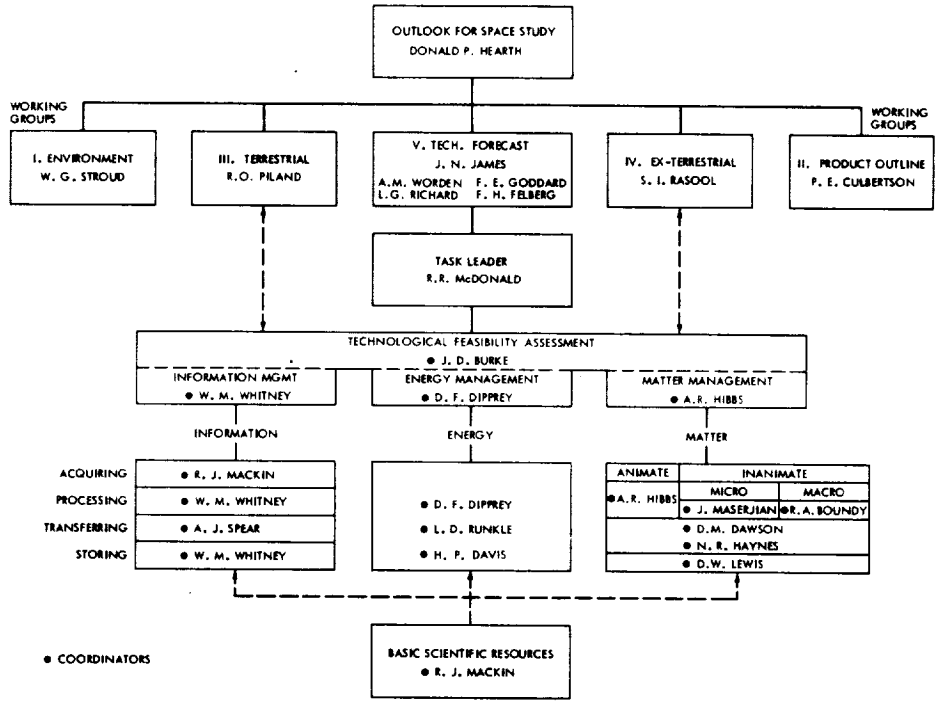


Figure 1-3. Technology forecast organization

- Matter: A. R. Hibbs
  - (1) Acquiring and Processing Animate Matter: A. R. Hibbs
  - (2) Acquiring and Processing Inanimate Micro-Matter: J. Maserjian
  - (3) Acquiring and Processing Inanimate Macro-Matter: R. A. Boundy
  - (4) Transferring Matter: K.M. Dawson, N. R. Haynes
  - (5) Storing Matter: D.W. Lewis
- Basic Scientific Resources: R. J. Mackin

3. Contributors

Contributors identified with each of the fields of the basic matrix involved approximately one hundred individuals from JPL and about sixty from other NASA organizations. Contributors were continuing members of the task activity who worked to support the Coordinators and who usually provided some element of the product output. They were dedicated members of a Committee and responsible for formulating the approach to be used in forecasting technologies within the assigned field, assembling an instruction package (under the guidance of the Coordinator) as a detailed plan for forecasting technology in each field, selecting the experts in the assigned field to do the forecasting, and reviewing those forecasts.

The Contributors in the several fields are designated in each of Parts Three through Six of this volume.

4. Consultants

Recognized experts in each of the fields were solicited as Consultants to the effort and used as required on a short-term basis. In general, they were individuals who were not continuing members of the task activity but whose advice and judgments were sought to lend additional credence and insight into the technology forecasts.

More than 200 Consultants were solicited and are listed in the respective parts of this volume pertaining to the forecasts to which they contributed.

D. METHODOLOGY

For this effort, technology forecasting was defined as "the prediction of foreseeable advances in technology in a given time period so as to show possible options and alternatives," referenced to such questions as "What will be?", and "What is possible?". Technology forecasting was also taken as a prediction, within a range of uncertainty, of a technical achievement in a given time frame and with a specific level of support.

Exploratory forecasting, using the intuitive approach and trend extrapolation, incorporated forecasts from the existing literature, interviews with experts in industry, government, and universities, and the large body of specialized information and skills within NASA. Consensus judgments were sought without resorting to rigorous Delphi or substitution techniques. Trend extrapolation was used with special attention given to the identification of technological barriers and breakthroughs required.

It was necessary to standardize the questions that would be asked of various experts so that the forecasts would have a common foundation. Those standard questions follow.

What Will Be? "What will be?" was asked as a preferred alternative to such questions as "What is probable?", or "What is 80% probable?", etc. Implicit in the question "What will be?" is a very high likelhiood or probability that the capability indeed will be achieved.

The question "What will be?" in the time frame 1980-2000 was predicated on:

(1) Today's state of the art.

(2) Today's funding level.

(3) Expected future funding assumptions.

What is Possible? The response to this question was generally intended to be unconstrained by consideration of funding limitations. Having determined "What is possible?" the expert was asked to identify the limiting or controlling characteristics of the concepts, devices, or elements. He also was asked to identify the funding or instituional assumptions that precluded the achieving of the possible in the will be forecast.

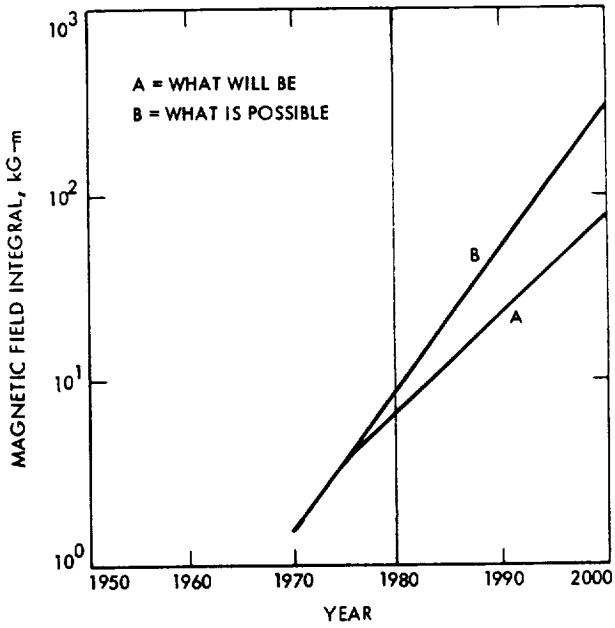
The methodology required identification of the key performance parameters or figures of merit in each of the fields. For these purposes, parameters were defined to be a quantitative measure of a technological capability. However, such parameters could not be found for all forecasts.

The highest functional level of parameters to be forecasted were identified as Primary Parameters. They were selected by the committees of Contributors associated with the respective fields.

In general, forecasted parameters are intended to be an aggregation of secondary parameters at a high-enough functional level to respond to the synthesis of functional elements which are the space tools needed to implement missions or systems. Primary parameters are forecasted either as an entity or assembled from a compendium of secondary parameter forecasts related to concepts, devices, and elements.

An example of a Primary Parameter in the field of Transferring Information is information rate (bits per second) at a specific quality (bit error rate). Secondary parameters would then be at the next lower functional level, such as receiver

FC 3-13. Superconducting Magnetic Spectrometer



DISCUSSION

Magnetic spectrometers use position sensitive detectors (e.g. spark chambers or nuclear emulsions) to measure the amount of deflection of high-energy charged particles in traversing a magnetic field. In combination with other . . . . . .

. . . . . .

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Figure 1-4. Sample of standard graphics

3. Costs

All cost information employed in the forecasts was based on FY'75 dollars (i.e., purchasing power of FY'75 dollars) with projections assuming no inflation or change in buying power.

Most of the forecasts are represented in a standard graphics format, an example of which is shown in Fig. 1-4. In selected situations where multiple parameters are required, a tabular form is used.

system noise temperature and size, and antenna gain and size.

Section III. INTERACTION OF WORKING GROUP V WITH OTHER ORGANIZATIONS

It was appreciated that considerable interaction would be necessary between Working Group V and other activities in order to benefit from the advice and critiques of existing bodies of space technology expertise.

Advisory groups contacted by Working Group V were:

(1) Aeronautics and Space Engineering Board of the National Academy of Engineering

(2) NASA Research and Technology Advisory Council and the following groups:
   (a) Panel on Space Vehicles
   (b) Committee on Guidance, Control and Information Systems
   (c) Research Panel
   (d) Committee on Materials and Structures
   (e) Committee on Energy Technology and Space Propulsion

(3) Space System Committee of the NASA Space Program Advisory Council

(4) Life Sciences Committee of the NASA Space Program Advisory Council

(5) American Institute of Aeronautics and Astronautics and the following committees:
   (a) Technical Committee on Space Systems
   (b) Technical Committee on Space Sciences and Astronomy.

For some of the space activities considered, feasibility assessments were made by NASA Headquarters Offices, and various members of the Outlook for Space Study Group, as well as by Working Group V.

In the area of exploratory forecasting, the total forecast was provided in draft form for comment to the Office of Aeronautics and Space Technology (OAST), the National Academy of Engineering Aeronautics and Space Engineering Board, the NASA Research and Technology Advisory Council, the American Institute of Aeronautics and Astronautics and various divisions of the California Institute of Technology. The OAST critique also included comments from members of the other NASA Headquarters Offices: Office of Applications (OA), Office of Manned Space Flight (OMSF), Office of Space Sciences (OSS) and Office of Tracking and Data Acquisition (OTDA).

Valuable advice and consultation in the approach, the structure, and the methodology and techniques of technology forecasting were provided by Marvin J. Cetron, President of Forecasting International, Ltd., through a contract with the Outlook for Space Study Group.

A FORECAST OF SPACE TECHNOLOGY

Part Two. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Principal Author: A. R. Hibbs

Contributing Authors: J. D. Burke, D. F. Dipprey, J. N James, R. R. McDonald, and W. M. Whitney

Prepared Under the Direction of
Outlook For Space Working Group V

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Section I. THE PROSPECTS FOR SPACE TECHNOLOGY

This Part of the Outlook for Space Reference Volume summarizes the forecast of space technology, draws some conclusions, and identifies certain critical areas. The particular fields of technology that were investigated are summarized, conclusions are stated, and a number of areas that are believed to be critical to the continued growth of a strong space program are recommended for emphasis by the National Aeronautics and Space Administration.

A. SOME GENERAL CONCLUSIONS

The forecasting data revealed that between now and the year 2000 a great number of advances will occur in technology applicable to space activities. These technological advances will bring about the feasibility of complex missions and systems and can significantly reduce the cost of accomplishing any specific objective in space.

As background to the forecasting effort the following general observations are made:

(1) Civilization manifests itself through its ability to manage energy, information, and matter.

(2) Technology is a high form of such management, in that it uses, in highly effective ways, the leverage of energy to more extensively communicate information and shape matter to our needs.

(3) The advancement of technology is the hallmark of developed nations; it achieves their standard of living. Thus, technological advancement is a fundamental requirement for those nations aspiring to a comparable condition.

(4) Technology is advanced by the sponsorship of government, through venture capital, and by the intellectual pursuits of academia.

(5) New space missions and systems will be approved only after their benefits are widely perceived and understood, and their performance, schedule, and cost risks are acceptable. In such a planning environment, strong research and technology advancement efforts are needed to demonstrate that potential problems have indeed been solved before the high-cost phase of an endeavor is entered.

(6) Whether or not any one nation chooses to advance technology, it will advance dramatically, on a global basis, for the remainder of this century.

A selected set of six predicted technological advances, described more completely in Parts Three, Four, and Five, deserves special attention. Each effects a broad spectrum of possible space activities, representing particularly important examples from the various fields of technology that were investigated. As a group, they typify three different methods by which the necessary support will be furnished:

(1) By industry, largely without NASA or other government support.
An important example in this first category – where industry will push ahead, alone if necessary – is the area of microelectronics, and in particular the area of ultra-high-density microelectronics for the storage of information. Industry is not likely to advance the reliable use of microelectronics for space requirements, however.

- Before the year 2000, ultra-high-density solid-state mass memory systems will be available, capable of storing 10^{12} bits per cubic meter – an increase of 10^4 beyond 1975's capabilities. This development will be the foundation for great advances in data management, and in particular in remote automatic information processing. Additional capability will be available for archival storage up to 10^{15} bits per cubic meter.

(2) Partially by industry, but requiring a fraction of NASA or similar government support.
In this second category:

- There will be major advances in automatic data processing including data compression, information extraction, and pattern recognition. There could be major advances in automated (machine) intelligence, enabling spacecraft and surface rovers to conduct important tasks or sequences of operations under human direction but without the need for constant step-by-step human control.
- Nuclear devices, particularly fission reactors with various electrical energy converters, if developed for space applications, offer the best promise for low-weight, low-cost energy storage systems deemed feasible between now and the year 2000. This forecast applies to the mass of the complete system required

to store energy and make it available on demand in the form of electricity. Such stored energy could be used for either propulsion or station operation.

- It will be possible before the year 2000 to design, fabricate, deploy, and control large lightweight structures in space, such as solar arrays with areas of hundreds of thousands of square meters. For antennas, where pointing accuracies are more demanding, areas could be tens of thousands of square meters. Fabrication, deployment and control capability will result primarily from NASA-sponsored developments. However, design capabilities and availability of important new structural materials will come, primarily, from industrial technological advances – many sponsored by governmental agencies other than NASA.

(3) Currently unique to space requirements and therefore relying almost totally on NASA support. In this category:

- It is forecast that it will be possible by the year 2000 to provide nearly fully closed (fully recycling) biological life support systems for large crews' in space or on the Moon. These systems could have reliable lifetimes of several years, and "farm" areas of the order of 10^3 square meters per capita. However, very little advance has occurred in this area to date.
- It will be possible in the time period in question to develop reusable, vertical landing (perhaps in water), heavy lift vehicles for low-cost Earth-to-orbit transportation. Such vehicles could be capable of delivering payloads of a few hundred thousand kilograms to low Earth-orbit at a cost of $50 per kilogram, or less.

As indicated above, the type of support which will result in the new technologies available for future space missions covers the spectrum from almost entirely industrial support to wholly NASA support. It is noted that some technologies seem to cluster toward one end or the other end of this spectrum.

Those technologies which appear to be rapidly advancing with the support of industry, in many cases on contract to other Federal agencies, include new materials, advanced design techniques, data processing and some aspects of non-space communications, and microelectronics, but not necessarily their long-term circuit reliability. Examples of those technologies which rely almost completely on NASA support for their advancement include propulsion, space navigation, and life support systems. The technologies required to assure reliability and extremely long life of systems in the environment of space will require primarily NASA support, because of the unique character of that environment. Only through advances in extending the life of space systems, will the costs of some candidate space activities reach the approval level.

Some advancement will take place in those technologies which lie somewhere in the middle ground of sponsorship, but NASA funding would make a major improvement. Many of the technological forecasts are twofold: "what will be" and "what is possible." The larger the gap between "what will be" and "what is possible," the greater the potential influence of government funding support if the greater capability is required.

Some of the forecasts are based on the assumption that certain breakthroughs will take place, although exactly what those breakthroughs are likely to be is unknown in 1975.

For example it is recognized that the speed of information processing is fundamentally limited by the velocity of light. For some of the projected increases in computer processing speeds to be realized, there will have to be significant advances in the architecture of large machines - employing parallel rather than serial or sequential processing techniques. Exactly how this will be accomplished, especially for very large processor arrays, is uncertain, but the forecasters are confident that it will be.

There are other areas in which the necessary breakthroughs do not seem so likely, at least before the turn of the century. An example of this is the technology which would enable space probes to be sent out from the solar system toward some other star with reasonable times of flight, say less than 50 years. One might speculate on how this might be accomplished using such things as lightweight nuclear fusion microexplosion rockets, gas-core nuclear fission rockets, or even the production and storage of antimatter. Certainly propulsion systems available today or in the near future are incapable of meeting interstellar mission objectives, and are not forecasted to be available before 2000.

It is worth re-emphasizing that the forecasts and conclusions given in this report represent the opinions of the authors. We have received many helpful comments and criticisms from a number of highly qualified reviewers. From these, many were selected for inclusion in the final version of the report. The decision in each case was made by the individual author who takes full responsibility for the results.

There was one particular aspect of future technology that received inadequate attention, namely, equipment lifetime and reliability. Several reviewers expressed a justified concern on this matter. However, the problem could not be responded to because of the limitations of time and resources in the completion of the study. Although a number of separate forecasts of individual elements of technology have made mention of developments of reliability, the study does not present a coordinated analysis of this important problem. Certainly, it does not present an analysis of the extremely important problem of system reliability. If any group were to undertake a similar study (or a revision or updating of the current one), then we feel it would be important to have proper attention paid to this particular area.

The following three subsections (B, C, and D) address some of the more specific findings of this report in respect to the management of Information, Energy, and Matter. Each discussion is divided into an Overview, an Elaboration of the Problem, and Elaboration of Technology for Solutions.

B. THE MANAGEMENT OF INFORMATION

1. Overview

The next 25 years will see a steady and rapid growth in the amount of data collected in space and returned to the Earth, combined with the necessity for acquiring, processing and disseminating this information at low cost. These two factors will provide the stimuli for the technological evolution of space-related information systems. As this technology advances, NASA will benefit from industrial activity leading to increased capabilities and decreased costs of digital hardware and high-rate ground communication facilities. NASA will contribute an increased capability and versatility of space-to-space and space-to-Earth communication links.

Greater autonomy will be given to remote systems as a result of these technological advances, particularly the capabilities of space-borne information hardware and application software. This will result in more efficient use of Earth-based control and communication facilities.

Increased understanding of information functions and their interrelation will result in more emphasis on end-to-end information system design. Improved system design approaches will take better advantage of the technology becoming available, and will minimize the overall costs of information management. At the same time, these design approaches will place increasing demands on software capabilities, which may not advance as rapidly as hardware capabilities and may become even more of a limiting factor than they are in 1975.

2. Elaboration

a. The Problem. The trend most likely to influence developments in information management is the rapid growth in the quantities of data which will be gathered from systems in space. By the year 2000, imaging devices on Earth application satellites will be capable of returning a thousand times more data than in 1975, that is, an increase from 10^{10} to 10^{11} bits/day to 10^{13} to 10^{15} bits/day. Non-imaging experiments will also provide increasing quantities of data resulting from both increases in sensitivity (by factors of 30 to 3,000) as well as increases in the range and versatility of remote sensing instruments. Thus, it will be necessary to provide for the efficient and economic handling of a much greater influx of data from both Earth satellites and remote spacecraft and to exercise more selectivity in transmitting that data from the source. The result will be large management and technological problems, and a requirement to find solutions.

The search for those solutions will place greater emphasis on designing the entire information system from end-to-end for a given application. While studies of this kind are conducted now, our ability to make use of their results is limited by lack of capabilities in the following area:

(1) High cost of meeting reliability requirements for complex flight data systems.
(2) Limitations in data compression and other information extraction algorithms.
(3) Insufficient capacity of space-to-Earth communication links for some applications, e.g., planetary spacecraft.
(4) The requirement for step-by-step human control of complex instruments and other systems used for remote tasks.
(5) Complex software systems whose generation is often slow and costly, and whose use often demands the user be a computer hardware and software expert to avoid being isolated from the data.

In all of these areas, significant advances will be made, leading toward more efficient and economical information management systems.

b. Technology for Solutions

(1) Communications. It is expected that communication links between Earth and both satellites and planetary spacecraft will increase in capacity to accommodate data handling requirements, and the cost of these links will decrease. Almost all deep-space links, and a majority of Earth-satellite links will continue to use microwave bands up to 30 GHz. Higher bands will be used for military applications both to avoid crowding the lower bands and to achieve secure communications. On Earth, extensive use will be made of optical cables.

This growth in communication link capacity will be paralleled by a growth in capabilities for data compression and onboard processing, as discussed below. Thus, the system designer will have at his disposal a wide variety of options to support trade-off analyses, including, at one extreme, the availability of low-cost, large-capacity communication systems, able to transmit all data from simple and inexpensive data acquisition systems to central data processing stations on Earth.

(2) Computer Hardware. The rapid development of large-scale-integrated circuit technology (LSI) and its diminishing cost are having, and will continue to have, a profound impact on all aspects of information management, but especially in the areas of processing and storing information. The single-chip processors being introduced today will expand the number of computers and the computing power available at an expected rate of three to four orders of magnitude per decade. This increase will reflect largely the growth of the market in the small dedicated "personal" computer rather than the medium-to-large-scale systems. The performance capability of

these computers is expected to grow at the rate of one order of magnitude per decade over the next 25 years rather than at the two-per-decade rate exhibited over the past 20 years. The increase will be achieved primarily through advances in parallel processing and intelligent peripherals. Users with limited computing facilities will have access to large-scale computing systems with additional processing capabilities and data bases through federated computer system networks, currently in the development stage.

LSI will also affect information transfer. More and more, communications systems will consist of integrated transmitters, receivers, and antennas. The antennas will be composed of arrays of small dipole elements mounted on large, erectable structures, each connected to its individual receiver. Phasing of electronic elements will point and shape the multi-antenna beams and adjust their polarizations. By this means, extremely large antenna apertures may be achieved. Various transformations of signals with large bandwidths requiring high spectral resolution will be accomplished inexpensively with micro-processors; for example, time correlations and fast Fourier transforms.

(3) On-Board Processing. The implementation of space-borne data processing and control functions will follow commercial trends. The concept of applying dedicated computers to individual functions will be realized on board space vehicles by 1985. Initially, these computers (micro-processors) will operate independently to simplify software and hardware complexity. Later, still more dense microcircuits and new software concepts will permit interaction of computer elements at higher levels and provide load-sharing and fault-tolerant operation.

Advances in spacecraft hardware and in a variety of applications programs will promote the transfer of more responsibility to spacecraft and satellite systems. Instruments will become more independent of step-by-step ground control during measurement procedures. Much routine processing of data now done on the ground will be carried out within the instrument. This advance, and the use of source encoding for data compression, will reduce requirements for channel capacity for space-to-Earth communication links and ease problems of rapid and economical dissemination of mission results. By the year 2000, the volume of transmitted data required to meet a set of space-mission objectives will be reduced by a factor of approximately 100 through application of information extraction and encoding methods. Users will interact with spacecraft and satellite image processing systems to select and control the criteria employed in on-board information extraction. In future years, perhaps beyond 2000, the in-space information system will organize itself to filter out the information contained in measurement data on the basis of a set of prescribed criteria and constraints.

(4) Robotics. The information return from missions on the surfaces of planets or their satellites will be greatly enhanced through the use of advanced robot systems. These will carry out certain operations automatically -- for example, the collection and manipulation of rock and soil samples and the control of scientific instruments. Human beings on Earth will plan such actions and initiate them, but will not guide their step-by-step execution. Such methods of supervisory control will also be employed near Earth in teleoperator systems used for Shuttle operations or in the construction of large space structures.

For spacecraft other than surface explorers similar control methods and more capable and reliable on-board operating systems will provide all classes of spacecraft and satellites with an increased autonomy. Ground system control and communications facilities will thus be used in supporting more missions at a given time than is possible in 1975 with the more dependent space systems. Automation of some ground-control functions will reduce the tedium of certain aspects of mission control. All of these advances in spacecraft autonomy will reflect and contribute to similar advances in the automation of similar functions on Earth, especially in industry and in deep-sea exploration.

(5) Software. Presently, the generation and use of computer programs present a serious bottleneck to the expedient use of computers. Difficulties in planning, estimating, producing, controlling, checking, and maintaining software make it costly. Lack of standardization in machines and in programming languages, rigidity in the format of discourse, and many other limitations make the interface between human beings and computers uncongenial and the exchange of useful or valuable information slow. The direct use of computers in accomplishing a wide variety of tasks, which could benefit many, thus remains the professional domain of relatively few.

Significant software advances are seen as essential to facilitate communications between user and computer for program generation and application, and to take full benefit of the projected increases in the availability of low-cost computer systems. Although no breakthroughs are foreseen in addressing the many complex problems involved, certain developments are considered likely. Present structured design procedures for the analysis of a processing task into program requirements will mature. There will be some standardization of programming languages, compilers, and hardware. Higher-order languages with syntax closer to English will be developed, with concurrent de-emphasis on efficient use of the computer hardware in order to increase the efficiency of the human-computer system. Computer-generated program listings that clearly communicate the functioning of the program to the human user will be developed. Progress in computer recognition of spoken English, measured in terms of size of speaker vocabulary allowed and the variety of speakers accepted, will significantly affect the accommodation between humans and machines.

The impact of these developments will be a reduction in software-generation costs, wider application of computers, and greater transparency of the machine to the user.

C. THE MANAGEMENT OF ENERGY

1. Overview

The examination of this field is separated into two subcategories: Earth-to-orbit operations and space power and propulsion.

It appears that over the next 25 years there will be the possibility of developing vehicles capable of lifting very large masses of payload into Earth orbit at low cost. Examples of space activities which would require such capability are the development of satellite power stations, commercial processing in space and the exploitation of Lunar resources. Although the Shuttle system and derivations of it can bring the cost down significantly from present values to levels below $200 per kg, it would be possible to do even better with new heavy-lift vehicles such as single-stage-to-orbit, vertical takeoff and vertical landing (VTOVL) designs with which launch costs could be less than $50 per kg.

In the category of space power and propulsion, there will be more efficient transmission, collection, storage and conversion of energy for both exploration and application activities in space. In the time frame of interest, space power transmission is likely to rely on microwave or laser technology rather than other transmission concepts. The most obvious source of energy for collection in space is the Sun, from which photon energy could be collected and then converted to electrical energy by photovoltaic cells, or by thermal conversion systems. In 1975, neither of these approaches can be ruled out in favor of the other. Lunar minerals may offer sources of chemical energy for propulsion purposes, although it will require more energy to gather and process such chemicals than they would yield, implying the need for in situ solar or nuclear power stations to take advantage of this possibility.

Energy needs to be stored on spacecraft both for station power and for course-changing propulsion. By far the lowest mass means for storing energy in space will be nuclear energy, particularly fission reactors developed for space use. Mass per unit energy stored and made available as electrical energy can be three orders of magnitude less than with chemical or mechanical storage. Cost of nuclear systems for storing energy is expected to be about the same as for chemical systems on a unit energy basis.

Conversion of stored energy to mechanical energy for propulsion use will undoubtedly continue to rely on thermochemical systems for Earth launching over the time period of interest. However, for space propulsion, such as that used for interplanetary flight, additional options may be made available for development before 2000. Electrostatic, electromagnetic and very high temperature thermal devices used with fission reactors could accelerate propellants to a new order of magnitude in exhaust velocity. It is not likely that fusion systems or antimatter systems will be available before the turn of the century, but work in these directions might lead to their availability within a few decades thereafter.

Conversion of various sources of energy to electrical energy for spacecraft power can be accomplished with a variety of approaches. Concepts which have received most attention to date, such as solar photovoltaic and solar thermionic systems, could yield mass efficiencies of the order of 10 kg/kWe, for the complete collection and conversion system, before the turn of the century. More advanced concepts, such as solar dielectric conversion, might achieve 10^1 kg/kWe for special applications.

2. Elaboration

a. The Problem. Developments in the Earth-to-orbit lift capability will be stimulated by a growing need to put increasingly larger spacecraft into orbit. These could include satellite solar power stations, large radio telescopes, manned space stations, and eventually manned Lunar bases. However, the desirability and practicality of carrying out any of these missions will depend critically on the unit cost of boosting them into space. This cost accounting must include not only the recurring costs on a flight-by-flight basis, but also amortizing the development costs of new space transportation systems. Thus, there are dual requirements: the cost of Earth-to-orbit launching must be brought down to a point which justifies a heavy investment in space applications and exploration, and the volume of traffic thereafter must be great enough to justify the investment in the development of new systems. It is presumed that if the first can be accomplished, the second will follow.

Another factor of the cost picture is the effectiveness with which space systems can be built and operated. Whether or not solar power stations, for example, will be competitive with Earth-based solar power generators will depend to a large extent on the mass efficiency of devices for collection, conversion and transmission of solar energy via satellite station, all of which can be measured in terms of power delivered on the ground per unit-mass in orbit. The practicality of other application missions, such as Earth-survey satellites and space processing, as well as a number of conceivable exploration missions to various planets and satellites, will depend on similar effectiveness ratios, as well as on the efficiency with which energy can be stored on-board and converted into forms suitable for powering station operations and providing additional propulsion. Space propulsion is required for trajectory establishment, station-keeping, attitude control and course correction. The first of these is, of course, particularly important when a mission requires high escape velocity from Earth, orbiting of another planet or satellite or descending to its surface. The fraction of mass that must be devoted to storing energy on-board determines, to a large extent, the fraction of spacecraft mass which can be devoted to the payload of instrumentation, communications gear and so on. Explorations beyond the solar system, perhaps aimed toward other stars, are completely impractical with propulsion systems available in 1975. As such missions become more desirable there will be an increasing pressure to develop new and highly efficient propulsion schemes, such as antimatter storage systems.

In summary, there is a long list of missions, both in the areas of basic and intellectual human needs, whose practicality can be either justified or not on the basis of (1) the cost of boost into orbit and (2) the mass efficiencies of energy systems in space.

b. Technology for Solutions

(1) Earth-to-Orbit Space Transportation Systems. To discuss such systems, four possible levels of capability are defined.

Level	Payload/Yr, 10^6 lbm/Yr (kg/Yr)		Payload/ Launch, 10^3 lbm (kg)
	Up	Down	
I	0.5 (0.23)	0	30 (13.5)
II	4 (1.8)	1 (0.45	60 (27)
III	20 (9)	2 (0.9)	400 (180)
IV	100 (45)	2 (0.9)	2000 (900)

The presently devised Space Shuttle system operating at full capacity could accommodate traffic up to Level-II. However, there appear to be recurring-cost reduction incentives for major technology advancements in the Shuttle after the present system has matured. The Level-III requirements could be made only by a completely new system. It is estimated that a special vehicle for the Level-IV class would not be economical since the economies of scale would already be met at Level-III. Level-IV capability would be accomplished by more launch sites and flights with a Level-III vehicle.

By the year 2000 the recurring flight costs of an upgraded Shuttle (Level-II) could be brought down to about \$180/kg of payload delivered, and a second generation, fully reusable Shuttle might reduce this cost to about \$110/kg. Beyond that, there are a number of other options which seem available such as a winged, single-stage-to-orbit (SSTO) vehicle or vertical takeoff vertical landing (VTOVL) vehicle, which might bring the cost down to about \$50/kg for Level-II operations.

A low-cost, heavy-lift vehicle (Level-III) for massive transport to orbit can bring recurring costs to a minimum by profiting from such features as single-stage-to-orbit, VTOVL, zero return payload, no cross range on return, unmanned operation if used in conjunction with a smaller manned Shuttle vehicle, and optimum combination of high-density and low-density (high-performance) propellants. Recurring costs of less than \$50/kg delivered to orbit can be envisioned for such Level-III systems. The development investment in the new heavy-lift system could range from $\$8 \times 10^9$ to $\$10 \times 10^9$.

At all levels of operation, high-pressure hydrogen/oxygen engines, possibly augmented by engines burning higher density propellants in the early part of the boost, will likely continue to find advantageous use.

The general conclusion is that there are many feasible approaches to reducing Earth-to-orbit recurring mission costs to a level of \$50/kg by the year 2000, provided program requirements generate the need to launch numerous large payloads and, hence, the rationale for the large nonrecurring investment implied for the new developments.

(2) Space Power and Propulsion Systems

(a) Energy Transmission. Only laser and microwave beam systems are considered to be feasible during the next 25 years for transmitting large amounts of power between systems in space or between the Earth and space, with the micro wave systems being the most advanced and appearing to be the most desirable for use in cislunar space over the time period in question. The high efficiency and high power density, predicted for microwave beams, will be made available for space applications to a large extent through industrial development without major application of NASA resources. Microwave beams can be collected by means of high-efficiency rectennas (rectifier-antennas) with masses on the order of a few kg/kW of beam power received. By the year 2000, overall transmission efficiency (dc power out of receiver/dc power into transmitter) of more than 70% can be envisioned with kilometer-scale apertures.

Laser beams, collected by photovoltaic cells and converted to electrical power, might be of use in special applications, particularly when longer distances than Earth-orbital are involved. Even though the projected efficiency of laser power transmission systems (≈10%) is considerably below that projected for microwave systems, the areas required for transmission and reception are only 10^{-4} as large.

(b) Energy Collection. Photovoltaic systems are the primary means of collecting energy in space for spacecraft in use in 1975, and will very likely continue in that role. It is reasonable to expect that such systems will also be used at a very large scale if satellite solar power stations should become practicable. However, there are some advantages in the use of large concentrators with thermal conversion by heat engines. In particular, this approach is more resistive to degradation from high energy particles such as would be encountered in the radiation belts around the Earth.

On the surfaces of other bodies, such as at a Lunar base, extraterrestrial materials can be collected and processed into chemical constituents which store the energy. This would of course require the development of either solar or nuclear energy sources to provide the necessary primary energy source, and in fact the net energy available would be less than that originally supplied. For example, electrolysis of water ice to make chemical reactants for power or propulsion requires an input energy of approximately 2.5 times the energy that can be recovered by later reaction of the chemicals. Nevertheless, such collection and conversion may be desirable as a means of providing energy which can be transported from the primary energy sites or can support peak loads; the primary power plants would of course be used for other purposes at such an extraterrestrial site.

(c) Energy Storage. On the basis of mass-per-unit of stored energy, primary batteries, stable chemicals, and flywheels are

competitive for storing energy and converting it to electrical energy. Forecast mass ratios for these devices by the year 2000 range from 10^{-6} to 10^{-7} kg/J. Neither metastable chemical systems nor superconducting magnetic systems appear to offer any particular advantages with regard to this parameter.

For large amounts of energy storage such as that required for space bases or for propulsion, fission nuclear devices offer very great reductions (factors of 10^3) in mass per unit stored energy, when compared with any other devices expected to be available before 2000. Nuclear device cost-per-unit of energy stored should be similar to that of chemical devices.

(d) Conversion to Mechanical Energy for Propulsion. Since the variety of propulsion needs is great, no single system will dominate this picture. Chemical propulsion will continue to be used extensively throughout the period. However, for missions which require extremely high velocity increments, such as solar system exploration, other propulsion systems will be employed once the spacecraft is in orbit. Solar electric and laser electric systems should show cost advantages over chemical systems for such missions as well as for raising an orbit from low altitude to synchronous altitude and return. Solar sailing may offer cost advantages for missions with modest payload mass operating at distances of the order of 1 AU from the Sun or less. Toward the end of the time period, it is likely that nuclear electric propulsion and power devices may dominate high energy missions to the outer portions of the solar system. Such systems would permit the delivery of very large payloads to and from the outer planets with trip times held to several years, and manned missions to the near planets with trip times less than a year.

It is likely that by the year 2000, advanced hydrogen-heating nuclear thrusters, such as the dust-bed concept, or the gas-core concept could be brought into being yielding exhaust velocities comparable to those of nuclear electric systems but with greatly reduced energy conversion system mass. Other, even more advanced ideas, might be on the horizon by the turn of the century: fusion systems or even antimatter systems. Such advanced propulsion systems will only be brought into being if there is a specific mission demand for high performance. It seems likely that a space nuclear fission power source in the 100 kWe to 500 kWe size range will be developed in the time period of interest.

One-half to one billion dollars and long-lead (10 years) development times would be needed to bring a nuclear electric propulsion system into being. This device, using electric thrusters, would then take its place along with chemical propulsion, solar electric propulsion, and solar sailing in establishing the space transportation capability of this century.

(e) Conversion to Electrical Energy. A number of conversion concepts were examined in this category corresponding to a variety of different input/output requirements and power levels. Most of the systems indicate mass-per-unit power parameters of the order of 10 to 100 kg/kW. The solar dielectric concept could conceivably be used to convert solar energy to electricity at a mass of 1 kg/kW for low-power spinning spacecraft. Even lower mass/power ratio will be possible with very large magnetogasdynamic converters. The forecasted advances of major importance for energy conversion to electrical energy are:

(1) Major reductions (order of magnitude) in the costs and specific mass of large photovoltaic solar energy conversion arrays.
(2) The use of thermionics for radioisotope energy conversion with a factor of 6 reduction in mass-per-unit power when compared with presently used thermoelectric converters.
(3) For very-high-power (multi-megawatt) systems with either chemical or nuclear sources, magnetogasdynamic converters will provide low specific mass (0.3 kg/kWe) and potentially long lifetime.

D. MANAGEMENT OF MATTER

1. Overview

As in 1975, space missions of the future will continue to demand structures with high strength-to-mass ratios, long-life microelectronic components, reliable protection and support of components and crew, and accurate positioning and guidance. Pressure for low cost will continue to be great, and determine not only how much can be done on a particular mission, but whether or not the mission will be done at all. For example, satellite solar power stations will come into widespread use if they demonstrate an economic advantage, but will not progress even beyond the prototype stage if they cannot demonstrate such an advantage. It is important then that technology advances continue for a wide variety of new materials coupled with increasingly powerful techniques of design analysis. This will result in major improvements in the mass, cost and reliability characteristics of space systems. As mentioned earlier, microelectronic systems, both processors and memories, are projected to have increases in capacity of several orders of magnitude based on today's technological understanding.

One could always specify a requirement for accuracy of positioning or guidance beyond any quoted number, so there is probably no such thing as "sufficient" accuracy. However, considering a wide range of missions conceivable between now and the turn of the century, advances in guidance and control technology will provide the capability of satisfying practical demands.

The field of technology which limits many space activities relates to life-support systems. 1975 technology does not provide substantial recycling capabilities: gases, liquids, or solids. Nor is there yet any medical solution to such problems as calcium loss from bones in a weightless environment. It will require several years to work out satisfactory solutions to problems such as these.

2. Elaboration

a. The Problem. Future space missions will require significant improvements in on-board data handling capability. This will demand high-density data processing systems and memories with low power requirements. Communications will demand large antennas capable of being accurately aimed at their receivers. New possibilities in space applications will be either practical or impractical depending on whether or not extremely large (many square kilometers in extent) structures can be assembled and controlled in Earth orbit with a low mass and for low cost.

Entry into the atmosphere of another planet, or landing on the surface of another planet or satellite will require accuracies similar to those demanded for re-entry to the Earth on return from the Moon. However, for planetary exploration, this accuracy must be provided at a remote distance, with moment-by-moment corrections generated by the spacecraft system itself.

Manned operations in Earth orbit, or on the surface of the Moon might offer considerable economic benefits. Some missions could be carried out by crews of only a few individuals staying in space for a matter of weeks. This capability has already been demonstrated. However, for missions requiring larger crew sizes and durations of years in an extraterrestrial environment, the problem of resupplying food, water, oxygen, and other needs is a very major challenge.

It is known that long periods of weightlessness cause bone resorption and it is reasonable to believe that the same problem might arise at a fraction of the Earth's gravity, such as on the surface of the Moon.

There is a continuing need to protect human crews and a number of sensitive instruments from the space environment by providing adequate pressure containment, thermal protection and radiation shielding. In addition, there are likely to be special needs such as the requirement to maintain superconducting elements at a sufficiently low temperature for long periods of time and the requirement to adequately seal samples of material returned from the surface of Mars, or radioactive waste products delivered for disposal outside the solar system.

b. Technology for Solutions

(1) Microelectronics. Advances in microelectronics have been rapid over the past several years and will continue to be. Both costs and power requirements will be reduced steadily while reliability and speed will increase. Artificial intelligence and robotics will be practical to implement in spacecraft. There will be a particularly important growth in the capabilities of data storage, using both semiconductors and magnetic bubble systems. By the end of the 1980s, storage systems such as optical memories using laser/read-write and holographic techniques, will be capable of storing data at a density of 10^{14} bits per cubic meter. It is also possible that a variety of superconductor elements will enter the picture in the 1980s, at least for Earth-based computers. In general, the microelectronics picture is quite encouraging. This area of technology is not likely to place any limitations on space missions in the remainder of this century with but one major exception: the configuring of these dense microcomponents into reliable systems.

(2) Materials and Large Space Structures. The ability to assemble and control large structures in space has yet to be demonstrated. However, there are a number of developments which indicate that this will become practical. Metal matrix and polymer matrix composites will play a very significant role in realizing large efficient space structures. The use of composites will provide a 30 to 50% saving in structural weight and a reduction by two orders of magnitude in thermal distortion of extended structures such as antennas, reflectors, and solar arrays. By the use of beryllium and beryllium-aluminum alloys, a fourfold increase in stiffness per unit density can be achieved. Improved polymers will provide a threefold increase in adhesive toughness, strength and durability. The steady growth of attitude control technology will permit accurate pointing of solar arrays with areas of hundreds of thousands of square meters, before the turn of the century. Many types of antennas require more accuracy in pointing, but this accuracy can be achieved for areas of tens of thousands of square meters before the turn of the century.

Clearly, a considerable development effort is required to learn how to assemble and control such huge structures, and undoubtedly this will require considerable advancement in our abilities to carry out human extravehicular activities. However, a research and technological advancement program aimed toward this objective can be laid out with confidence that the basic technologies of structures, materials and control techniques will be available.

Major advances will continue to be made in all areas of structural materials, and not by concentrated efforts devoted to only a few materials or structures systems.

Superalloys and refractory metals with use temperatures of 1200°C will result in efficient space radiators and reusable heat shields. Computer-aided analysis and design methods will result in faster, lower-cost vehicle design cycles. Active controls on launch and reentry vehicles will provide 50 percent alleviation of gust loads. Fire-resistant, high-temperature polymers will continue to be developed, leading to greater space vehicle safety. In the area of space processing, breakthroughs will be made in homogeneity and purity of semiconducting materials, as well as production of materials with unique mechanical and electrical properties. It is likely that in the zero-gravity environment, ultrasmooth, pure, non-nucleated materials can be formed with controlled shapes.

(3) Guidance and Control for the Transfer of Matter. Technologies required for this objective are currently well developed and will continue to improve. With the advent of such techniques as differential very long base line interferometry (ΔVLBI), on-board optical and pulsar navigation, techniques for the delivery of spacecraft to the inner and outer planets will have accuracies in the range of 2 to 20 kilometers. Position accuracy of orbiters around the planets will be

better than a few kilometers, and be approaching 2 to 20 centimeters for satellites of the Earth. It will be possible to control the entry corridor into the atmosphere of Venus for example to 0.2 degree and to locate a roving vehicle on Mars or the Moon to within the order of 100th of 1% of the distance to a referenced landmark. Spacecraft instrument pointing accuracy will improve to 0.005 degrees for interplanetary spacecraft and to 0.0001 degrees for Earth orbiters.

(4) Life Support Systems. As yet, no fully-closed, fully-recycling life support system has been built that can accommodate human beings. There has been success in maintaining small closed systems supporting minute marine animals for extended periods of time, which gives indication that the concept is at least feasible. However, a considerable amount of work needs to be done if a system for human beings is to be fully recycling. Chemical-physical techniques are available for recycling CO_2 and O_2, and for purifying and recycling water. However, the production of food by the recycling of human waste products does not seem to be practical without the help of biological systems. As soon as biological systems are included, it would seem logical to rely upon them for the complete recycling operation, that is, gases and liquids as well as solids.

It does not seem possible to grow food plants directly on human waste products in an otherwise sterile environment. A number of decomposing organisms must be included and this implies the need for a complex ecological system in which only a portion of the primary product produced by photosynthesis would be available for human consumption. On the basis of present knowledge, it would be unreasonable to predict long-term success of a closed ecological system smaller than about one hectare per capita. However, it would be perfectly reasonable to begin experiments with smaller acreages and carefully controlled environments. By the very nature of biological processes, it would take several years to determine whether or not such limited ecosystems could be maintained in a stable condition over extended periods of many years. If experiments in this direction are initiated at an early date, it should be possible by the year 2000 to bring down the area requirements for a space farm to a fraction of a hectare per capita. It might be difficult to guarantee even then that the system could be absolutely closed, but at least the requirements for resupply could be reduced to a minor fraction of the overall mission cost.

(5) Space Medicine. There are a number of problems in space medicine which require attention and research both in Earth-based laboratories and in orbiting stations. Those which appear to be the most critical are problems encountered by long duration at zero or fractional gravity, such as bone resorption, cardiovascular effects and maintenance of muscle mass and neuromuscular coordination; psychological effects on crew behavior for very extended missions in comparatively confined quarters; and radiation hazard. At the present, there is no indication as to how or when such problems can be solved but clearly a final solution will require extensive experimentation with both laboratory animals and human beings at various levels of gravity, including zero. Thus, an extensive space-station research program must be considered a prerequisite to long-duration space missions, coordinated with a parallel program in Earth-based research laboratories.

(6) Protection and Storage. In general, the technology available for the protection and storage of both crews and instruments is well developed and will continue to progress. There will be improvements in meteoroid and radiation shielding. There are other areas in which the technology will advance with significant reduction in the cost of employing the capability. An example is the providing of cryogenic storage over long periods of time for large superconducting systems.

There seems to be no technical problem in providing reliable containment of dangerous solids such as nuclear wastes or biological samples. However, no container is guaranteed to be absolutely safe with 100% probability. Failure rate specifications that are so small as to exceed technical feasibility will call for systems synthesized to provide redundant capabilities and safeguards.

Section II. RECOMMENDATIONS FOR FUTURE NASA EMPHASIS

The general conclusions, which have been summarized in the previous section, indicate that there are many areas of technology which will require NASA support to reach full capability. A number of these areas, selected as being critical to the continuation of a strong space program, are discussed in this section.

The function of this section is to advocate additional emphasis, by NASA, over the next twenty-five years for these selected areas of technology. With such emphasis, our nation will be prepared to embark on the more desirable missions with acceptable risks, when the potential benefits of those missions are identified.

Such advocacy recognizes as a reference the current NASA support to space related research and technological advancement and it is not intended that this be disturbed. Rather, it is proposed that additional support be provided in the areas discussed in this section. The actual proportions and timing of additional emphasis are, of course, quite dependent upon the target dates selected for the achievement of those candidate objectives which eventually become a part of the total national program.

The areas advocated for additional emphasis generally have the following characteristics:

(1) They are predominantly peculiar to space activities and can therefore expect inadequate support for advancement from commercial or other non-space government sources. Eventually, as in the case of communication satellites, many objectives, once demonstrated by the national space program to be feasible and cost effective, will begin to attract the involvement of industry with venture capital and the cooperative support of other governmental agencies.

(2) They are considered to be the advances that will have the greatest impact on the future space objectives.

(3) They, as a rule, affect a broad spectrum of potential space objectives.

The areas of technology selected for additional emphasis are tabulated below.

Preparedness technology selected for special emphasis

- Low cost Earth-to-orbit transportation
- Large, controllable lightweight structures
- Space energy converters
- End-to-end information management
- Communication elements
- Very-long-life components and systems
- Large-scale, reliable microcomponent utilization
- Autonomous spacecraft and vehicles
- Precision navigation
- Instruments and sensors
- Data interpretation
- Nuclear space power and propulsion
- Advanced propulsion
- Closed ecological life-support systems
- Long-flight physio-psycho-socio implications
- Lunar resource recovery, processing and space manufacturing
- Planetary environment remedial processes

A discussion of each of the areas follows.

A. EARTH-to-ORBIT TRANSPORTATION - LARGER SCALE, LOWER COST

Space transportation technology advancement continues as a dominant need for certain missions, not because the missions are basically infeasible using present capabilities, but simply because their cost would be prohibitive. The Shuttle transportation system can be expanded to full capability to give both improved flexibility and lower cost for a variety of missions envisioned for the next 10-15 years. For more advanced missions such as

large orbital power plants, nuclear waste disposal, and assembly and processing operations in space, and eventually bases or outposts in space, a new heavy lift vehicle can provide a factor of three or more reduction in the cost of lifting massive quantities of material to low Earth-orbit. This reduction will more than compensate for a large development cost for the new vehicle system.

B. CONTROLLABLE, LIGHTWEIGHT, LARGE-SCALE STRUCTURES

A complete new technology needs to be developed for such structures so that they can be delivered into space, unpacked, assembled, and maintained with the required precision in orientation, shape, thermal stability, and rigidity. Some of these structures will have dimensions on the order of kilometers and in many cases the shapes of their surfaces will have to be controlled by servo-mechanisms to within centimeters or millimeters. Examples of such structures in the future catalog of space activities include very-large microwave reflectors, microwave antennas, solar-energy collectors, radiators, solar sails, telescopes, and enclosures for farms and habitats.

In addition to structural integrity and shape control, the dynamic interactions involved in the pointing control of such structures are unprecedented.

C. VERY-LARGE-SCALE, LOW-COST SPACE ENERGY CONVERTERS

The attractiveness of collecting solar power in space and beaming it back to Earth depends on the development of either low-cost photovoltaic solar arrays or solar energy concentrators with thermal converters deployed on extremely lightweight structures. In the case of photovoltaic arrays, the high voltages and multi-gigawatt power levels imply that the structural array must have insulating properties. The complete structure should be adaptable to space assembly and subsequent maintenance-free operation for many years. The interactions of efficiency, radiation susceptibility, temperature, and lightweight requirements, along with the need to reduce the cost of such arrays by orders of magnitude, provides a significant challenge. In the case of the concentrators with thermal converters, the problems of orientation, shape, thermal stability, and rigidity of large-scale structures identified previously must be solved.

D. LARGE-SCALE END-to-END INFORMATION MANAGEMENT

The exponential rise in first the need, and then in the ability, to gather data through diverse space activities makes this subject of special interest to the space agency. A great majority of the systems and missions visualized to meet future space objectives harness energy and matter to facilitate the acquiring, transferring, processing, and storing of information. The quantities of data that will result from the projected deluge from space may indeed be unique to NASA. Many Earth-oriented activities, for example those involving meteorological, agricultural, and marine observations, though now feasible for pilot demonstrations on a small scale and in selected areas, will require major advances in information management to be put into operation on a global scale. Future space information systems devoted to these applications will be able to benefit significantly from the miniaturization of processing and storing capabilities, from more sophisticated on-board software systems, from more economical and efficient data distribution facilities, and from advanced methods of man-machine interaction.

Fundamental to the full exploitation of future global information systems is the development of methods whereby users can interact with them. Present space systems serve mainly as information sources to diverse communities of users who may or may not be in a position to take action on the basis of the data provided them. In the future, intervention may often be required, so that control loops between the users and the observed phenomena are closed. Such feedback will surely be necessary if, for example, large-scale, responsible weather modification were to become technically feasible, and economically and sociologically desirable. There will then be a need for very advanced, reliable, economical, high-capacity information systems capable of transferring information at gigabit/second rates, processing it as received or as needed, preserving it in large memories in flight or Earth-based systems, or making it available to users in a form that enables them to make intelligent use of it on a national scale.

It is advocated that NASA undertake a comprehensive study of the entire NASA, end-to-end, information management activity. Among the issues that should be studied are those relating to software and hardware standardization, on board versus ground processing capability, performance measures, agency-wide information distribution networks and facility sharing. This should enable space information management activities to be viewed from a central perspective, to be planned, to be measured or appraised and to have resources allocated in relation to technological needs and importance of application. The result of the study may be a restructuring of NASA efforts (application, operations and research and development) in information management.

E. COMMUNICATION ELEMENTS

It is recommended that low-cost large antenna apertures be developed for use on Earth and in Earth orbit. These antenna apertures will be required for a wide spectrum of candidate space missions, ranging from radio instrument sensing at high resolution and spacecraft tracking throughout the solar system to interstellar communication - the search for extraterrestrial intelligent life.

In addition to employment of classical large-dish reflector antenna techniques, development of low-cost methods of arraying integrated dipole elements for achieving the required antenna aperture size should be considered in light of continued advances in LSI technology and microprocessors. Not only may this become a cost-competitive approach to conventional reflector antenna design but it will also provide for multi-beam operation and electronic beam shaping and steering. In addition to the need for large-aperture antennas, special antenna designs are required at L, S, X, and

K bands for radio sensing and satellite communications. These applications will emphasize special coverage patterns, sidelobe control and multiple frequency and polarization operation. Lens antenna technology and small-element array technology will be used to a large degree to provide these classes of antennas.

It is recommended that LSI technology be exploited to develop compact, integrated communication systems composed of receiver amplifiers and transmitter power amplifier elements connected their respective antenna dipole array elements. Reduced cost, increased reliability, and flexible, electronically-controlled antennas are the major advantages of this integrated design approach. Using microprocessors, the total system would also include data processing and attitude control functions. The size will be primarily dictated by the antenna collecting area. Thus, the spacecraft communication system will be built into the antenna-face, most likely a flat, thin, polygon-sided plate, its area representing the antenna aperture.

Development of complex, high-data volume, real-time digital processors is recommended for a number of information transfer applications such as radar imaging, random access satellite communications and for detection of interstellar microwave signals in a search for extraterrestrial intelligent life. For the latter application, as an example of the extent of processing required, a real-time search of 100 to 200 MHz of bandwidth might be required with a spectrum resolution to 0.1 Hz for detection on weak, highly monochromatic signals.

F. VERY-LONG-LIFE COMPONENTS/SYSTEMS

Many of the candidate objectives warrant the utilization of space activities only if the capitalization cost of the missions or systems can be amortized over a long period of time, requiring little maintenance or resupply. For example, a solar-power station in space might achieve a competitive position with alternative stations on Earth, not only as a consequence of a reduction in the cost of the energy conversion system and the space transportation costs to orbit, but also simply through the station's operation over many maintenance-free years in space.

Systems properly designed for the environment of space actually find space to be a benign environment. Thus, the unique environment of space itself offers the opportunity for space application systems to compete with Earth-based systems. Concomitantly, deep space missions, by the very nature of their long flights to their targets, demand long-life systems lasting for decades.

G. LARGE-SCALE, RELIABLE MICRO-COMPONENT UTILIZATION

The incredible miniaturization of components will continue, altering the whole architecture of space and Earth information systems leading, for example, to distributed systems with balanced use of standardized and customized processor elements, arrayed in optimum fashion for their tasks.

Ultra-high-density microelectronics for information storage is an example of a necessary prerequisite to an expanded and enhanced information management capability. Mass memory of 10^7 bits will be stored on a silicon chip less than one square cm in area; present devices can hold less than 10^4 bits/chip.

As mentioned in Section I, industry will push ahead in this field, but additional emphasis from NASA is required to adapt the new advances for proper utilization in space activities. The potential use of such large quantities of active devices places extraordinary demands on designing reliable systems. These must be either component fault-free, heavily redundant, self-repairing, or a combination of all of these attributes. Because of the unique cost of maintenance operations in space, a significant portion of the burden of the achieving the requisite reliability in the use of such large quantities of these devices will rest with NASA.

H. AUTONOMOUS SPACECRAFT AND VEHICLES

The uniqueness and vastness of the space environment both requires and permits human beings to venture there with their surrogate machines more extensively than to some regions on Earth. Thus, a large share of the burden of developing autonomous machines remains with NASA.

Throughout all of the activities examined by the Study Group, a relationship between human operators and machines in space is implied. Whether the humans are in the machines, on the Moon, or on Earth, there exists a multitude of operator-machine control loops. Already, we have seen the early steps in a technology whose purpose is to develop adaptive human supervisory control of machines having some degree of autonomy. This technique appears to offer a good potential for performance enhancement, cost and cost-certainty improvement, and increased probability of success for many space activities. The use of semiautonomous robots will call for on-board capabilities approximating those of present-day commercial minicomputers, plus visual, manipulative, and analytical instrumentation sufficient to permit a real-time (except for propagation delay), high-level interaction between humans and machines. These capabilities imply kHz to MHz channel rates, megabit on-board storage, microsecond operation times, and four- to ten-level hierarchical command structure. The high-density data storage and end-to-end data management technologies mentioned earlier contribute to achieving these capabilities in semiautonomous spacecraft.

To provide efficient execution of tasks at a remote site, it is necessary to go to higher levels of autonomy and remove the human beings from the sensorimotor control loop, while retaining their involvement in planning, decision making, and problem solving.

To perform even the simplest tasks autonomously, machines must be given the ability to acquire data from their environment, build

models of them that incorporate prior knowledge, physical laws, and "common sense," and use these models for task execution and problem solving.

Such abilities under human direction can yield returns of scientific information a hundred times greater than that provided by 1975 control methods. These techniques could then be used on Earth to reduce the cost of operations here.

In deep space, on missions requiring fast reaction time, round trip light times make Earth-based navigation and control impractical. At such remote locations, machine autonomy is required to move safely from one location to another, determine current location, implement control sequences, and provide a desired set of dynamic states independent of unexpected internal or external forces, equipment failures, or other unexpected occurrences.

I. PRECISION NAVIGATION

High accuracy, in-orbit, position knowledge is intrinsic to many of the potential activities studied. Order of magnitude improvements are required in gravity models, station location accuracies, and in atmospheric density effects with companion efforts in multilateration techniques for Earth orbit determination.

Navigation delivery accuracy to the inner and outer planets using Earth-based radiometric data is limited by the low declination of the target planet as viewed from Earth and errors in the planetary ephemerides in directions unobservable to Earth-based tracking systems. The low declination limitation will disappear when the ΔVLBI navigation technique comes into widespread use.

The planetary ephemerides need to be transferred to an extragalactic radio source coordinate system which will eventually permit angle measurements to spacecraft of 0.01" of arc when used in conjunction with ΔVLBI.

J. INSTRUMENTS AND SENSORS

Substantial upgrading of instrumentation which is peculiar to space ventures is called for by the potential space objectives studied. Scientific and applications missions will each benefit from this upgrading.

The requirement for increasing the effectiveness and capacity of remote sensing systems stems both from the global nature of the problems and from the extraordinary difficulty of some of the required measurements.

Moreover, looking outward, only the earliest and most primitive studies have been made using the spectral windows opened up by space observation platforms. Each of these windows can be expected to yield a panorama of new celestial phenomena with potentially great impact on man's concept of the universe.

Instrument capabilities may be drastically enhanced by technology advancement in space cryogenics and large lightweight optical systems. Most advanced detectors of infrared and microwave radiators, as well as some of the more powerful nuclear and gamma-ray detectors rely on cooling to cryogenic, sometimes superconducting, temperatures in order to function. Considerable non-NASA support may be expected in cryogenic technology.

Lightweight optical systems, employing continuously adaptable optical surfaces formed of multiple elements, will permit extraordinary growth in the light-gathering capacity for both astronomical and remote sensing applications.

In the use of infrared techniques, present requirements to measure trace atmospheric constituents are beyond 1975 instrument capabilities in a number of instances.

K. DATA INTERPRETATION

There is a need to upgrade drastically the level and sophistication of theoretical models for the design and interpretation of remote sensing techniques. As an example, the capabilities of radar and microwave radiometry to measure desired quantities are only understood, with any precision, in a small number of areas and, even in those, there are requirements for enhancement of modelling precision (e.g., temperature sounding).

Such an effort in upgrading measurement conception, data interpretation, and modelling is necessary in order to permit quantitative interpretation of remote sensing data in terms of quantities and phenomena of interest to the user.

L. NUCLEAR SPACE POWER AND PROPULSION

The specific mass and cost benefits of nuclear power capabilities in space have been previously mentioned and are a necessary complement to solar power for many applications.

High levels of operational power must be supplied for long durations in situations where solar energy is not available. The cost-effective solution is the employment of nuclear energy storage converted to tens of kilowatts to megawatts of electric power in space.

The shielding, safety and waste disposal aspects of nuclear power in space are amenable to solution.

Radioisotopes provide a very efficient mechanism for storing energy. When used at power levels below 10 kWe, in conjunction with thermoelectric or thermionic conversion, radioisotopes provide electrical energy on a mass-per-unit energy basis three to four orders of magnitude more favorable than electrochemical batteries. Projected improvements in thermoelectric or thermionic converters and in isotopic fuel can significantly reduce costs from today's levels.

For larger orders of energy and power, 100 kWe to multi-megawatt, nuclear fission reactors will hold the same level of mass-per-unit energy stored and reduce energy storage costs one to two orders of magnitude below that possible with radioisotopes. Development of a

fission nuclear power system of 100 to 500 kWe is advocated for providing power for spacecraft and landed stations and for advanced propulsion in the last decade of the century. If nuclear propulsion is to be used for high-load transportation such as placement of solar power stations in synchronous orbit, multi-megawatt systems should be produced.

M. ADVANCED PROPULSION

Storing and processing energy for propulsive purposes is one of the few major cost drivers in accomplishing two major classes of missions:

(1) Highly energetic missions:
- to the edge of the solar system and beyond.
- within close vicinity of the Sun.
- out of the ecliptic plane.
- to landings and returns from extraterrestrial bodies.

(2) Missions requiring transport of very large amounts of matter:
- nuclear waste disposal.
- solar or nuclear power stations in space.
- bases on the Moon.
- bases in orbit.

These missions could be achieved with energy stored in stable chemicals and propulsion systems having the necessary number of stages.

However, the high costs associated with the required large mass leaving the Earth and the long flight durations can be drastically reduced by the use of systems which accelerate the exhaust mass to very high velocity by electric or magnetic means and which employ energy stored in the nuclear states of matter or collected from the solar radiation in space.

An examination of potential space activities presents a strong case for the development of solar and nuclear-fission electric propulsion in the next 20 years. An early capability would provide a propulsion system specific mass on the order of 23 kg/kWe at propellant exhaust velocities of 2×10^4 to 10×10^4 m/s and thrust levels of up to 20 newtons.

Even more advanced propulsion concepts, which would be brought into operation after the turn of the century, offer the prospect of system mass per unit power levels two to three orders of magnitude less than is possible with currently envisioned solar and nuclear electric propulsion. Comparable exhaust velocities can be maintained. Such characteristics will enable travel into interstellar space with reasonable mission times. Candidates for this class of propulsion system that merit study and research include:

(1) Gas core nuclear fission rockets.

(2) Fusion microexplosion rockets.

(3) Metastable hydrogen rockets.

N. CLOSED ECOLOGICAL LIFE-SUPPORT SYSTEMS

At a certain crew size and duration in space, the cost, mass, and complexity associated with a closed life-support system become less than that of resupplying expendables from Earth.

A number of attractive space objectives will ultimately reach this trade-off point and, since the development lead time is very long, it is advocated that this general technology advancement begin with the last quarter of this century.

At this time, the success of any particular design for closed ecological systems cannot be assured. Whether the recycling of all gases, solids, and liquids can best be done by purely biological processes, or whether certain steps are better done by non-biological chemical-physical subsystems is not known, but must be determined. Even though it might not be possible to guarantee long-term fully closed operation, a vigorous pursuit of this technology should permit substantial reductions in resupply.

Monitoring and control systems need to be developed for temperature, humidity, and probably for CO_2, particulate and bacterial matter, and trace contaminants, even if major recycling is accomplished biologically.

O. LONG-FLIGHT PHYSIO-PSYCHO-SOCIO IMPLICATIONS

As human beings in greater numbers spend more time in space, the physiological implications discussed in the previous section (page 2-9) titled "Space Medicine" must be understood and dealt with.

Consideration has to be given to the appropriate forms of social order for large space ventures involving people. Though the form that this order might take in a small, isolated community is now unknown, its components can be imagined under the title "Quality of Life" and they would include communications, aesthetics, education, law, entertainment, work products, and other such elements that are recognized as the hallmarks of successful human communities on Earth.

Translating our knowledge of social and political science to the environment of space, and understanding the special problems and opportunities provided by this environment requires leadership by NASA.

P. LUNAR RESOURCE RECOVERY, PROCESSING AND SPACE MANUFACTURING

At some point in the future, it is estimated that it will become cost effective to process some minerals into products on the Moon and transport them to facilities in Earth orbit or possibly on Earth.

The obtaining of such resources from space would ease the pressure on the demand for energy and minerals obtained on the Earth.

Present on the Moon are: oxygen for life support and propulsion; metals (e.g., Al, Mg, Fe, Ti) for structural materials and propulsion; ceramics and glasses for construction; silicon for photovoltaic devices; and thorium for nuclear breeder reactor fuels.

The special requirements of resource recovery and processing in the Lunar environment, quite different from those typical of Earth-based industrial processes, need to be examined now and developed over the next one or two decades to prepare for potential opportunities near the turn of the century.

The assembly of small components or modules into large structures in orbit will become necessary. But it may be economically desirable to undertake much more extensive industrial activities, in a space station, using Lunar mineral resources. A rotating station could provide a variety of gravitational fields (from 0-g to normal, or beyond) not easily available on the Lunar surface, as well as uninterrupted solar power.

Taking advantage of this possibility will require the development of special manufacturing techniques appropriate for the space environment.

Q. PLANETARY ENVIRONMENT REMEDIAL PROCESSES

The continued increase in the aspirations of all people of the world to raise their standard of living portends a major unfavorable impact on the Earth's biosphere.

Much of the monitoring of these initially subtle changes is available only through space activities. Efforts to control future damage to our environment and repair the damage already done will be greatly enhanced by the availability of global environmental information gathered from space. This enhancement may well become crucial for the successful preservation of our environment. How such information is to be gathered, interpreted and disseminated needs to be much better understood. We must gain this understanding rapidly. The problem is already here.

Ultimately, once we have learned to preserve our own biosphere and the pristine state of near planets needs to be preserved no longer, the knowledge will be in hand to shape nearby planet biospheres as benign environments for human beings.

A FORECAST OF SPACE TECHNOLOGY

Part Three. MANAGEMENT OF INFORMATION

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GLOSSARY

AADC	All Application Digital Computer
ADP	Automatic Data Processing
AED	ALGOL extended for design
AGC	Apollo Guidance Computer
ALGOL	Algorithmic Language
ALWAC	Axel L. Wenner-Gren Automatic Computer
ANIK	Canadian Communications Satellite
AOP	Advanced On-board Processor
APL	A Programming Language
Arecibo	Antenna located near Arecibo, Puerto Rico
ARPA	Advanced Research Projects Agency
ATN	Augmented Finite State Transition Net
ATS	Applications Technology Satellite
AU	Astronomical unit
BABEL	Computer program for the reproduction of English sentences
bps	Bits per second
CCD	Charged-coupled device
CCS	Computer Command Subsystem
CDC	Control Data Corporation
CMP	Ceslestial Mapping Program (sponsored by U. S. Air Force)
Coherent Tracking	Acquiring both the frequency and phase of the signal
CONNIVER	Computer language for artificial intelligence applications
Copernicus	OAO Number Three
CPAFSK	Continuous-Phase-amplitude Frequency-Shift Keying
CPFSK	Continuous-Phase-Frequency-Shift Keying
CPT	Chief Programmer Team
CRT	Cathode ray tube
CW	Continuous wave transmission, as opposed to pulsed transmissions
Cyclops	Project name for design study conducted in 1971 under NASA sponsorship
dB	Decibels

dBi	Decibels antenna gain referred to isotropic antenna
ΔVLBI	Delta differential very long baseline interferometry
EDSAC	Electronic Delay Storage Automatic Calculator
ENIAC	Electronic Numerical Integrator and Calculator
ERP	Effective-radiated-power
ERTS	Earth Resources Technology Satellite (renamed LANDSAT)
Fast-Fourier Transform	An algorithm for the transformation of a time-varying signal into the frequency domain
FET	Field effect transistor
FORTRAN	Formula Translator, a programming language
FSK	Frequency shift keying
GE	General Electric Co.
GPS	General problem solver
GT40	Graphics display terminal from Digital Equipment Corp.
HAYSTACK	Antenna array operated by MIT Lincoln Laboratories in Westford, Conn.
HDC	Honeywell Digital Computer
HEAO	High Energy Astronomy Observatory
HiSTAR	Sky survey sounding rocket project (sponsored by U. S. Air Force)
HSI	High Speed Interferometer
IBM	International Business Machines Corp.
IC	Integrated circuit
IDIIOM	High speed graphics terminal
ILLIAC	ILLInois Automatic Computer
IMLAC	Graphic display device from Imlac Corp.
INTELSAT	International Telecommunications Satellite
INTERLISP	Improved form of LISP (LISt Processor)
I/O	Input-Ouput
IRAS	IR Astronomy Satellite
IRIS	IR Interferometer Spectrometer
ITPR	IR Thermal Profile Radiometer
LARC	Livermore Atomic Research Computer
LGP	Librascope General Purpose
LIMS	Limb-scanning IR Mesospheric Sounder

LNA	Low-noise amplifier
LRIR	Limb Radiance Inversion Radiometer
LSI	Large scale integration
LST	Large Space Telescope
LT	Logic theorist
LUNAR	Computer program for answering questions about Lunar soil composition
M-ary	M states (e.g. binary if M = 2)
MARGIE	Meaning Analysis Response Generation and Inference in English
MICRO-PLANNER	Computer language for artificial intelligence applications
MIT	Massachusetts Institute of Technology
MJS77	Mariner Jupiter Saturn 1977 mission
MM64	Mariner Mars 1964 mission
MM69	Mariner Mars 1969 mission
MM71	Mariner Mars 1971 mission
MNOS	Metal-nitride-oxide-silicon
Monochromatic signal	Signal whose power is continued in a very narrow frequency band (a frequency spike)
MRPPS	Maryland Refutation Proof Procedure System
MSI	Medium-Scale Integration
Multibeam	Antenna either transmitting or receiving two or more signals simultaneously, each beam generally pointed in a different direction
MULTICS	Time sharing computer system developed at MIT
Multiple Access	Usually the capability of reception of more than one signal at a time
MV67	Mariner Venus 1967 mission
Nadir	Looking straight down from a satellite
Nd	Neodymium
NF	Normalizing factor
NIMBUS	NASA Experimental Meteorological Satellite
Non-coherent Processing	Processing a signal with unknown phase
NRE	Non-recurring engineering
OAO	Orbiting Astronomical Observatory
OGO	Orbiting Geophysical Observatory
OSO	Orbiting Solar Observatory

P	Pioneer
pixel	Picture element
PARAMP	Parametric amplifier
PDP	Digital Equipment Corporation computer prefix designation
PL/1	Programming Language number one
PMR	Pressure Modulated Radiometer
PN code	Psuedo random noise digital code exhibiting unique correlation properties
POPLAR	Computer language for artificial intelligence applications
PPM	Periodic permanent magnet
ppm	Parts per million
PSK	Phase-shift keying
R&D	Research and development
Radar Altimeter	Measures height between the radar and a surface by measuring return time of radar pulses
Radiometer	A passive instrument (no signal transmission) which measures radiated energy in selected frequency bands
RAMTEK	Graphic display devices from RAMTEK Corp.
RF	Radio frequency
RMS	Remotely manned system
rms	Root mean square
SAIL	Stanford Artificial Intelligence Language
SAMS	Stratospheric and Mesospheric Sounder
Scatterometer	A radar that derives measures of target surface roughness from radar signal return
SCR	Selective Chopper Radiometer
SDS	Scientific Data Sysems
SEASAT	A satellite scheduled for a 1978 launch which will make sea state measurements using radio sensing instruments
SHRDLU	Computer program for answering questions about English sentences
Signal Arraying	Addition of signal, added together phase coherently
SIMS	Shuttle Imaging Microwave System
SIR	Semantic Information Retrieval
SMS-VISSR	Synchronous Meteorological Satellite-Visible and IR Spin-Scan Radiometer
SONAR	Radar-type sensing using acoustic signals

SQUID	Superconducting QUantum Interference Detector
SRI	Stanford Research Institute
STAR	Self-Test and Repair (JPL computer concept)
STAR	STring ARray (CDC computer)
STARAN	Trademark of Goodyear Aerospace Corporation
STRETCH	IBM Computer for Los Alamos
STRIPS	Stanford Research Institute Problem Solver
Synthetic Aperture Imaging Radar	Derives images with individual picture resolution cells derived from range and doppler-frequency processing
System Noise Temperature	Related to the noise power of a receiving system in a 1 Hz bandwidth by $N_0 = KT$, where N_0 is the noise power, T is the noise temperature, and K is Boltzmann's constant
TDA	Tunnel diode amplifier
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
Time Share	Sequential use of a communication system, one user at a time
TIROS	Television IR Operational Satellite
Tse Computer	New computer concept for processing two-dimensional data in parallel
TWT	Traveling-wave tube
UDAM	Universal Digital Avionics Module
UDS	Unified Data System
UNIVAC	UNIVersal Automatic Computer
VLBI	Very long baseline interferometry
V75	Viking 1975 Mission to Mars
VO75	Viking Orbiter 1975
VORTEX	Venus Orbiter Radiometric Temperature Sounding EXperiment
WESTAR	Western Union Telecommunications Satellite
YAG	Yttrium aluminum garnet

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Section I. INTRODUCTION

W. M. Whitney

A. SCOPE

The concept of information is so basic in human thought that to define it without using the word is difficult. In communications engineering, the information carried by a message is related to its unpredictability and its value or importance to a recipient. In everyday usage, information is associated with data and facts, with relationships as embodied in organization, form, and structure, and with knowledge. Two essential attributes of information are that it must be able to be given some physical form, so that it can be communicated or transferred from one person to another, and it must be able to affect the thoughts or actions of the person receiving it.

Human beings spend much of their time seeking information, creating it, exchanging, talking, and thinking about it, and preserving it for future retrieval and use. The family of artifacts invented over the centuries to assist in these activities includes such unlikely kin as smoke signals, books, spectacles, and digital computers. In this part of "A Forecast of Space Technology," the term "information management" is to be understood as the organization and interrelating of all the information functions of people and their many and varied devices to fulfill some purpose or to reach an objective.

Because of the enormous breadth and diversity of information systems and their central importance in human life, a forecast covering all of their ramifications and applications would call for resources far greater than those available in conducting the Outlook for Space study. The scope of the discussion is thus limited in several important respects. First, the focus is primarily, though not exclusively, on information systems necessary for operations in space or their support on Earth. Second, while people are the most important elements of information systems, the forecasts deal not with them but with the machines or devices that facilitate or supplant human performance of information functions. Third, the forecasts are concerned more with functional elements than with systems that combine several functions. Those systems treated are ones thought to be of special future importance. A total system usually arises out of a highly specific set of objectives, requirements, and constraints, and simply to catalog the possible space applications of information systems over the next quarter century would have been a difficult and lengthy undertaking. Finally, the scope of the forecasts has been further restricted by relating them to rather comprehensive, high-level functional parameters. It may not now be known how the implied capabilities are to be achieved. Coverage of the approaches and disciplines that may contribute to their implementation is not uniform. Forecasts have been prepared for some fields because they have shown especially rapid progress, or because their potential seems high for delivering better performance.

The net result of the above restrictions in scope is that many large and active areas of information-management technology have been excluded from consideration. It is hoped that their absence, whether through judgment or through oversight, will not lessen the value of the forecasts in those areas that are represented.

Many of the trends upon which projected changes in information technology are based reflect recent or expected advances in semiconductor processing and microelectronic circuit fabrication. These developments are described and forecast in Part Five, Section III, "Acquiring and Processing Inanimate Matter – Microstructures." Readers may find it worthwhile to refer to this material in association with the forecasts to be presented here, especially those dealing with computing and storing hardware characteristics.

B. ORGANIZATION AND APPROACH

Following the morphology described in Part One, information functions are grouped into the categories of Acquiring, Processing, Transferring, and Storing.

In space operations, the acquisition of information is primarily the function of measurement or sensing. The first group of forecasts (Section II) is thus devoted to scientific instruments and experimental apparatus for measuring physical phenomena. While an instrument is always an element of an information system as well as a physical sensor or probe, the emphasis in Section II is on its role as a probe.

Information transfer (Section III) is the function of communication. This category includes the distribution or dissemination of information to its ultimate users via networks or by other means, and also the channel encoding and error correction necessary for faithful transmittal. An important link in the communication chain is that between human beings and the input or output devices of the machines with which they interact directly. Because the interaction has less to do with transferring information than with changing its representation so that it can be conveyed across the human-machine interface, this link is assigned to processing.

Processing covers the operations necessary to extract, represent, or transform the information acquired from sensors or other sources (for example, people) so that it can be delivered to a communication link or directly to a human user. Source encoding for efficient data or information transfer (data compression) is included in this category. Storing or preserving information for later retrieval and use may be necessary at all stages of acquiring, processing, and transferring, and for varying periods of time. Forecasts for processing and storing are combined in Section IV for reasons given there.

The concluding section, Section V, summarizes the highlights of the forecast and discusses some of their implications.

The approaches taken by the Coordinators in organizing and developing forecasts differed from field to field; they are described in the introductions to each of the following three sections. Some additional general comments need to be made in this section about variations in the choice of parameters, in form and approach, and in outlook that are evident in the forecasts themselves.

An objective in planning all the information forecasts was to establish, for each function, one or more quantitative performance measures whose past behavior could be determined and used as the basis for a projection into the future. In a few areas, this goal was reached without difficulty. The capacity of a communication channel is routinely expressed in bits/second, so it was natural to employ this measure in most of the information-transfer forecasts. The bit and the bit/second are also useful in specifying (respectively) the capacity of memory and the rate at which information can be passed through a processor, largely because digital methods are used to represent information in storage systems and in processing registers as well as in communication links. Another measure of processor throughput used in Section IV is the operation/second. The operation is a weighted average of machine instructions, introduced to establish a common basis of comparison among machines with different numbers of bits per word. For a given machine, this unit can be converted to bits/second.

Data provided by measuring instruments can also be expressed in bits, once they are digitized and encoded in a form that allows them to be stored, transformed, and transferred. Such a measure is both useful and necessary in assessing the impact of a given instrument on an information system, but it is only one of several measures necessary to specify instrument capabilities completely. Since the forecasts in the category of acquiring information relate to extensions of the performance limits of instruments, the parameters chosen relate to the physical properties measured and the techniques and principles employed. They do not necessarily gauge the suitability of the instrument in any given application. To determine this demands specific knowledge not only of the instrument but of the requirements and constraints on the whole system of which it is but one part. Such comprehensive considerations do not fall within the scope of this study; hence the decision to regard the sensor as a physical probe.

In some areas, no useful performance measures could be found or invented. The effectiveness of a computer in executing a program can be defined and scored, but there is no generally accepted or unambiguous way of judging the efficacy or value of what the program does. For numerical algorithms, speed and accuracy (in a given computer) are useful criteria, but their development does not seem to be leading into new territory and they are not forecast here. Of considerably greater interest are programs that carry out symbolic procedures of the kind required for understanding and using language, proving mathematical theorems, or making decisions despite incomplete knowledge of possible outcomes, as in playing chess. Is a chess-playing computer program that makes mediocre but legal moves in one minute better or worse than one that makes excellent moves in one hour? The answer may depend on the user and his goals (and on who pays for the computer time). Extending information theory, or developing a new theory, so that quantitative statements can be made about such complex situations remains a problem for the future. In the absence of a better approach, our forecasts for "intelligent" computer programs and for complex sensor-effector systems — teleoperators and robots — activated or controlled by such programs are presented in descriptive, qualitative terms.

More than one hundred people have worked directly or indirectly, as contributors or consultants, in developing the information forecasts. Given the expected variations in technical perspective, temperament, and "Weltanschauung" of such an ensemble of forecasters, it is inevitable that different degrees of vision, optimism, caution, and hope are manifest in their forecasts. Reviews of earlier drafts of this material have revealed a number of oversights and apparent conflicts. Many of these have been corrected or resolved, but not all. Given that forecasting is not yet an exact science, it has been concluded that considerable amounts of uncertainty and nonuniformity go with the territory. Thus, except for the changes already noted and for certain changes in format and content made for editorial reasons only, the projections of our experts have been preserved.

C. CURRENT TRENDS AND PROBLEMS

Certain difficulties in present information management activities are widely recognized as limiting performance below what is desired or needed. Trends are evident that may accentuate these difficulties or create new ones. The purpose of this final subsection of the introduction is to highlight some of these problems and trends in the belief that such things drive technology. Efforts successfully made to alleviate problems, or to counter the effects of trends, play a role in shaping the future. It is not the intent to imply that technology alone will provide the solutions; what is needed may already be at hand, and require only better management or planning to be successfully applied. At the very least, however, today's problems, obstacles, or bottlenecks, and today's trends - the "first derivatives" of the problems - provide a useful normative context against which forecasts can be viewed and interpreted. These

paragraphs thus serve as prologue to the forecasts, and the final Summary and Implications section as epilogue.

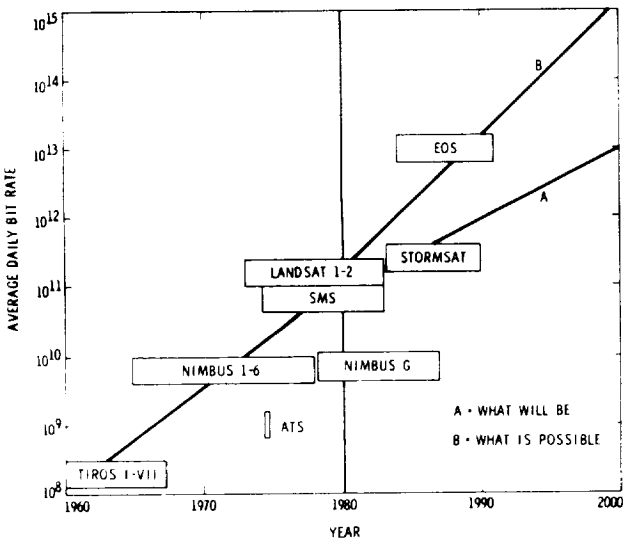
The purpose here is not to catalog all current problems, but rather to examine four recurrent central themes encountered in the course of this study.

1. The Data Deluge

The trend of most significance for space-related information management activities is the growth in the sheer volume of data sent back to Earth by satellites and by extraterrestrial spacecraft and probes. An extrapolation to the year 2000 of the expected return of imaging data from a series of projected or planned Earth-applications satellites (Forecast FC 3-1) shows that the daily rate will be 10^{13} - 10^{15} bits. On the assumption that 10^7 bits will encode an average 300-page book (4000 characters/page, 8 bits/character), the accumulation will be the equivalent, in bits at least, of 10^6 books/day, 30 Libraries-of-Congress/year -- each with holdings of over 10 million volumes -- from this source alone. The contributions of all other spaceborne systems, in sum if not individually, are certain to be comparable or greater.

MANAGEMENT OF INFORMATION FORECAST

FC 3-1. Growth of Image Data Rates from Applications Satellites



The prospect of such a deluge from space, from which there will be no surcease after forty days and forty nights, poses an awesome challenge to information management. We must contain and channel the flood and avoid engulfment to derive the benefits that are sought. Large stores of data from previous flights await analysis and interpretation, much of it becoming obsolete. Will such backlogs inevitably grow, or can their buildup be prevented by better mission planning and experiment design? Other questions suggest themselves whose answers require thorough analysis and understanding of the total information system for each application. Should all data acquired by the spaceborne instruments and sensors be returned to Earth? What is the maximum rate of return of data from deep-space probes that can be justified economically? What are the most effective and least costly means of distributing data and information to users? Is there enough capacity in projected Earth systems to process all the data received? How can the receiving stations, the communications facilities, and the mission control centers be best employed to effect the collection of information from concurrent missions? How much standardization of approaches and systems can be achieved without hindering the development and introduction of new technology?

The importance of end-to-end studies of the information management process is recognized, but until recently the focus in planning and in development has been on individual functional elements rather than on their interrelationship or on the optimization of the performance of the whole system. Furthermore, lack of knowledge, immature technology, or the cost of making modifications has often prevented putting into practice certain changes that would benefit the overall handling of the information flow. Spacecraft processing is in its infancy; on-board data systems lag those on Earth in capability; and most data-compression or information-extraction algorithms (for example) require fast, medium-to-large processors. Despite steady and significant reductions in the cost of providing high data-communication-rates, requirements have increased still faster, with the result that the data collected by the tracking stations cannot always be relayed as received (in "real time") to control centers or to users. Some data acquired by spacecraft in flight are lost because the ground systems must be directed to other missions of higher priority. The projected increase of data will exacerbate these and other problems. There is an awareness, however, of the importance of identifying those problems that have the most impact on the information system and developing the technological and management approaches needed to mitigate their effects.

2. The Human-Machine Interface

Without the speed and accuracy of automated data handling, the space ventures in which the United States and other countries are now engaged would be neither practical nor possible. Use of the computer now pervades all NASA activities, so much so that it is surprising that its necessity was not foreseen in most of the science fiction written about Lunar and planetary exploration before it actually began.

As increasingly ambitious missions have placed heavier demands on information systems, the preparation of computer programs - "software" - has become a major NASA activity. The speed and efficiency with which people can develop such programs have improved, but they have not kept pace with the work load, and the fraction of total effort devoted to software has increased. Furthermore,

while the cost of hardware for a given level of performance has fallen sharply, the cost of human labor has gone up. Thus, software production is an important element in the cost of flight projects. Raising the productivity of people who work with computers is an important avenue to less expensive missions.

Programming can be viewed as the translation of human information processing requirements into instructions that can be executed by machines. Because modern computers are so fast, most of the time that elapses between formulation of the requirements and receipt of results from the computer is usually attributable to programming. Since this process depends in a complex way on the characteristics of people and machines and their complex interaction, it is useful to think of it as occurring at a "human-machine interface."

Two aspects of human-machine interaction, although interrelated, can be discussed separately. The first is the process of software production — its design, coding, testing, and maintenance, and the management activities concerned with planning and controlling these steps and estimating the resources that must be allocated to them. The second is the process of working or interacting directly with machines to develop programs or to use them to execute a program or to perform a task requiring computer intervention or control.

Software has been more resistant than hardware to the introduction of systematic procedures for design and development and for schedule and cost control. Programming still calls for much human ingenuity, and remains as much the domain of the artist and craftsman as of the engineer and technician. The productivity of programmers varies over a wide range. Software development has typically been difficult to manage. Cost overruns and schedule delays are common, and every organization that develops its own programs usually has several software skeletons in its closets.

Increases in programmer productivity have resulted from the introduction of compilers and other high-level languages. Smaller but significant gains have been achieved through innovative approaches to software structuring and management control. Attempts to automate steps in software development, for example, the verification of program correctness, have not as yet led to results of general applicability. While there is now widespread awareness of "the software problem," concerted attempts to come to grips with it (or with them, since "the problem" is many) have been made by only a few large organizations. The writing of programs is still such an integral part of most day-to-day activities that it is difficult to recover information essential to problem diagnosis and correction, for example, the sum and distribution of costs for program coding and maintenance.

The difficulties associated with human-machine interaction derive largely from the vast differences in the capabilities and structures of humans and machines. Even when people do not speak the same language, they can communicate with one another to some degree (using gestures, facial expressions, etc.) because they share common biological structure and needs, common patterns of thought and behavior, and large overlapping stores of knowledge about the world. Machines and humans do not share these things, and most of the burden of communication falls on the human. The languages employed must be ones acceptable to the machine. Strict rules governing format, syntax, and vocabulary must be observed. The user must be familiar with the protocols of the local operating system and sometimes with the characteristics of the processor and its peripheral equipment to make effective use of the computer capabilities.

A variety of problems like those discussed above limit the rate of information flow across the human-machine interface and presently keep the cost of using computers from following the steep decline exhibited by information hardware costs. Furthermore, because the interface is not yet congenial and transparent for the average person, the use of the computer remains the domain of the specialist.

3. Reliability

Of all the performance characteristics of space-related information systems, reliability may be the most important, and providing it may be the most difficult and expensive single task in spacecraft data-system development. The effects of unreliability are most apparent in the flight systems. If a subsystem of an unmanned system fails, it cannot be repaired. A malfunction in a manned craft may jeopardize the safety of the crew as well as the success of the mission. Although ground systems can be more easily repaired, reliability is an important aspect of their operation as well. Valuable data from remote spacecraft have been lost because of failures in the Earth-based data systems during critical times.

As systems grow more complex, they generally become more prone to failure. A measure of complexity is the number of parts and interconnections — for example, the number of signal paths in circuits, or the number of branches in computer programs. There are many sources of potential malfunction in spacecraft data systems, and all of them have been experienced at one time or another. The stresses and wear arising from repeated use have made the tape recorder one of the most unreliable elements carried on spacecraft. Microcircuits used in the construction of electronic subsystems are subject to a variety of failure modes — electrical short-circuits, mechanical separations of connections, and chemical corrosion, to name a few. Also, structural failures have been experienced in antennas. Because of the tendency of all human artifacts eventually to deteriorate, the general dictum has been to keep the complexity on the ground where failures can be dealt with.

There is, however, a lower limit to the complexity of data systems carried on spacecraft that reflects an engineering tradeoff between the capabilities of the ground and the flight systems. The mission may have a greater chance of success, or may cost less, if certain functions can be performed on the spacecraft. The limit goes up as the requirements placed on spacecraft increase; flyby and orbital spacecraft have been required to do more with each successive mission. More ambitious undertakings may demand additional operating modes and functions, and may expose the systems to a greater range of environmental

conditions. Examples of space activities that will require much more capable information systems than have been used in the past are provided by Space-Shuttle operations, data handling for Earth applications satellites, teleoperator control in Earth orbit for satellite servicing and in the construction of large structures, remote surface exploration, and missions of long duration at great distances from Earth. There is also a natural tendency for system complexity to grow with experience in design and use.

Many approaches are used today to increase system reliability. Known failure modes are carefully studied and modelled. Conservative designs are adopted to counteract failure modes or reduce their impact; redundant components or subsystems are carried, functional redundancy is provided by using systems that can exchange functions, design and construction methods are standardized, and architectures are developed that facilitate the isolation and identification of faults on the ground during testing. During manufacture and assembly, parts and subsystems are carefully screened and inspected. Rigorous testing is done at all levels to identify short-term failures and problems introduced in integration. Computer programs are exhaustively exercised. Models are developed that enable the reliability of systems to be predicted from knowledge of reliability of their individual components. Failure data are accumulated and analyzed to guide system development the next time around.

The above approaches are relatively effective, as is demonstrated by the generally good record of success in NASA undertakings, but they add significantly to mission cost. There have been some important reliability gains, for example, in integrated circuits. As the level of component integration has gone up, so has the reliability per element — an entire large-scale integrated circuit chip is now approximately as reliable as a single transistor. However, system complexity has gone up faster, so the overall reliability of flight systems has not greatly increased.

An important contributing factor in the cost of reliability is the uncertainty attached to predictions of system life. Because it cannot be stated with precision when a given part will fail, there is a tendency to design too conservatively, as evidenced by the many missions that have far outlasted their nominal design lifetimes.

Several limitations can be observed in present approaches to the design and integration of information systems that eventually must be overcome to reduce the cost of making them more reliable. There is inadequate understanding of the causes of failure at the component level. Physical mechanisms must be determined so that predictions of hardware failures can be made on the basis of physical as well as statistical models. Such knowledge will reduce the uncertainties of predictions and cost of overdesign. At the organizational level there must be increased understanding of how to create reliable structures from unreliable parts. This challenge was recognized long ago by von Neumann but the basic problem remains. Nature has found a solution, but it still lies beyond our detailed understanding. Presently it is not known how best to allocate reliability among various hierarchical levels or between hardware and software. Certain concepts of self-test-and-repair involving both hardware and software capabilities have been demonstrated and studied but not applied in flight systems.

The problems of making reliable information systems are difficult and there is likely to be no single simple solution. Reliability is a major underlying theme in all space-related information activities. It outweighs other criteria in many decisions concerning the introduction of new technology. Until better methods are found to cope with reliability, it will continue to play a major role in setting pace and direction for the evolution of space-related data systems.

4. Automation of Information Functions

The missions undertaken during the first two decades of space exploration display a steady upward progression in complexity and difficulty, a trend that is unlikely to diminish during the next 25 years. Programs now under consideration will involve a great diversity in space-borne systems and applications of them, but one common characteristic is that their tasks will place heavy demands on both the flight and the Earth-based information systems. Eventually, for reasons of cost and performance, it will be necessary to automate on the spacecraft far more of the information functions presently performed on Earth, many of them by people.

There are many advantages to doing more data handling on board the flight systems. Extensive preprocessing of instrument data, followed by source encoding to enhance the content of useful information, could greatly reduce the requirements placed on the communications channel, and also mitigate problems of collecting and disseminating information on Earth. If planetary landers or rovers could conduct more of their operations independently, there could be a reduction in the number of control and status messages exchanged with Earth and their tasks could be carried out more rapidly. Spacecraft less dependent upon constant surveillance for continued safe operation could enable Earth-based control and communication facilities to divide their attention among a number of missions simultaneously, thereby reducing the overall cost of ground operations.

There are also benefits to be derived from more automation of Earth-based information functions. From the discussion of the human-machine interface, it is clear that substantial cost savings could result from even a small increment in the automation of software production, and that increased use of computers could follow from any advances in machine capabilities that would make human-machine communication more comfortable. Astronauts could perhaps benefit from a more conversational or at least less highly structured mode of interaction with spacecraft subsystems. Greater automation of spacecraft design, testing, simulation, and status monitoring during flight would also

appear to be achievable and desirable. Research within NASA and elsewhere is being conducted to give both spacecraft and ground systems some of these capabilities. Some useful techniques already exist, and await only the development of sufficiently cheap and reliable flight data systems to be implemented and flown.

It is not at all clear, however, that the needs for better mechanization of data handling can be met simply by extensions of present knowledge and approaches. While the stated emphasis in this part, Part Three of "A Forecast of Space Technology," is on machines that facilitate or supplant human information-processing functions, present machines, by and large, do more of the former than the latter. They can perform any function rapidly and well that can be reduced to an algorithm. Progress in the simulation of "higher level" functions like those associated with human thought and perception seems blocked or greatly retarded by the slowness of advances in understanding these processes. Nearly all living systems — but predominantly people — are able to organize actions around needs or goals, and to extract from a wealth of sensory stimuli the information needed to satisfy the needs or accomplish the goals. There are principles of motivation and of value or utility exhibited by such behavior that are not understood and that are not represented with generality or sophistication in present machines.

Future machines will be significantly better than our present ones if they are able to do some of these things:

(1) Extract, from a large collection of data, the information relevant to some purpose, according to criteria supplied externally or developed internally in response to a plan. Obvious applications are reduction of the data stream from multi-spectral imaging Earth satellites by large factors, sifting through sensory data to obtain information needed for robot operations, or tailoring the telemetry stream from a planetary spacecraft to fit within the limits of the communication channel capacity.

(2) Represent information in such a way that facts and relationships can be assessed and identified by attribute or by association for use in a variety of contexts, and modified or reorganized on the basis of new information ("experience") without requiring an exponential growth in storage capacity. The facility for doing these things seems important to all systems that must deal with a very large data base in order to plan and conduct tasks requiring an interaction with the world or with changing information sources.

(3) Make branching decisions on the basis of qualitative criteria ("values") and ordered priorities. This capability would be useful in some on-board data management tasks but it would be especially valuable in Earth-based systems, not to replace human judgment but rather to model human decision processes and display the consequences of alternative management strategies.

(4) Control a large number of parallel operations, the individual steps of which may be interlinked and dependent upon conditions of time, priority, and prior event.

(5) Detect malfunctions and correct or nullify their effects by internal reorganization.

Research at the frontiers of information and computer science is presently directed toward achieving all of the capabilities discussed above, but the problems faced are difficult, progress is slow, and some truly significant advances seem to be needed during the coming quarter of a century if attributes of the spacecraft computer HAL in the motion picture "2001: A Space Odyssey" are to be achieved on schedule.

Section II. ACQUIRING INFORMATION

R. J. Mackin, Jr.

A. SCOPE

Information is acquired in space activities primarily through the means of space instrumentation and of apparatus for laboratory experiments in the space environment. This section is a forecast of the capabilities of 24 selected space instrument types and summary projections concerning nine others. One of the forecasts is of a class of ground-based instruments of major importance for achieving space program scientific objectives, radio telescopes.

The instruments for forecast were selected on the basis of (1) clear importance to space activities of continuing prominence, and (2) promise of significant advancement during the forecast period.

The authors have attempted wherever possible to factor into the forecasts unclassified data on advanced instruments or components which are part of otherwise classified systems. It is inevitable that there will be classified instruments in existence whose performance exceeds that quoted in these forecasts. The forecasts may be said to represent the instrument performance available for NASA programs.

These forecasts relate to hardware developments only. Innovations in measurement principles and techniques, and progress in precision of quantitative interpretation of data, are apt to advance space-experimental capabilities at least as much as hardware developments.

While the field of "apparatus for laboratory experiments in space" may someday grow to considerable importance, it is judged to contain little now that is appropriate to forecast. With few exceptions (one is mentioned in E below), it appears that standard laboratory equipment will be adapted for such experiments, since they will be conducted largely on manned Earth-orbital flights. Presently planned experiments are for the most part limited to the fields of space processing, plasma in space; and physics, chemistry, and biology in zero-gravity. Forecasts related to space processing are presented under the Management of Matter, Part Five, Section III.

B. BACKGROUND

Department of Defense forecasts have offered general guidance as to approach and to areas of promise. In very few instances have they provided unclassified instrument data of direct use for this forecast.

The forecasts contained here are perforce exceedingly terse and imperfectly documented. The references cited at the end of this section may provide clarification or supporting data. In addition, there are available upon request expanded versions of the forecasts containing some additional data (see H below). NASA and NAS Space Science Board planning documents of the past few years are useful for providing a detailed perspective on instruments required to meet most NASA objectives (e.g., Refs. 3-1 and 3-2).

C. ORGANIZATION AND APPROACH

For cataloging purposes, the field of instrumentation was divided into classes in the manner shown in Table 3-1. In this breakdown, the electromagnetic and particle instrument classes generally comprise spacecraft-borne instruments. A given forecast might cover space-astronomical as well as remote-sensing instruments and Earth-orbital as well as planetary deployment. Instruments in the other three classes are generally of the kind that would be carried on entry probes or planetary landers.

For instruments dedicated to a single purpose (such as astronomy), it has usually been possible to forecast parameters that describe instrument capability in units of the entity to be measured (e.g., flux units of an astronomical source). For instruments of broad applicability and several modes of deployment, it has been necessary to forecast parameters that describe the functional performance of a given instrument or instrument class, supporting this where necessary with component (e.g., sensor) forecasts. Each of the instrument applications requires a separate analysis for translating instrument functional parameters into quantitative units of the entity to be measured. There are numerous important applications for which no one has accomplished such analyses to a useful degree of precision.

Each forecast was developed by an individual actively involved with research in the specific instrument discipline cited. Most forecasters used trend projection, supported by knowledge of current development goals. Most instruments required more than one parameter for characterization. Sensitivity and resolution (geometric or spectral) were usual ones.

D. FORECASTS

This section presents 24 forecasts of individual instruments or instrument systems in the order in which they appear in Table 3-1. Each of the

Table 3-1. Instrument classification

Instrument	Forecast
Electromagnetic Class:	
Space Microwave Radiometer (Spectral and Imaging)	FC 3-2
Radio Telescope	FC 3-3
Space Radar Imaging/Sounding	FC 3-4
Space Telescope	FC 3-5
Infrared Remote Sensing Instruments	FC 3-6
Active Laser Absorption Spectrometer	FC 3-7
Multispectral Imaging System	FC 3-8
Solid State Cameras	FC 3-9
X-Ray Astronomy Instruments	FC 3-10
Hard X-Ray/Low Energy Gamma Ray Telescopes and Astronomical Spectrometers	FC 3-11
Gamma Ray Spectrometers (Orbiting, Surface, and Subsurface)	FC 3-12
Medium-Energy Gamma Ray Telescope	FC 3-13
Superconducting Josephson Effect Infrared Detectors	Summary only
Aerosol Photometer	Summary only
Ultraviolet Instruments	Summary only
Particle Class:	
Superconducting Magnetic Spectrometer	FC 3-14
Solid-State Detectors	FC 3-15
Large Area Position Sensitive Devices	FC 3-16
Energy Measuring Devices for Cosmic Rays	FC 3-17
Space Plasma Instrumentation	Summary only
Chemical Property Class:	
Mass Spectrometry/Gas Chromatography	FC 3-18
Nuclear Magnetic Resonance Spectrometer	FC 3-19
X-Ray Fluorescence	FC 3-20
Surface Micro-Analysis Instrument	FC 3-21
Alpha Particle Scattering	Summary only
Thermal Analysis Instrument	Summary only
Microwave Spectrometer (in-situ)	Summary only
Physical Property Class:	
Gravity Wave Detector	FC 3-22
Gravity Gradiometer	FC 3-23
Optical Electron Microscopes	Summary only
Passive Seismometer	Summary only
Biological Property Class:	
Characterization of Planetary Environments and Biota	FC 3-24
Life Detection	FC 3-25

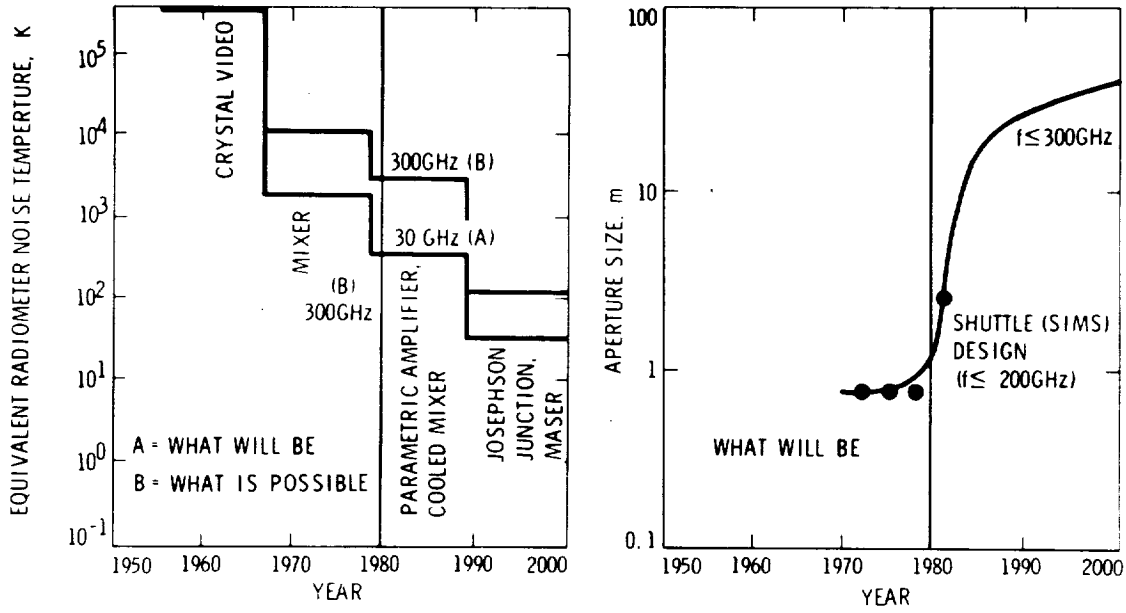
forecasts but one presents one or more graphs depicting historical and predicted values of parameters that characterize the instruments' limits of capability.

Wherever feasible, forecasts are expressed both in terms of "what will be" and "what is possible" as defined in Part One. The "what is possible" curves were projected on the basis of how fast progress might be made, given essentially unlimited resources. The accompanying notes usually contain a statement of the R&D funding requirements associated with some aspect of the "what will be" curve. In a few areas of especial importance to a number of interests (and corresponding large investment), "what will be" was judged to coincide with "what is possible." The "what will be" curves project the availability of a technology and do not imply the programmatic prediction that it will be used.

The descriptions also cite important applications of the instruments, give a rationale for the parameters plotted in the graphs, indicate factors which affect their rate of change, and predict progress of other parameters.

The forecasts are followed by nine summary forecasts of instruments expected to have only specialized use or whose foreseeable advancement could be covered by a capsule statement, as well as some general observations pertinent to all of the forecasts.

FC 3-2. Space Microwave Radiometer (Spectral and Imaging)



DISCUSSION

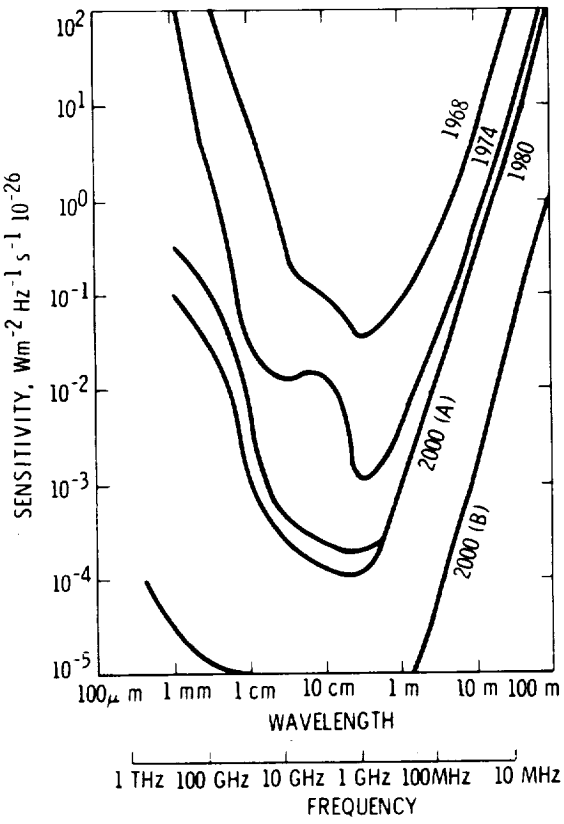
Microwave radiometers measure the upwelling thermal microwave radiation from the Earth and atmosphere in a specific set of frequency bands at a particular polarization. If the antenna beam is scanned and data are collected from a number of points, the data may be formatted as an image.

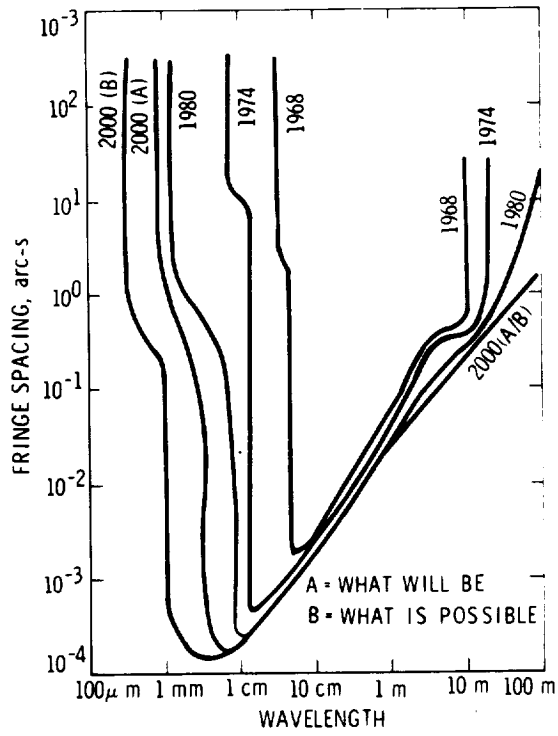
The primary parameter forecast for radiometry is the equivalent noise temperature of the radiometer. This parameter has continually improved historically as a result of advances in detector technology and is anticipated to continue this trend, culminating in the use of the cryogenically cooled (4°K) Josephson junction device. Major advances are required in the technology of space-borne cryogenic systems to permit realization of this ultimate sensitivity.

The noise in the radiometer measurement is approximately proportional to the sum of the equivalent radiometer noise temperature and the noise temperature of the observed signal. In certain applications the noise temperature of the signal, rather than the noise temperature of the radiometer, may limit the measurement sensitivity. The measured radiation is related to a number of geophysical parameters, notably atmospheric composition and temperature profiles, water vapor and liquid water content; wind speed and water temperature at the ocean surface; temperature, moisture content, snow cover over the land areas, and sea ice coverage in the polar regions. Because of this mixture of effects, interpretation requires simultaneous measurements at many frequencies and polarizations.

The number of channels is forecast to grow from 5, covering 1-60 GHz (1970 technology), to about 30, covering up to 300 GHz (1000 GHz, possibly) in the year 2000. In the 1980s, microwave radiometers may become prominent on planetary missions either for heat-flow measurements on airless planets or atmospheric sounding on others, often in conjunction with IR measurements. These planetary experiments are not expected to press the limits of technology in general. The most serious limitation of imaging measurements is geometric resolution. The primary parameter to characterize imaging systems then is aperture size which, together with the wavelength, determines the diffraction limit of resolution. The forecast curve relates to aperture usable at shortest wavelength. Trend projection is based on existing use of such a system and is consistent with corresponding forecasts of attitude control capabilities and data rates (q.v.) and presently developmental systems. R&D cost to develop a 1980-technology instrument (11 frequencies, 2 polarizations) is about $20M. (Refs. 3-3 – 3-7).

FC 3-3. Radio Telescope





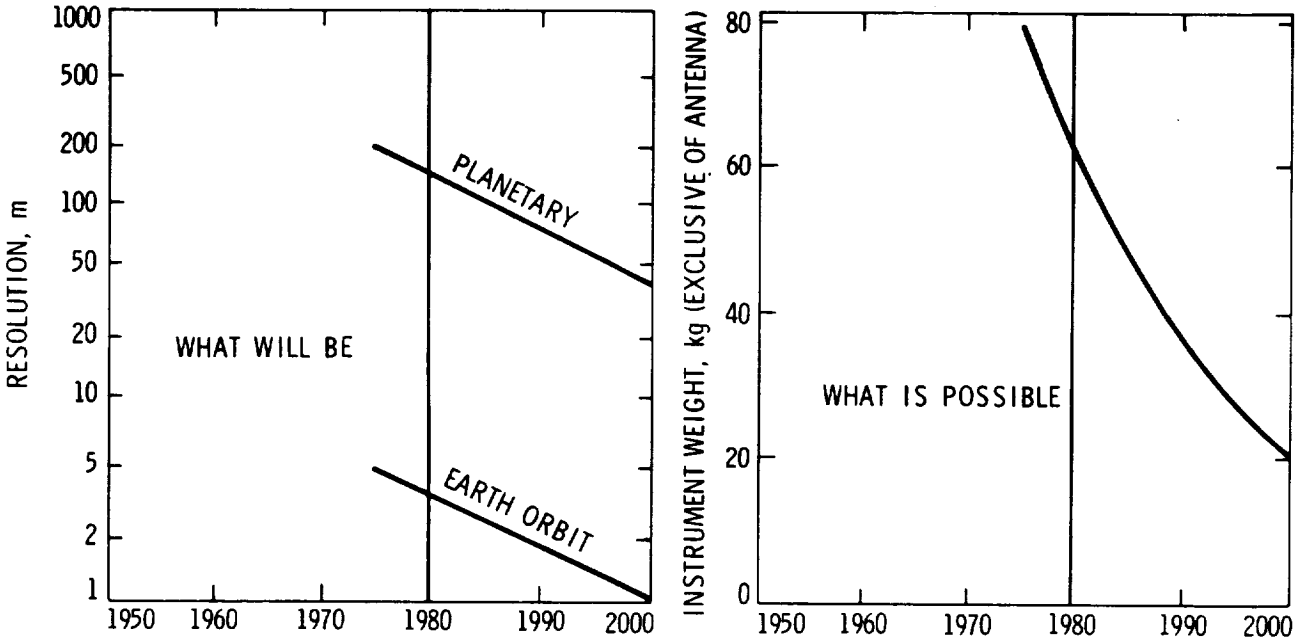
DISCUSSION

The term radio telescope includes the antenna or antenna array and the rf receiver, which measures the incident power from space. Primary parameters are sensitivity and spatial (angular) resolution. Operating wavelength is an essential descriptive parameter which has been included by use of isochron plots. The plotted receiver sensitivity values do not include thermal emission or transmission loss of terrestrial atmosphere; these effects are important for $\lambda < 1$ cm and vary with λ and with site elevation. An important justification for conducting radio astronomy in Earth orbit or on the Moon is to circumvent these effects. The antenna sizes of FC 3-2 probably represent a lower limit of what will be available for radio astronomy from orbit.

The year 2000 (B) curves incorporate an interstellar communication array ($\lambda > 3$ cm) (Project Cyclops design) and a mini-array of similar design ($\lambda > 1$ mm). Cost of the latter is about 2.5% that of the larger array. These would be extraordinarily powerful tools for radio astronomy; for instance, they would permit study of the Andromeda Galaxy with the same resolution and sensitivity presently available for studies of our own galactic center.

The forecast was made on the basis of a trend extrapolation of 1974 technology, with no major breakthroughs required. (Refs. 3-8 – 3-11)

FC 3-4. Space Radar Imaging/Sounding

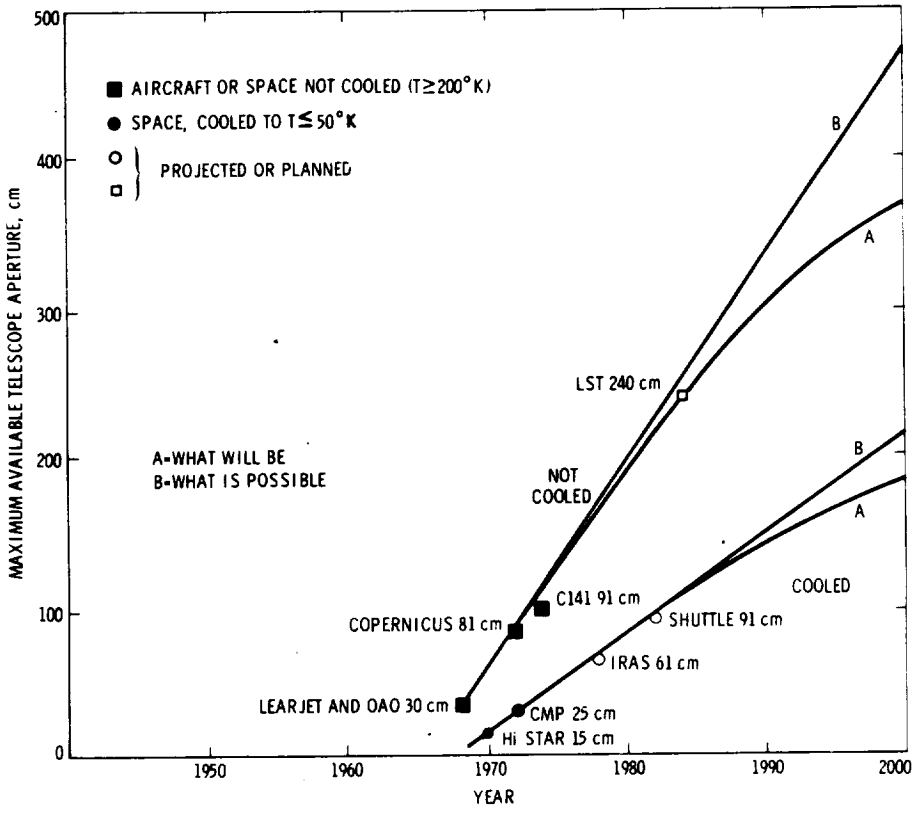


DISCUSSION

Even though spacecraft radars are still in their infancy, airborne coherent radars are at a relatively advanced technological stage. Imaging radars were first developed in the late 1950s, and a wide variety of them are presently available. Their operating frequencies span the range 0.1 GHz to ~15 GHz. Most of them process the data in an analog form (on film or by direct analog data link); however, some recent systems have digital data handling capability, and even real-time image correlation and processing. Only a few sounding radars are presently available. These systems have mainly been used to sound continental ice fields and dry regions.

The main thrust in the next 25 years is toward the development of spacecraft radars with the capability of presently available aircraft radars. These remote sensors are expected to have a major role in future Earth and planetary missions. The main technological developments expected are: higher-frequency, higher-power, solid-state transmitters, larger space antennas, smaller, more efficient digital electronics, and new methods for handling the radar echo data. Radar component capabilities and available power sources are such that progress in achievable surface resolution is mainly paced by available data handling rates. The forecast resolution curves are based on the "will be" data rates forecast in Part Three, Section III, "Transferring Information," and assume scans of a 100 km surface swath. NASA R&D cost to develop a 1980-technology Earth-orbit instrument is about $30M, excluding the data system.

FC 3-5. Space Telescope



DISCUSSION

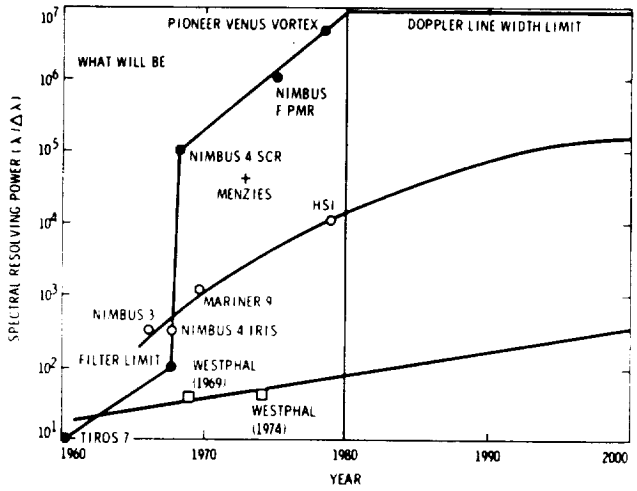
The performance of an optical sensor system is directly related to the aperture of the collecting optics. The aperture diameter (D) of Earth-orbiting telescopes for general astronomical observations is forecast. These are assumed to give a diffraction-limited image at wavelengths greater than 0.5 μm. If this restriction is relaxed, much larger sizes appear possible now (not cooled). The trend projection is based in part on aircraft - and balloon-borne instruments. The two performance parameters directly related to the telescope aperture are the minimum detectable flux density (inversely proportional to D^2) and the angular resolution (proportional to λ/D where λ is the wavelength of interest).

Two classes of telescope are distinguished: (1) not cooled, i.e., operating temperature of the optical elements in the vicinity of 200°K and (2) cooled: cooling is accomplished by active means (cryogenic cooling, mechanical heat pumps) or passive (radiative cooling into space). Cooling is particularly important if operation at wavelengths longer than 4 μm is to utilize the full sensitivity of available detection.

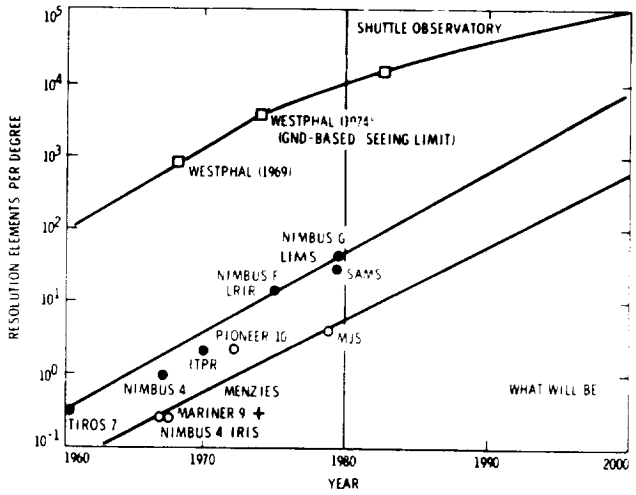
Use of new lightweight optical structures and the emerging technique of continuously adaptable optical surfaces formed of multiple elements permits considerable growth without extraordinary weight penalties ("what is possible").

FC 3-6. Infrared Remote Sensing Instruments

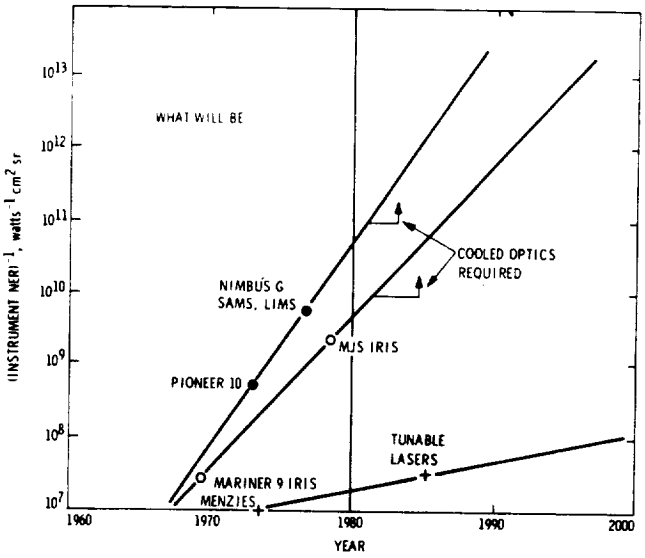
a. Spectral Resolving Power



b. Angular Resolving Power



c. Noise Equivalent Radiance



LEGEND

- □ = Earth-based and orbital thermal imagers
- \+ = flight laser spectro-radiometers
- ● = flight radiometers
- O = flight spectrometers

All curves are "what will be".

DISCUSSION

The forecast covers infrared instruments designed for deployment from the Earth's surface, Earth orbit and planetary flyby or orbit to make remote measurements of atmospheric or surface properties. All such devices work by measuring the specific quantities of infrared flux emitted or reflected by the planet and by identifying and quantifying spectral features associated with physical properties of interest. IR instruments are key components for programs of global weather forecasting, pollutant measurement and planetary exploration. The principal classes of device considered include conventional spectrometers (prism and grating types, etc.), multiplexing spectrometers (Fourier and Hadamard transform types, etc.), radiometers (including gas correlation types), laser heterodyne spectroradiometers (passive only), and thermal imaging systems. Most of them operate in the thermal IR spectral region. Performance vs. wavelength is not analyzed here.

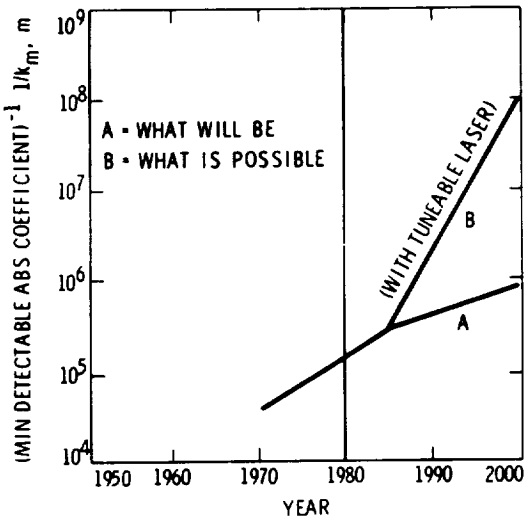
The primary parameters which have been forecast are: (1) spectral resolving power, defined as $\lambda/\Delta\lambda$, which is a wavelength-independent measure of spectral resolution; (2) angular resolving power expressed in resolution elements per degree, which is a measure of spatial resolution independent of method of deployment; and (3) noise equivalent radiance (NER), a measure of signal detectability which is independent of the target. Laser heterodyne devices have the characteristic of very narrow bandwidths, essentially limited only be signal detectability considerations. Thus, only their NER is forecast.

All the forecasts are curves of "best" performance for a given parameter and would not necessarily represent optimum operating points for specific measurements. For many applications, background radiation noise is likely to set a practical limit on useful radiometric sensitivity not far from present values.

This forecast is based on extrapolation of current laboratory and flight instrument trends assuming tunable lasers and cooled optics will be available for space by 1985. Helium-cooled instruments with $(NER)^{-1}$ greater than 2×10^{10} have already been flown on rockets by A. F. Cambridge Research Laboratory.

Technology in Forecast 3-9 (Solid State Cameras) is in process of being adapted to that of thermal imagers using Schottky barrier matrices. DOD is the major source of funding for this and for sensor development. Required NASA R&D funds are strongly dependent on requirements placed on individual instruments. For instance, funding of $10M is required for development of a 1980-technology high-speed Fourier spectrometer for Earth orbit. (Refs. 3-12 – 3-17).

FC 3-7. Active Laser Absorption Spectrometer



DISCUSSION

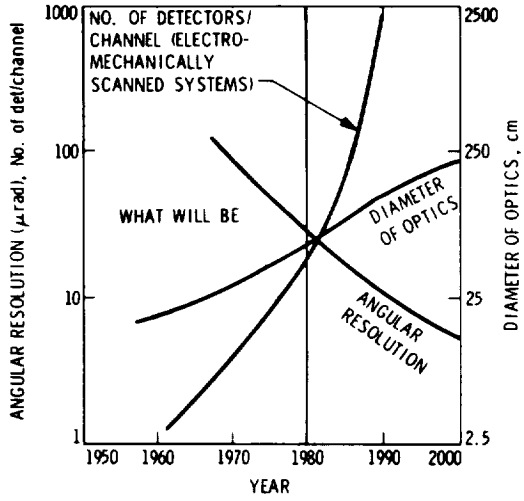
The instrument is used to measure, remotely, the concentration of trace atmospheric constituents. It consists of at least two infrared laser transmitters (CW or pulsed) and heterodyne receivers. With the transmitted laser signals aimed at the Earth or a planet, the receivers detect and record the signals scattered off the surface. The lasers are tuned to two separate, closely spaced wavelengths, one coinciding with an absorption line of an atmospheric constituent, and the other with a "clear" wavelength. The difference in return signal between the two indicates the amount present of the selected constituent. Two-dimensional mapping of the concentration is possible by scanning. Determination of the pressure-altitude profile of the constituent is also possible by use of a laser that can be tuned across the absorption line, supported by knowledge of the variation in line width with pressure. Accurate knowledge of the temperature vs. altitude profile is not necessary, since the absorption line strengths are weak functions of temperature. Passive instruments that depend upon thermal emission require accurate temperature profiles.

Using present-day laser technology, a spacecraft instrument would require several hundred watts of prime power, and a receiving telescope aperture of about 0.5 meter. Several atmospheric constituents could be monitored sequentially with one laser-pair by using frequency-selectable lasers. The primary parameter forecast is $1/k_m$, where k is the minimum detectable atmospheric absorption coefficient in the atmospheric transmission equation $S = S_o e^{-kx}$. Knowledge of the line strength of the constituent being measured is necessary to determine the concentration.

The 1990 prediction assumes the ability to measure 10 laser line-pairs simultaneously, and the 2000 prediction assumes a 100 line-pair capability. Altitude resolution is limited by the accuracy of the knowledge of the pressure broadening of the absorption line used. Presently, the altitude resolution is 2 km for h below 5 km, and 5 km for $5 < h < 50$ km. h is the altitude of the layer being sensed.

The 1985-2000 what is possible forecast assumes the existence of wideband, tunable laser sources that operate in the infrared, and are capable of high power levels. These devices have not yet been developed. Tunable infrared laser devices exist today, but they are cumbersome and require cryogenic temperatures for operation. It is reasonable to expect a significant improvement.

FC 3-8. Multispectral Imaging System



DISCUSSION

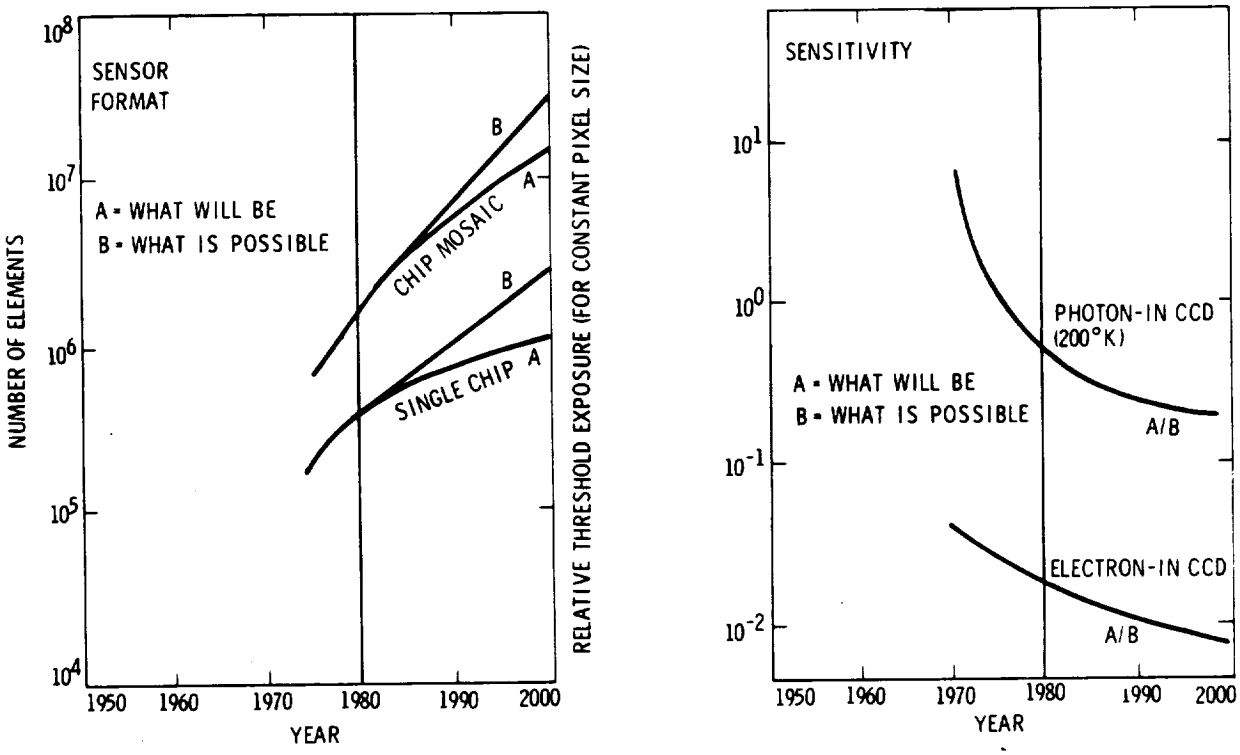
These instruments generate images of a scene in a number of spectral channels (visible and near infrared), using arrays of detectors that scan the object or image plane in a manner that permits reconstruction of the scene radiance (e.g., ERTS-1, SMS-VISSR). The forecast includes scanning radiometers and electromechanical scanners. The multispectral image data are used to characterize the nature of the scene and have been shown to be directly applicable to a large fraction of the Earth-oriented problems considered in this study.

Primary parameters are angular resolution, aperture diameter and number of detectors per channel. A half-dozen other parameters can be important for particular applications. Note that the forecast aperture diameter is smaller than that for space telescopes (FC 3-5). The difference is largely imposed by the imager's larger field of view, which requires a field-correcting lens.

The primary key to the acquisition of increased angular resolution is the use of detector arrays with large numbers of elements. Development of a "year 2000" instrument will require about $300K/yr R&D funding through 1995 and an additional $10M for a feasibility model at that time.

The forecast is based on trend extrapolation supported by consideration of known current development activities. Numbers and order of magnitude larger than "what will be" are believed possible by 1990. Examples of measurement capabilities defined by given performance parameters can be found in Ref. 3-18.

FC 3-9. Solid State Cameras



DISCUSSION

Charge-coupled devices (CCDs), more than any other solid-state camera sensors, offer the capability of high resolution, high sensitivity, low cost, high reliability cameras of minimal size, weight, and power consumption. They are expected to replace vidicon and other devices for planetary camera sensors almost entirely by 1980. The size, weight, cost and monolithic nature of the sensor will make possible universal modular camera design compatible with a variety of planetary and Earth-orbital imaging applications.

The primary parameters forecast are those of resolution (sensor format) and sensitivity. Absolute threshold exposures are not well known at this time, but a reasonable value for a 1975 photon-in CCD using a precharge preamp and exposed to a 2800°K source is about 3 microjoules per sq. meter. In addition, significant improvements are expected in intrinsic noise reduction and broader spectral bandwidth capability. Present silicon CCDs have a bandwidth covering 0.4-1 m. As other materials are adopted, the limits will be extended below 0.2 m and (not the same device) above 10 m. An alternative under development is based upon internal photo emission from metal/semiconductor Schottky-barrier arrays on a silicon or germanium substrate. These arrays can employ either vidicon readout or CCD readout and signal processing.

The performance forecast was made on the basis of trend extrapolation of current CCD technology, and anticipated improvements in fabrication techniques which should overcome current-day definition limits. Because of its applicability to several classes of devices, CCD technology is being advanced rapidly at present, benefiting both from large military and commercial funding support and from advances in the related technology of large-scale integrated-circuit fabrication. NASA or other government funding for CCD imaging system technology will be required to utilize applicable technology advances and develop in parallel specific sensors for flight missions or systems.

FC 3-10. X-ray Astronomy Instruments

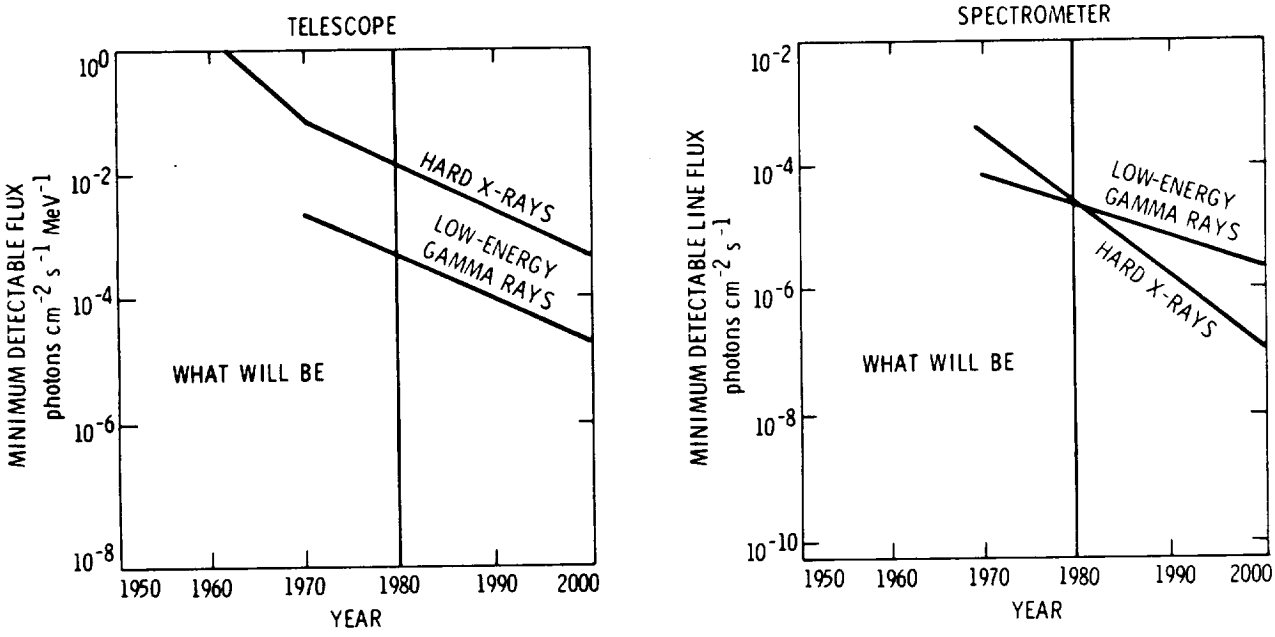
DISCUSSION

Within the next 10 years, grazing incidence X-ray optics flown from satellites (e.g., HEAO-B) and rockets will give us images of many of the more interesting regions of the X-ray sky. This will be done to a resolution of a few arc seconds and will be restricted to soft X-rays (i.e., photon energies less than about 4 keV; equivalently, for wave-lengths greater than about 3 angstroms). Extending these observations to harder X-rays with comparable resolution and sensitivity is a worthwhile goal for the next decade.

For obtaining hard X-ray images, the most promising technique is probably that of the scatter-hole camera. For example, a two-dimensional imaging proportional counter, with a spatial resolution of 1 mm, could achieve imaging to an angular resolution of 20 arc seconds when placed 10 meters behind an appropriately perforated entrance plate. Such an imaging proportional counter is now being prepared by the Smithsonion-Harvard group for use at the focus of the HEAO-B grazing incidence telescope. Based on the design of Borkowski and Kopp, this instrument has achieved a resolution of 1 mm for a unit with a total area of 6 cm x 6 cm. While this is sufficiently large for a detector at the focus of a telescope, it is too small for use in a scatter-hole camera. A more appropriate instrument for hard X-ray imaging would consist of a detector on the order of 1 m x 1 m. Considering a 50% open scatter-hole pattern for the entrance plate, the effective collecting area for such an instrument would be 5×10^3 cm^2, comparable to the large area proportional counter arrays on HEAO-A, and would have a field of view of about 6° (i.e., corresponding to a 1 m x 1 m entrance plate and matching imaging proportional counter separated by 10 m, yielding 20 arc second resolution for 1 mm positioning precision).

As pointed out by Giacconi, hard X-ray point sources with rapid temporal variations may be located by the use of long-base time delay measurements. For two detectors separated by 1 AU (i.e., 15×10^{10} m) and located to a precision of better than 1 km, the relative timing of signal arrival to a precision of about a microsecond would yield the source location to a precision of about a milli-arc second. For a source at a distance of 1 kpc this corresponds to spatial resolution of about 1 AU at the source (i.e., about the diameter of the orbit of Cygnus X-1 about its optical companion). The appropriate technology requires: (1) large area detectors (comparable to or larger than those on HEAO-A) separated by 1 AU (the potential impact here is placing something like HEAO-A at 1 AU and locating it to 1 km) and (2) accurate timing (the microsecond timing can be achieved today; however, getting the required precision in comparing the two signals on the ground would call for something special, e.g., it might involve relaying the signal from the distant satellite via the nearby companion satellite in order to minimize propogation errors). It is estimated that $1M funding over a 5-year period will be required to bring these experiments to flight readiness (Refs. 3-19 – 3-22).

FC 3-11. Hard X-Ray/Low-Energy Gamma Ray Telescopes and Astronomical Spectrometers



DISCUSSION

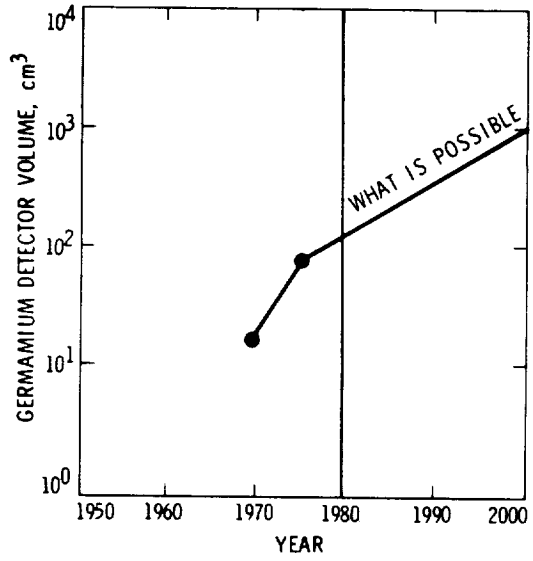
The instruments covered by this forecast are made up of a prime sensor surrounded by an active guard shield of inorganic scintillation material. The shield reduces background radiation; a gap in it defines the aperture of the prime sensor. In a telescope, the prime sensor is a scintillation counter; in a spectrometer, the prime sensor is a cryogenically cooled crystal counter (currently germanium). The distinction between "hard X-ray" and "low energy gamma ray" instruments is related to the thicknesses (efficiency) of both the prime sensor and the shield. Hard X-rays are defined as 0.02-0.3 MeV in energy. Low energy gamma rays are defined as 0.3-10 MeV.

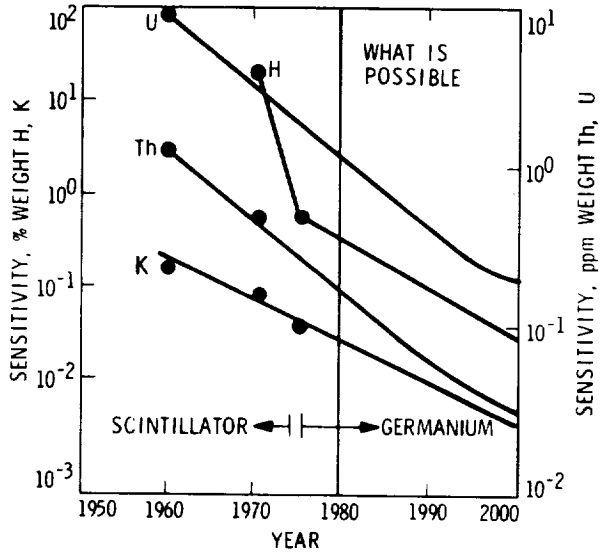
Telescopes are of relatively low resolution and perform "photometric" measurements of celestial objects from Earth-orbiting spacecraft. Spectrometers are similarly deployed but designed for high-resolution spectral studies of known sources. Stable platforms, instrument pointing capability and minimal sources of background radiation (i.e., spacecraft mass) are required for realization of forecast sensitivities for both instruments.

The primary parameter selected in both cases is flux sensitivity, defined as the minimum flux detectable. For definiteness, we have stated the sensitivity for a measurement made at 100 keV for the hard X-ray instrument and at 1 MeV for the low energy gamma ray instrument. This parameter is a function of exposed detector area, attenuation efficiency and exposure or integrating time.

The forecast is based on trend projection employing parameter values for instruments already flown or presently scheduled for flight (e.g., OSO-1, III, V, VII, OGO-V, HEAO-A and -C). Development and balloon-flight demonstration of a 1980-technology instrument will require a 4-year program costing about $2M total (telescope) or $3M (spectrometer, exclusive of cryogenic system development). This same component technology (including detector volume) is the basis for Forecast 3-12.

FC 3-12. Gamma Ray Spectrometer (Orbiting, Surface, and Subsurface)





DISCUSSION

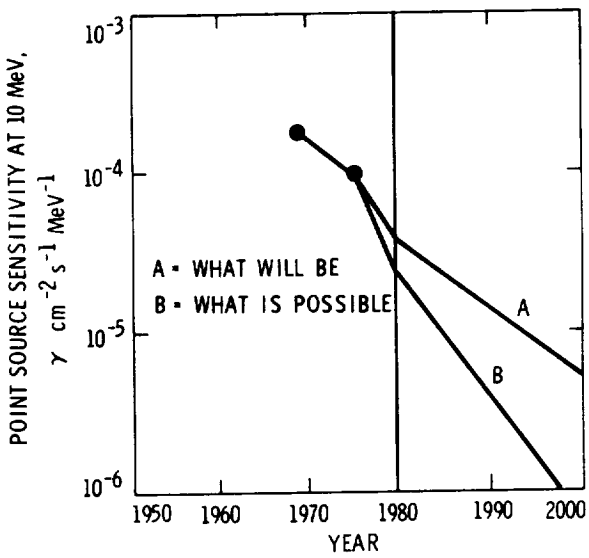
The concentrations of selected elements are determined by the detection of characteristic gamma rays. The source of these gamma rays is either the decay of the naturally radioactive elements, K, U and Th, or induced radioactivity following the interaction with high-energy cosmic rays. The emitted gamma rays are detected through the deposition in a detector of part or all of their energy, which is subsequently transformed to proportional electrical pulses. The accumulation of sufficient events produces an energy spectrum whose features can be correlated with the characteristic emission energies of the sources of gamma rays. Space instruments to date have used scintillation detectors, but germanium detectors with superior resolution are now available. This type of instrument is capable of returning meaningful compositional information from a suitable orbit around any planetary body with an atmospheric density comparable to or less than that of Mars.

Gamma ray spectrometers must be deployed from a boom or provided with sufficient active shielding to limit the background contribution due to spacecraft sources. The use of a germanium detector will require cooling to a temperature below 150°K during operation; therefore, cryogenic system development is an associated requirement. Measurements capable of providing relatable information include X-ray fluorescent emission, photography, altimetry and IR spectral photometry.

The surface/subsurface gamma ray spectrometer will perform analyses of naturally radioactive elements or cosmic-ray-induced radioactive nuclides (e.g., Fe, Ti, Mg, S, O, and H). Induced activity can be detected down to 50-cm depth on a planet with little or no atmosphere. A surface instrument is an essential source of gamma ray data on a planet whose atmosphere is too thick for surface gamma rays to be detected from orbit. (A measurement of naturally radioactive isotopes was performed on the surface of Venus by Venera-8.) Prospects for subsurface gamma-ray measurements are enhanced by the recent development of CdTe gamma-ray detectors (Refs. 3-23 – 3-25).

The primary parameters forecast are germanium detector volume and sensitivity expressed as minimum detectable (fractional) abundance in planetary surface material. The component technology is basically that of the gamma ray spectrometers of Forecast 3-11. Energy resolution (at 1.3 Mev) could improve from 2 kev (1975) to 1.2 kev (2000). The sensitivity forecast is derived from the forecasts for detector volume and energy resolution but is consistent (for Th and K) with trend projection that includes scintillator-technology data points from Ranger (1960), Apollo (1970), and Russian Lunar missions. The numbers assume a low orbit, no atmosphere and a data accumulation time of one hour. The cost of developing a 1980-class instrument to the stage of preflight readiness is estimated at $300K, assuming continued support from industry and from ERDA in the development of germanium detectors.

FC 3-13. Medium-Energy Gamma Ray Telescope

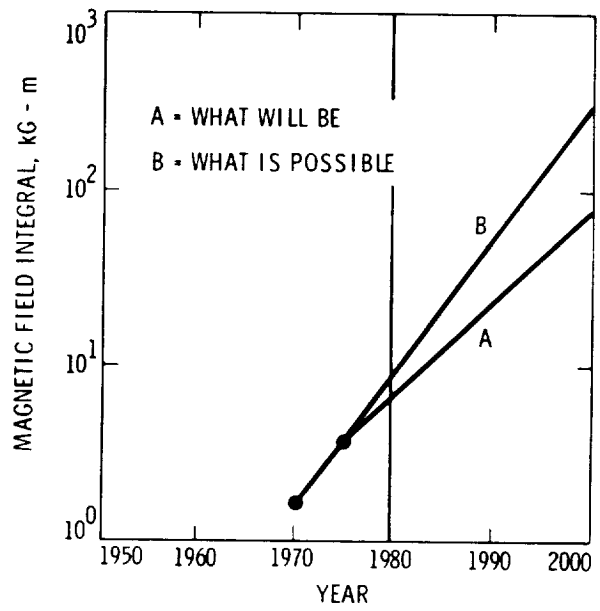


DISCUSSION

This type of instrument is designed to measure the flux, energy and direction of gamma rays from 0.5-30 MeV. It is also sensitive to neutrons from 2-100 MeV. Detection of gamma radiation is accomplished by Compton scattering in each of two liquid or solid scintillators located about 1 meter apart. To improve the angular resolution, the second detector is divided into a multiple symmetric array of detectors, each with its own photomultiplier. The first detector may also be an array, if it is desirable to give up some angular resolution for increased intensity of response. Measurement of the Compton electron recoil energies in each scintillator gives an estimate of the incident gamma ray energy to 25% and restricts its incident angle to a cone. Both the energy and the angle of the incident gamma ray can be better determined if the gamma ray scattered from the first detector can be fully absorbed in the second. Discriminating time of flight between scintillators separates gamma ray from neutron events and eliminates the backward component. Efficiency depends on incident angle and energy of the gamma ray and ranges from 0.4% to 5% for present instruments. The instruments are surrounded by an anticoincidence system for the rejection of charged particles.

The primary parameter forecast is sensitivity expressed as minimum detectable source strength at 10-MeV assuming a 4-hour integration time. Sensitivity improves with increasing gamma ray energy, being a factor of 5-10 times greater at 30 MeV than at 10 MeV. The application of this technique will be for studying the continuum spectra of discrete gamma ray sources in the 0.5-30 MeV range where fairly long observation periods are possible and good energy resolution is not considered vital. It requires a weight of 100-500 kg and more, scaling up to provide more sensitivity. In a multi-instrument payload, a collimated X-ray spectrometer and a spark chamber for lower and higher energies, respectively, would be a potent combination for simultaneous observation of celestial objects and particularly, those for which transient behavior might be expected. This technique, while known in the laboratory for two decades, is not yet applied in space but has been employed on balloon flights. The forecast was made largely on the basis of trend projection, assuming that more massive detectors and better discrimination systems will be developed (Refs. 3-26 – 3-30).

FC 3-14. Superconducting Magnetic Spectrometer



DISCUSSION

Magnetic spectrometers use position-sensitive detectors (e.g., spark chambers or nuclear emulsions) to measure the amount of deflection of high-energy charged particles traversing a magnetic field. In combination with other types of particle detectors, magnetic spectrometers may be used to distinguish matter from antimatter in the cosmic rays, to resolve isotopes of cosmic ray nuclei, and to measure the composition and energy spectrum of cosmic ray particles at high energy.

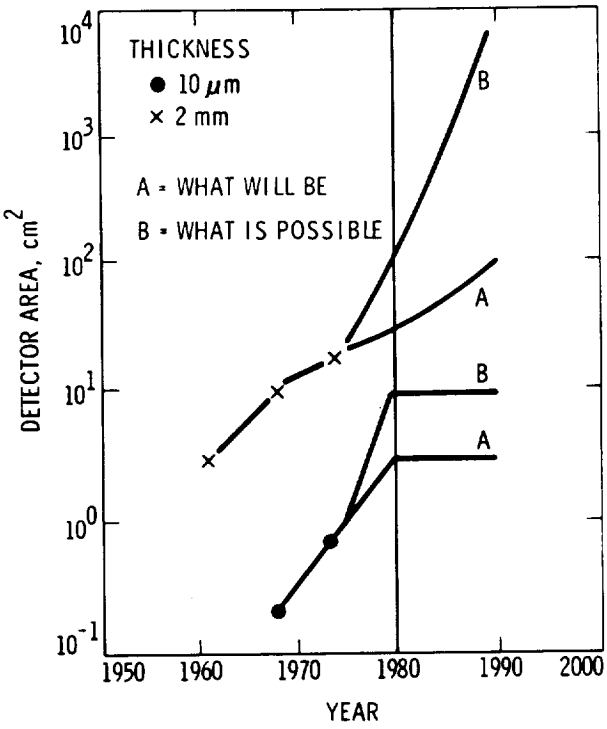
The magnitude of the deflection of a particle in the field, and hence the resolution of the spectrometer, is proportional to the strength of the field and the length of the particle's path in the field (i.e., the "field integral," $\int B \cdot dl$). This is the primary parameter forecast.

Experiment sensitivity, dependent upon collection area and duration, is expected to receive its greatest impetus from longer flight durations (up to ~1 year) than are presently available on balloons (~1 day). Additional increases in collection area by factors of ~100 may also be anticipated (Ref. Forecast 3-15).

Superconducting spectrometers support a wide variety of experiments bearing on different astrophysical questions such as the symmetry of matter in the universe, the age, propagation and origin of cosmic rays, and the mechanisms of synthesis and distribution of elements in the galaxy. The different experiments using magnetic spectrometers require somewhat different instrument parameters and different resolution and sensitivity.

This forecast is based upon development of existing technology; no "breakthrough" is required. The forecast assumes constant-level R&D support for spectrometers and associated experiment equipment at ~$0.5M to $1.0M per year. The forecast through 1990 is based upon scaled-up versions of existing balloon-borne superconducting spectrometers using the same commercially-available superconductive wire (Nb Ti). Extrapolation beyond this date will require more efficient superconducting material.

FC 3-15. Solid-State Detectors



DISCUSSION

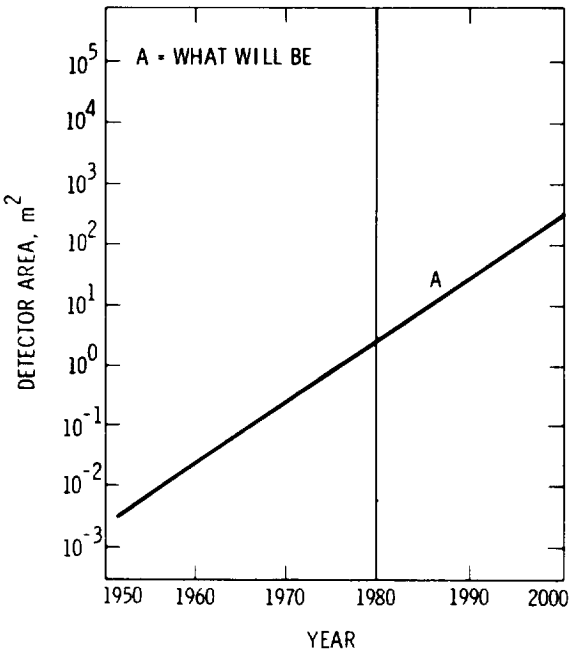
Solid-state detectors are devices used to detect and measure the characteristics of ionizing radiation. For example, they are commonly used on scientific satellites for observing particles in the Earth's magnetosphere, particles produced in solar flares, and galactic cosmic rays. They are commonly in the form of thin disks ranging from a micron to 10 millimeters thick and having areas up to 15 cm^2 for the thickest devices. In appropriate combinations, they can be used to identify the charge, energy and mass of nuclei in an energy range approximately 50 keV to 50 MeV. They can also be used to detect X-rays. The types of solid-state detectors in current use are surface barrier detectors and lithium drifted detectors. Devices < 1 mm in thickness are generally of the former type while devices >1 mm are generally of the latter. Solid-state detectors are extensively used in satellite experiments because of their high resolution, low noise, low weight, and high reliability.

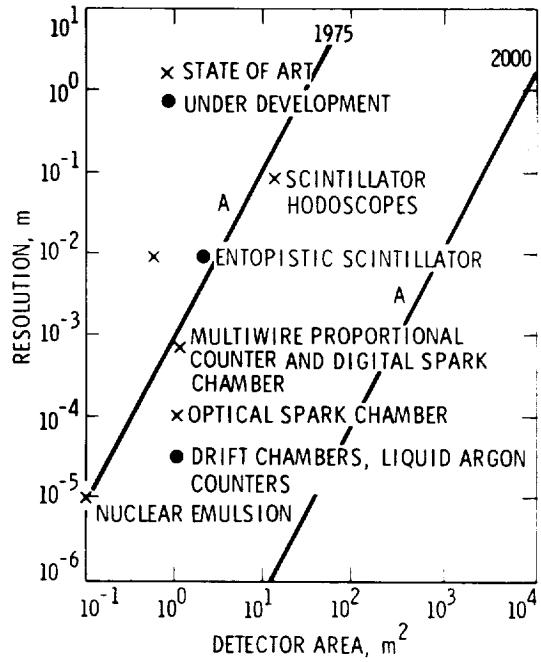
Position sensing detectors are currently under development. Devices approximetely 5 cm^2 with 1 mm resolution in one dimension are currently available. By 1980 it may be possible to have resolution to 0.1 mm for devices 25 cm^2 or larger. For the thicker (>500μm) devices it may well be best to determine position using other position sensitive devices (e.g., drift chambers, multi-wire proportional counters). For the thinner detectors, position sensing will have to be done using the solid-state detector itself. Area and thickness of detectors are the primary parameters forecast since these two parameters govern the sensitivity (and observation time) and detectable energy range respectively.

Improved position sensing will yield improved mass resolution for isotopic studies. When used in conjunction with magnets, improved position sensing implies a higher momentum range for a fixed magnet size. Position sensing can remove many of the systematic biases which now limit telescope particle identification capabilities.

This forecast is based upon significant advances in manufacturing techniques of detectors. The "what is possible" curves assume Space-Shuttle-based growing of detector crystals in a zero-G environment.

FC 3-16. Large Area Position Sensitive Devices





DISCUSSION

Many constituents of the cosmic radiation are extremely rare. The energy spectra are very steep functions of energy:

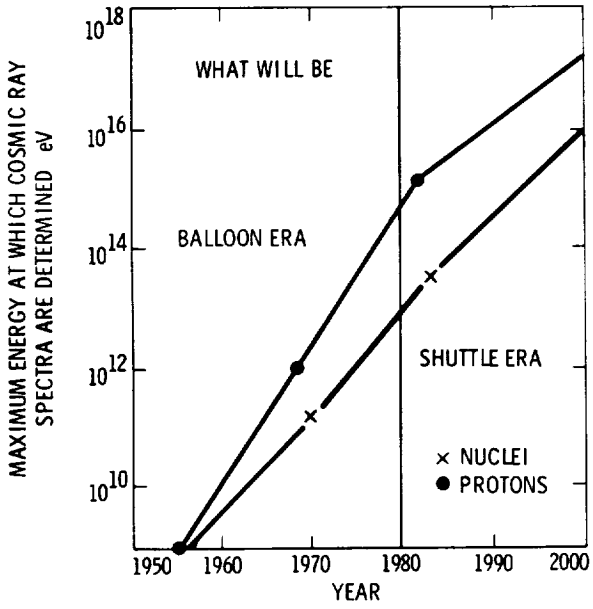
$$\frac{dN}{dE} = kE^{-\gamma} \text{ where } \gamma = 2.5.$$

Intensities vary from 1 per cm^2 per sec to 1 per km^2 per century. Thus the driving design problem for identification and counting of the particles requires large area detectors. At the same time particle identification requires mass/charge accuracies of a few %, and so particle trajectories (in an applied magnetic field) are essential. What is required are increasingly larger area detectors and trajectory measuring devices sensitive to the various cosmic ray constituents, nuclei, electrons, antiparticles, etc. These devices include entopistic scintillators (position sensitive scintillators), drift chambers, spark chambers, hodoscopes of scintillators, geiger tubes, or proportional counters, and perhaps many other as yet unthought-of combinations. These devices all work by recording the position of the ion pairs created by the passage of the incident particle through the detector material. Position sensitive counters (e.g., multiwire proportional counters, spark chambers, hodoscopes) of 100 cm^2 were available in 1970. Entopistic scintillators of 500 cm^2 were in use in 1970 and are currently under development with 1.4 m^2 area.

Both resolution and detector area are forecast as primary parameters. It is anticipated that the 1975 isochron could be moved one decade in area to the right every 10 years. Since the differential intensity of cosmic rays is inversely proportional to energy to the 2.5 power, detector area collection time is related directly to the upper energy limit of collectable statistical accuracy. To go each decade up in energy, collection area x time must go up a factor of 40. Big new jumps in time will come about when these typical balloon payloads are put on satellites (e.g., HEAO-C) and flown in the Shuttle, first as sortie-mode payloads and then as free flyers.

The forecast is based upon trend extrapolation over the past 20 years, and no major breakthroughs are required. It is anticipated that inexpensive free flying apportunities will become available in the late 1980s.

FC 3-17. Energy Measuring Devices for Cosmic Rays



DISCUSSION

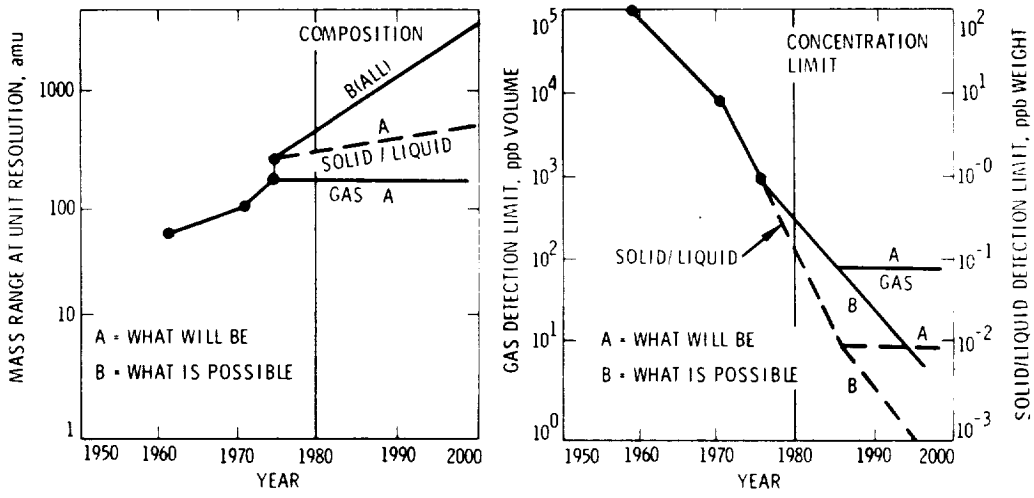
These instruments are for measuring the energies of cosmic ray particles above 10 GeV/amu. At present only preliminary identification of the spectra of the different components of the cosmic radiation has been accomplished above this energy. Large devices which totally absorb the energy of these particles are called ionization spectrometers. They have large dynamic range and hence are ideal for measuring spectral exponents. These exponents are intimately related to the acceleration processes of cosmic rays. Since size or geometry of collection area is so important in these devices (see large area detectors, Forecast 3-16) at high energy, dense materials (which optimize the number of interaction lengths in a given height) are important for detectors less than a cubic meter in size. The ionization spectrometer can be made of any material which is sensitive in some way to the total number of electrons produced in the cosmic ray/detector interaction (e.g., a scintillator).

Devices are gas Cerenkov detectors and transition radiation devices. The former are just now beginning to be used in the energy range 10 to 100 GeV/amu. With sufficient improvements in ultraviolet reflecting white paints, photomultipliers and counter volumes, they might be extended to 1000 GeV/amu, perhaps by 1985 or 1990. Above this energy, transition radiation detectors should take over. These devices have been shown to be capable of identifying electrons at $\gamma = 1/\sqrt{1 - v^2/c^2} = 10^3$, and have response proportional to γ which, if properly designed, can extend to $\gamma = 10^4$. Such devices have not yet been successfully employed in actual measurements, but that will occur in the next few years. These devices will probably become important for electron measurements in the early 1980s and for nuclear measurements by the late 1980s.

Maximum energy at which cosmic ray spectra are determined is the parameter forecast. The major constraint on spacecraft will be the very large volume and weight of these devices. It is therefore desirable to maximize the collecting area/volume ratio. Devices of sufficiently large area in near-Earth orbit could accomplish several scientific goals not now even contemplated. Anisotropy measurements of individual cosmic ray constituents could be made at energies sufficiently large for trajectories to be unaffected by the Sun's magnetic field. Particles could be studied at energies sufficiently high that containment in the galactic magnetic fields is difficult.

This forecast is based upon a working knowledge of current research in energy measuring devices and design points for Shuttle instruments. No major breakthroughs are required, and progress is paced by expected resources. These are multi-ton instruments, and later generations require multi-visit in-orbit aggregation of successive modules.

FC 3-18. Mass Spectrometry/Gas Chromatography



DISCUSSION

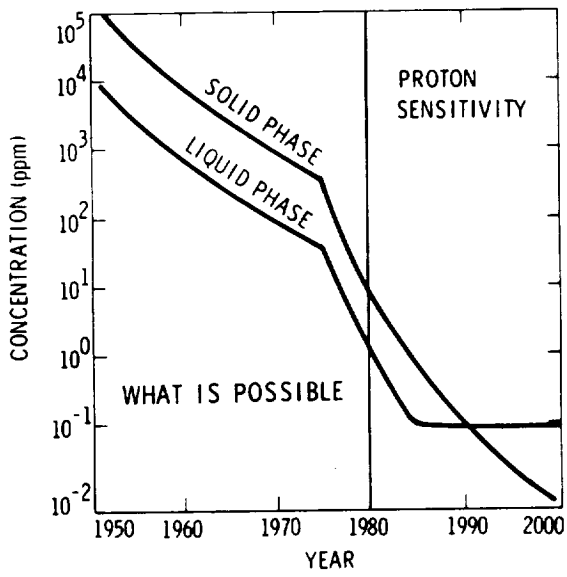
Mass spectrometry is used to measure the molecular, elemental, and isotopic composition of gases and of volatilizable solids and liquids. It is an in situ measurement in which the sample must be presented to the vacuum environment of the instrument. As a result, vacuum pumps and specialized sample handling and processing devices are generally required (e.g., thermally programmed ovens, pre-analysis chemical separations, etc.). The mass spectrometer (MS) is presently in use in rocket and space applications for gas analysis and is in flight configuration for the analysis of solids (Viking).

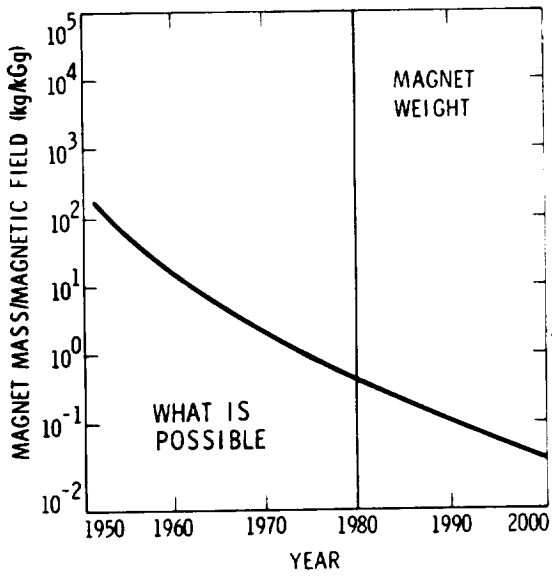
The primary parameters forecast are composition and concentration. Composition is expressed in terms of the mass range over which the MS can resolve and quantitatively measure mass peaks (molecular or atomic weight). Concentration limit is expressed as the least detectable fractional value abundance of a given species in a material sample. Mass spectral signatures are usually a unique indication of molecular structure; therefore, mass range and detectability truly reflect the instrument's performance in a given application.

Industry is a major source of R&D support for gas chromatography (GC). The major NASA role in advancing GC is to flight-qualify existing systems. We forecast that it will be possible by 1980 to equal 1975 laboratory instrument resolution, and by year 2000 to improve this by a factor of 10. GC sensitivity is now about 10^{-9} grams; it should be possible, by 2000, to improve this to 10^{-12} grams for atmospheric samples and to 10^{-13} grams for organic samples. The combined use of the gas chromatograph and mass spectrometer (GCMS) is a particularly powerful tool in that an exceedingly wide dynamic range in concentration measurements can be achieved via the species separation capability of the GC, which minimizes or eliminates mass-spectral overlapping.

The forecasts for MS and GC are based on trend projection, consideration of laboratory instrument developments, and assumption of acceptable advances in auxiliary devices. Data points represent flight instruments. Sustaining R&D funds of about $0.5M per year will be required to keep pace with laboratory technology in the sense of qualifying increasingly capable components for space flight. Important space applications are planetary probe and lander missions, cometary encounter or rendezvous missions, and low-altitude planetary orbital missions (Ref. 3-31).

FC 3-19. Nuclear Magnetic Resonance Spectrometer





DISCUSSION

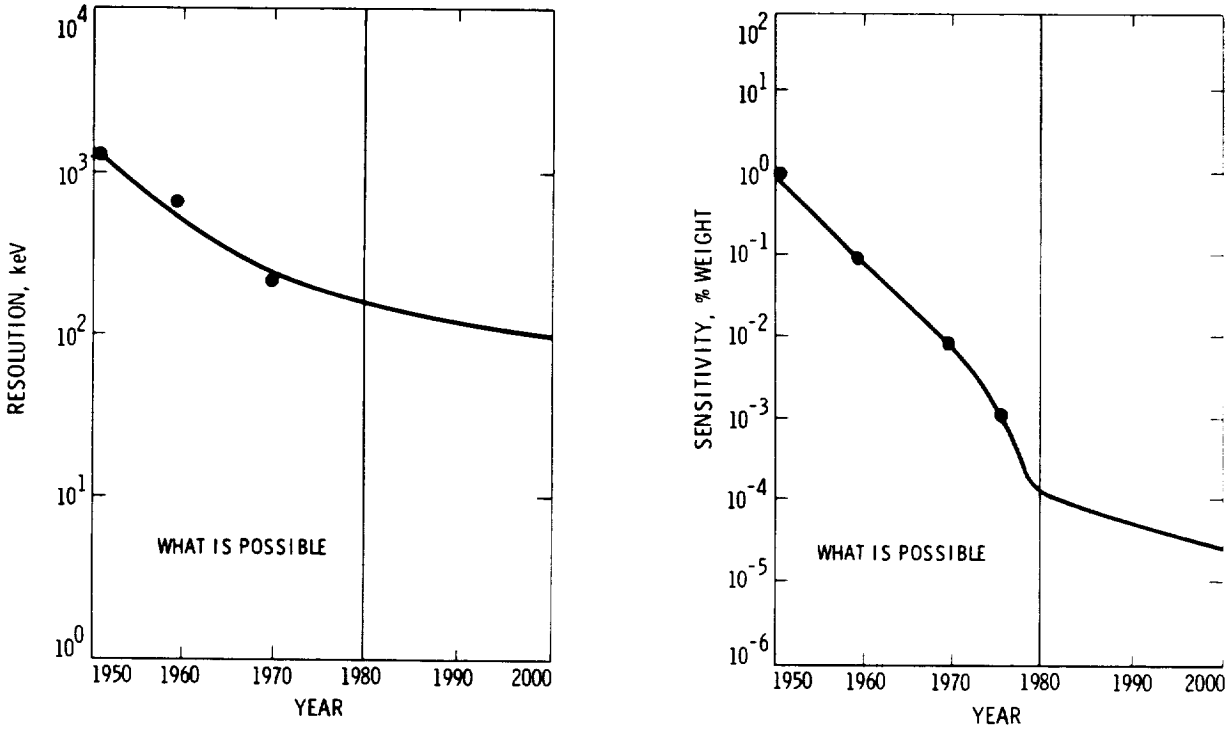
Nuclear magnetic resonance (NMR) spectroscopy is a widely used laboratory technique that can be used to analyze liquids and solids and to a limited extent gases for their isotopic content, molecular composition and the physical state of the substance. Nuclear magnetic resonance works on the physical principle that when nuclei that possess magnetic moments are placed in a magnetic field they will precess at a characteristic frequency and will absorb and radiate electromagnetic energy applied at that frequency. Each isotopic species will absorb at a different frequency. For a magnetic field of 10^4 gauss, a hydrogen sample would absorb at 42 MHz and deuterium at 5.4 MHz. Only those nuclei that possess a magnetic moment can be detected, therefore species such as He^4, O^{16}, C^{12} cannot.

If the spectrometer magnetic field is stable and constant to 1 part in 10^5 over the sample, small shifts in the resonance frequency of the isotopic species can be detected for different chemical compounds (exemplified by protons in different organic molecules).

The sensitivity of NMR detection of nuclear isotopes varies vastly depending upon the phase of the material in which the isotopes are imbedded. Liquid and gas phases show higher sensitivity simply because they have narrower absorption lines. However, recently developed line narrowing techniques as well as double-resonance techniques greatly enhance the sensitivity for solid phases, too.

The major obstacle to utilization of NMR in space is the need for high magnetic fields. This forecast assumes the development of space-adapted superconducting magnets as the means to decrease the magnet-mass/k-gauss ratio. Sensitivity for proton detection has also been forecast as a primary parameter, with future improvements based upon assumed development of dynamic nuclear polarization techniques for solid and liquid analysis. NMR would be an important payload component for lander missions or comet encounter missions where samples could be collected in situ. R&D funds of about $1.5M, spread over a 10-year period, would be required to achieve readiness for flight-instrument technology commitment.

FC 3-20. X-Ray Fluorescence



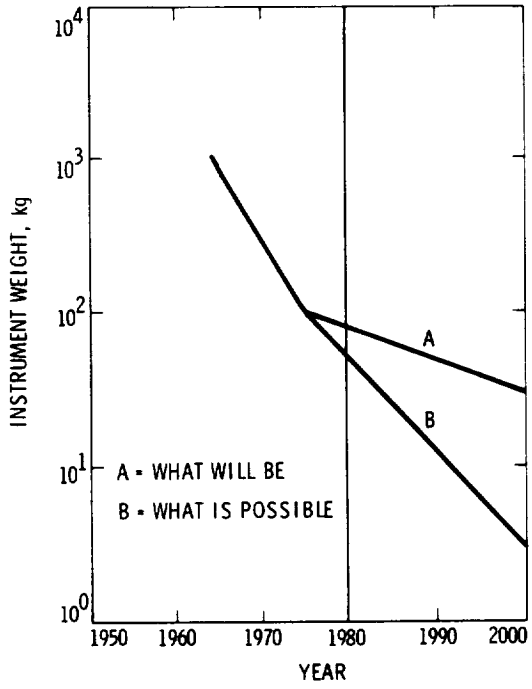
DISCUSSION

The elemental composition of a sample is determined by the excitation of characteristic X-ray transitions with the emission of fluorescent radiation. The source of excitation may be either an X-ray tube or, more compactly, a radioisotope emitting alpha or beta particles or X-rays. The emitted X-rays are detected by the deposition of their energy and its conversion to a proportionately sized electrical pulse. The accumulation of sufficient pulses produces an energy spectrum, the features of which are correlated with the characteristic X-ray transition energies of the sample. The effective sampling depth is small because of the limited X-ray range. Any layer of atmosphere or structural material between the emitting sample and the detector must be small relative to the range. The sensitivity of the technique can be greatly enhanced by the use of a cooled solid-state detector, a version of which is presently under development. The technique has and will be used for remote sensing from orbit in the absence of a significant atmosphere (Apollo), and for surface analysis where the atmospheric pressure is comparable to that of the Earth or less (Viking).

Energy resolution and sensitivity have been forecast as primary parameters. Resolution characterizes the ability of the instrument to resolve the X-ray incident energy in terms of the characteristic emission energy and measures the capability of distinguishing between two elements of adjacent atomic number and detecting distinctive electron shell transitions for the same element. Sensitivity expresses the limit of detection of elements in percent by weight. The values shown are typical; the characteristic value for a given element will depend on the choice of sources, source-sample-detector geometry, detector resolution, and atomic number of the element under detection.

X-ray fluorescence is particularly suited for lander missions (e.g., rover, penetrometer) where either in situ or delivered samples can be analyzed. Realization of this forecast requires acceptable improvements in solid-state detectors, optimum X-ray sources, geometric improvements, and the necessary lander-qualified cryostat systems.

FC 3-21. Surface Microanalysis Instrument



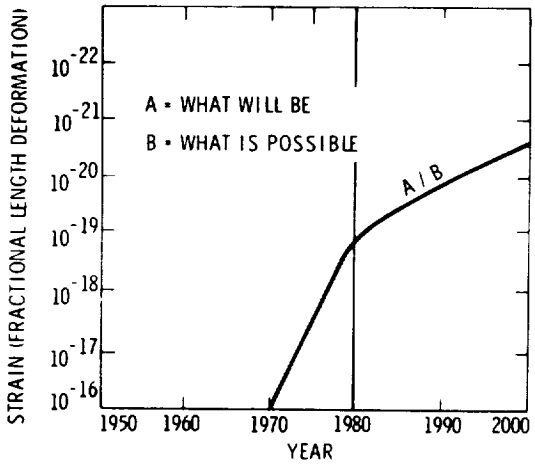
DISCUSSION

The title denotes a family of laboratory instruments which yield compositional surface analysis of solid samples and which are considered adaptable for space use. They are capable of measuring the elemental composition and state of the sample over areas as small as one micron square or less, with sensitivities of 10^{-3} monolayers of material over this area, and with capabilities of measuring composition and state from one monolayer to the next as the material is sputtered down to some 100 monolayers or more. They are extremely powerful tools for surface analysis, and in some cases bulk analysis, of very small samples and give mineralogical analysis of bulk samples.

Ion and electron microprobes are typical of this family of instruments, which operate by measurements of particles or radiation which are reflected, emitted, or sputtered from a surface under bombardment. Included in this family are: auger electron spectroscopy, low energy electron diffraction, electron microprobe, X-ray fluorescence, X-ray photoelectron spectroscopy, secondary ion spectroscopy, and ion microprobe. The sensitivities, resolutions, and ranges of these instruments are all very similar: spectral resolution ≈ individual atomic masses, geometric resolution ≈1 micron to 1 mm sq., sensitivity ≈ 1 ppm to 1 ppb, range ≈all atomic masses except H and He in the case of electron and X-ray scattering.

The primary driving parameter for space applications is considered to be instrument weight. The instruments' resolution, sensitivity, and range are not required to change nearly as rapidly as their miniaturization over the appropriate time period. Auxiliary sample handling and processing apparatus (including a vacuum interlock) is required. The instrument requires a smooth sample surface and is best implemented if a single impinging radiation source is used and several peripheral detectors are used to observe different types of emitted radiation. These instruments could be important for lander and cometary encounter missions. (Refs. 3-32 - 3-36)

FC 3-22. Gravity Wave Detector



DISCUSSION

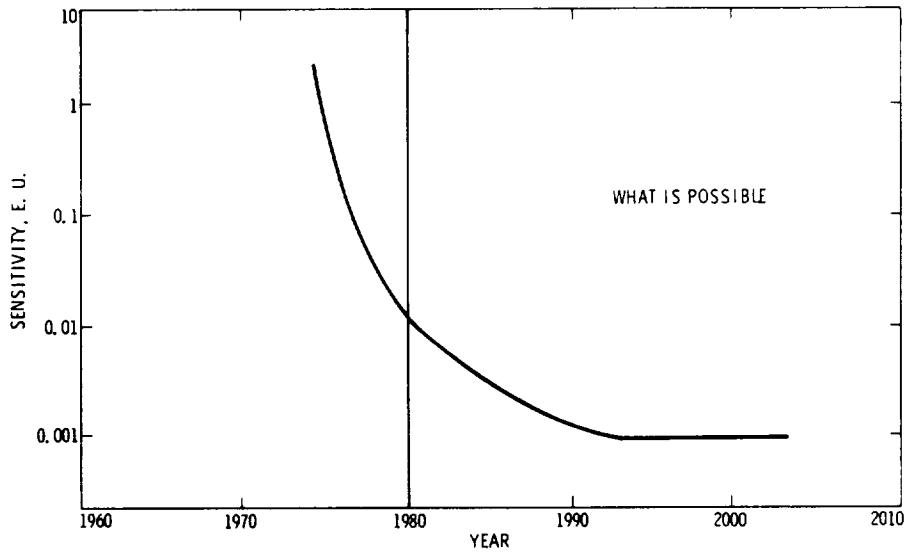
Gravitational wave antennas are large, passively gravitating, very-high-Q mechanical systems, matched to very-high-Q electromagnetic resonators for readout and cooled for low noise and for superconductive levitation. They will be acoustically and electromagnetically isolated. The gravitational wave nature of excitation will be finally established by light-time delayed excitation of physically separated antenna arrays. The expected astrophysical sources of excitation known are: binary stars, pulsars, black holes, supernovae, and close encounters in galactic nuclei.

Within the next 25 years, it is reasonable to expect significant advances in detection instrumentation in two frequency regimes: (1) medium frequency (MF), 100 Hz - 100 kHz, and (2) low frequency (LF), 0.1 Hz - 100 Hz. The expected astronomical sources in the MF range are events in the neighborhood of rotating black holes, catastrophic collapse of stars, close encounters of condensed masses in galactic nuclei, supernova explosions. The LF range is more characteristic of pulsar phenomena. The very low frequency (VLF) range from 10^{-4} Hz to 0.1 Hz, which contains binary system frequencies, is subject to very serious environmental interference both on Earth and in space, and will most likely not be accessible to measurement with resonant antenna.

MF detectors can be resonant mechanical systems on Earth or in orbit (Weber type, with various modifications), or can use moving—i.e., rotating—masses for heterodyne detection (Braginsky type). LF detectors must use lumped resonators (hollow squares, etc.), heterodyne detectors, or masses distributed on very long scales. The salient design improvements which can be foreseen are in acoustic isolation and thermal noise elimination—both to be achieved by cryogenic and superconductive technology—and in the development of extremely-high-Q systems. High-Q mechanical systems will be achieved with the perfection of very large mass (~10 kg) single crystals such as sapphire. High-Q electromagnetic parametric transducers can be achieved by continuing state-of-the-art improvements in superconductive resonant microwave cavities and oscillators. SQUID devices will lead to quantum-limited detector noise.

This forecast is based upon the availability of superconductively levitated, cooled detector arrays by 1985 and the perfection of very low temperature quantum detectors by 2000. It might be speculated that the isolated environment of a space station will be found necessary for the projected further improvement of sensitivity by A.D. 2000. If this can indeed be achieved, studies of spectral distribution, polarization, etc., can finally be made of this most basic wave phenomenon. In view of the global R&D support of this technology (including NSF in this country) and assuming active development of cryogenic technology for other purposes, a NASA support level of ~$0.5M per year over a 5-year period could give most of the needed elements of technology readiness.

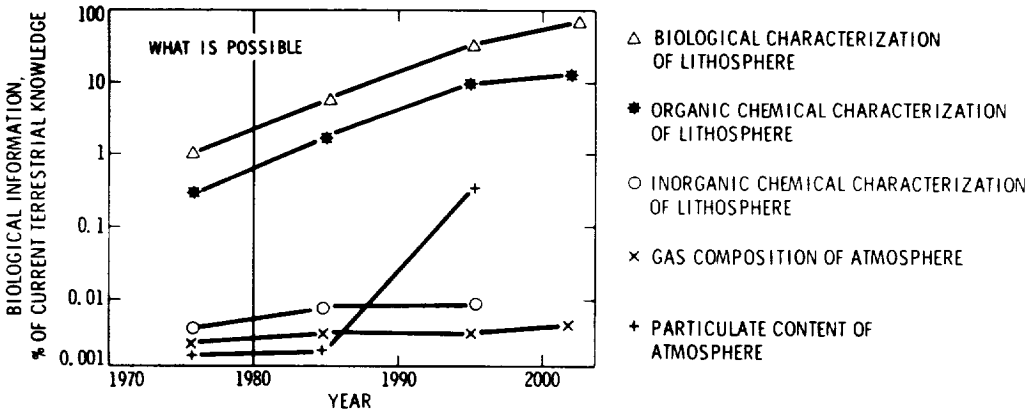
FC 3-23. Gravity Gradiometer



DISCUSSION

The gravity gradiometer measures the derivative of the gravity field. This satellite technique offers an alternative to trajectory perturbation analysis and is particularly attractive for mapping the higher frequency effects of the gravity field. It offers the potential to improve the resolution of gravity maps over the entire Earth to a few hundred kilometers. Two approaches to a gradiometer are presently being developed; both methods have the configuration of a cruciform rotor and differ in the way forces on the rotor are sensed. A sensitivity of 0.01 Eotvos Unit (1 E. U. = 10^{-12} grams per centimeter) is considered to be the present state of the art. With this sensitivity it should be possible to map the variations in the geopotential field of the Earth in the 100 - 400 kilometer wavelength range. This would require the gradiometer to be mounted on a spinning spacecraft in an extremely low polar circular orbit. A dedicated spacecraft will probably be required because of stringent constraints which this instrument would place on the spacecraft. Knowledge of orbit altitude to the order of 5 meters is required. A sensitivity of 0.001 E. U. is considered technologically possible but would require a larger cruciform and development or invention of new approaches to solving thermal-noise limitations. Going beyond 0.001 E. U. does not seem realistic in either applications requirements or technology requirements. The forecast through 1980 is based on plausible instrument scaling using present technology. Progress to the 1990 level requires new inventions or breakthroughs. Development of a 1980 capability would require R&D funds of $10M covering both instrument and spacecraft.

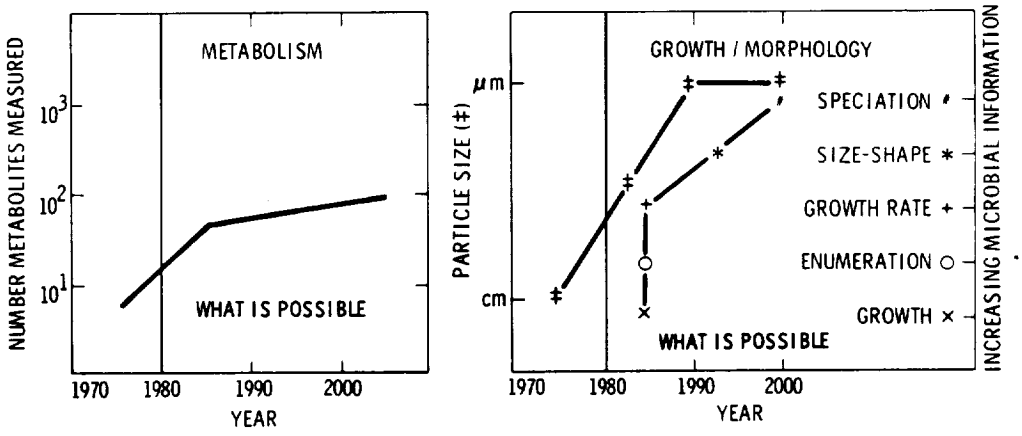
FC 3-24. Characterization of Planetary Environments and Biota



DISCUSSION

The characterization of a planet from a biological viewpoint includes studies of the planet's atmospheric gas composition and particulate content and studies of the inorganic, organic, and biological contents of the lithosphere. The forecast is based upon information about biological systems which are assumed to have been detected (see Life Detection Forecast). The scale of information is based upon our current knowledge of terrestrial biology, which is taken to be full scale. Inorganic and physical measurements have little biological information content, but can be important precursors to an understanding of the environment from a biological viewpoint. The gas measurements are to be made by mass spectrometry (MS), gas chromatography (GC), and combined GCMS. The inorganic measurements are to be made by classical geological instruments augmented by special probes for specific ions, trace elements, and water. The organic chemical characterization relies on GCMS analysis of derivatives of amino acids, N-heterocycles, sugars, and fatty acids. Analysis of biopolymers is included. The biological characterization and the biological examination of particulates relies initially on Viking class life detection instruments and is followed by more complex instruments to measure energy mechanisms, metabolic pathways, genetic macromolecules, and cellular organization. The forecast is based largely on Viking instruments for the initial points followed by post- Viking instruments currently in early development. The later forecast points are based on complex extrapolations of the above. Characterization measurements are to be conducted primarily on landed missions but can be carried out in probes and orbiters to a lesser extent.

FC 3-25. Life Detection



DISCUSSION

Life detection comprises a complex series of measurements designed to elicit from a sample responses such as metabolism or growth which are characteristic of life as we know it. Life detection experiments require collection of samples, some perturbation to initiate the process to be measured, suitable detectors, and provision for assessing the validity of the response. Metabolic experiments involve measurement (by GC, MS, chemical tests) of the appearance or disappearance of gases and/or biomolecules as a result of conversion processes unique to living systems. Growth/morphology experiments involve determination (by conductivity, light scattering) of increase in microbe numbers or recognition (by imaging) of biological entities.

Primary parameters forecast are number of metabolites measured, particle size, and microbial information content. Life detection is not a single instrument, but rather a complex series of measurements which, when taken as a whole, provide an assessment of the presence or absence of life. Therefore, the forecasts really represent confidence values and information content rather than instrument specifications. The forecast requires acceptable advances in detector sensitivity, chemical or biological processing, and micro-imaging techniques. Life detection instruments are conceptually adaptable to subsurface penetrator, hard surface lander, and atmospheric probe missions, in addition to soft landers (including rovers).

Certain metabolic life detection instruments have been fabricated for use on Viking 1975. Others, as well as growth/morphology measurements, are based on concepts which were undergoing some development prior to selection of Viking payload. Development is continuing on selected instruments in this category.

E. CAPSULE FORECASTS AND GENERAL OBSERVATIONS

The following statements summarize the prospects for certain instruments whose detailed forecasts are not included.

1. Superconducting Josephson Effect Infrared Detector.

The sensitivity (noise effective power) could be reduced by two decades from the present value of $\sim 10^{-4}$ watts/$\sqrt{Hz}$ by 1980. Fundamental limitations may impede appreciable further progress. The device shows promise of being superior to existing sensors in sensitivity and spectral selectivity over the frequency range from 100 GHz to 3000 GHz. The device is just entering astronomical use and is not yet space-qualified.

2. Aerosol Photometer

This multiwavelength photometer measures forward scattering of sunlight by aerosols. The minimum achievable volume extinction coefficient of scattering is expected to drop two decades from the present value of $10^{-4} m^{-1}$ by 1990.

3. Ultraviolet Instruments

The several types of UV astronomical or remote sensing instruments are primarily useful for studies of low density atmospheres, where they can serve as exceedingly sensitive detectors of certain constituents or as indicators of temperatures or mass velocities. Principal advances in the forecast period are expected to be: (a) sensitivity increase by a factor of 2 to 3 for $\lambda < 1000$ Å; (b) resolution improvement by a factor of 3; (c) weight reduction by a factor of 3; and (d) coupled use of area sensors for UV imaging and tunable filters for spectral selection.

4. Space Plasma Instruments

Space plasma instruments available by 1980 will probably be adequate to perform the investigations of the period 1980-2000. Instrumentation will be used in new environments and in active experiments.

5. Alpha Scattering Elemental Analysis Instrument

Between 1975 and 2000 the sensitivity (detectable percent by weight) for light elements could improve from 0.6 to 0.06 and for heavy elements could improve from 6×10^{-4} to 3×10^{-6}.

6. Thermal Analysis Instrument

This instrument, employing a differential scanning calorimeter and possible accessories, determines the form and amount of water and stored volatiles in situ in planetary materials. Its differential power resolution could be brought down by about one decade from the present value of 3×10^{-4} calories/sec.

7. Microwave Spectrometer

This laboratory device could be adapted to space use and could measure trace atmospheric constituents (in situ) with number densities extending below 10^6 molecules/cm^3.

8. Optical and Electron Microscopes

Both instruments appear adaptable to planetary landers. Development work has been done only on the former. By about 1990 the resolution of space electron microscopes could be as good as 10 naonmeters. Substantial advances in auxiliary devices will be required.

9. Passive Seismometer

Improvement of the displacement sensitivity by a factor of 3 below the 30 picometer level of the planned Viking instrument appears desirable and achievable. A net of three or more widely spaced instruments is highly desirable for definitive planetary experiments.

No qualitatively new instruments have been introduced. Their absence represents a limitation in the report. The development of superconductivity, integrated optics, and coherent light techniques gives clear promise of the invention of such instruments, and completeness would require some consideration of these.

One noteworthy instance of an apparatus probably peculiar to laboratory experiments in space is under development at present, namely one for acoustic handling and shaping of free liquids or other materials whose contact with walls must be avoided. The present development program can be expected to result in a space-qualified technology by 1980. Most other hardware for these purposes appears to be an adaptation of laboratory equipment.

As a final generalization, microcircuit computer technology will clearly be applied to space instruments as vigorously as it is starting to be to other subsystems (see FC 3-61 in Section IV). The result will be a transformation of the instruments themselves to include internal data processing and feedback control as a standard organic element of the conceptual design. Design goals will include maximizing both the degree of autonomy of operation and the efficiency of information gathering and output.

F. SUMMARY

This section has presented forecasts of representative scientific instruments expected to be of importance for future space objectives and to experience significant advance during the forecast period.

The forecasts include not only instrument types actively in space use but also a few in early stages of development for space use, and a few laboratory instruments which, in the light of foreseeable technology, are considered adaptable for space.

Some generalizations from the forecasts are:

(1) Most remote sensing instruments show promise of performance improvement by factors of 30-3000 (usually in sensitivity) by year 2000.

(2) The strong interest of NASA and DOD in remote sensing instruments gives a strong argument for continuing to provide necessary resources to support these developments.

(3) Many instrument advances depend critically on the development of high-capability spaceborne cryogenic systems.

(4) In order to utilize remote sensing adequately to meet the requirements of goal-oriented missions, it will be necessary to upgrade strongly the level and sophistication of effort directed to theoretical modeling for design and interpretation of remote sensing measurements.

(5) Forecasts of X-ray and gamma ray astronomical instruments project performance improvements by factors of 10-100, thus promising significant opportunities for exploration in this important new astronomical window.

(6) Lander instrument forecasts suggest a comparatively modest upgrading in capability (factors up to 10, typically) of existing instruments, and the possibility of adapting for space a number of instrument types so far used only in the laboratory. However, the considerable uncertainty in programmatic resources in this area makes "what will be" forecasts indeterminate.

G. LIST OF PARTICIPANTS*

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H. INDEX OF MICROFILMED FORECASTS

The following forecasts, concerning the acquisition of information, are available at the Jet Propulsion Laboratory. To retrieve copies of individual forecasts call Mr. George Mitchell at (213) 354-5090 and give the document number (1060-42) and volume number (Vol. III) followed by the correct page reference numbers as listed below. These particular forecasts are categorized by instruments and are identified by the following numbers and letters:

	Title	Page No. (1060-42, Vol. III)
1.	Electromagnetic Instruments	
a.	Spaceborne Microwave Radiometers	3-15 — 3-22
b.	Imaging Passive Microwave System	3-22 — 3-28
c.	Radio Telescopes	3-29 — 3-37
d.	Radar Imaging/ Sounding	3-38 — 3-49
e.	Space Telescope (Size)	3-50 — 3-52
f.	Infrared Remote Sensing Instruments	3-53 — 3-58

Title	Page No. (1060-42, Vol. III)
g. Superconducting Josephsen Effect Infrared Detectors	3-58 – 3-61
h. Active Laser Absorption Spectrometer	3-61 – 3-64
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Section III. TRANSFERRING INFORMATION

A. J. Spear

A. SCOPE

Forecasts of "what is possible" and "what will be" are provided for space-related communication technology out to the year 2000. Included are Earth transmission links which are usually in series with space links.

Information transfer encompasses those technologies required to code, modulate, and transmit a signal over the transmission media and to receive, demodulate, decode, and reconstruct the best estimate of the signal as it existed prior to coding:

(1) Channel coding and modulation - signal design.
(2) Transmitters, antennas, receivers.
(3) Signal detection, decoding, autocorrelation and frequency spectrum measurements - signal processing.
(4) Combinations of the above into systems and links.

The forecast is limited to technology for communication over standard electromagnetic links in the microwave and optical bands. Not included are forecasts for communication by acoustic waves, X-rays, and other novel means. This is not to say these types of links are not possible or probable by 2000. However, most communication will continue to occur over microwave and optical electromagnetic links for the next 25 years.

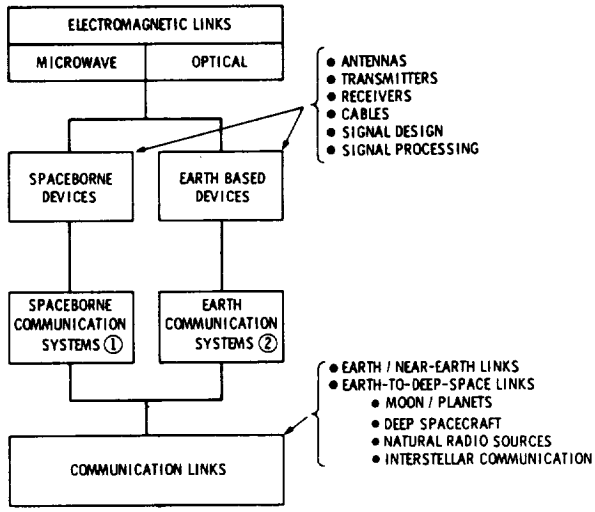
Two categories of forecasts were developed:

(1) Communication device forecasts.
(2) System forecasts synthesized from the device forecasts.

The forecast end-product is communication links and the major forecast parameter is information rate. Although the link forecasts are structured around certain applications, the emphasis is on communication technology.

B. ORGANIZATION AND APPROACH

Electromagnetic link technology was organized as shown:



① SATELLITE, SPACECRAFT, ORBITING / LANDED SPACE STATIONS
② TRACKING AND DATA ACQUISITION, RADIO SCIENCE, EARTH COMMUNICATION

Figure 3-1. Electromagnetic link technology

The forecast effort was subdivided into units of work which match the expertise of the individual forecasters. Earth and spaceborne devices were forecasted initially and synthesized into parameter forecasts at the functional element level. These were then compared with extrapolations of system information rates for Earth, near-Earth, and deep-space applications.

The breakdown into device and system forecasts among individual forecasters was more complete for microwave technology (matching well-established discipline organizations) than for

optical communications, where device and system forecasts were generally made by the same person.

A goal was established to draw upon expertise from industry, government agencies, military, etc. to the maximum extent possible. A team of forecasters was assembled from Ames, Goddard, Langley, JPL, Marshall, Lockheed, and Wright-Patterson, representing a good cross-section of the technologies to be forecasted and providing in-depth support in those fields not emphasized at JPL (such as Earth-satellite and laser communication). All forecasters in turn sought expert opinions from their peers in each technology. An attempt was made to investigate all existing, available forecasts. Military and industry forecasts were especially important since large segments of communication technology are being driven by their research and development.

An analysis was made to determine who and what applications will drive communication technology.

Listed below are the technologies emphasized by organization:

Organization	Technology
University	Basic research, fundamental to military, industry and NASA research and development.
	Radio science, radar astronomy.
	Interstellar communication.
Military	Satellite links.
	Radio sensors.
	Optical-cable links.
Industry	Satellite and deep-space links.
	Microwave and optical-cable links.
	Interstellar communication.
NASA	Deep-space links.
	Radio science, radar astronomy.
	Radio, radar sensors.
	Interstellar communication.
	Optical-cable links.

Listed below are the technologies emphasized by application:

Application	Technology
Satellite Links	Microwave bands at S, X, K_u and higher frequencies.
	Infrared and visible optical frequencies.
	Large spaceborne antennas: Arrayed, wideband, multi-beam, shaped and electrically steerable beams. Large front-to-back ratios.
Satellite Links (Contd)	Large transmitter power.
	Megabit-per-sec. microwave links.
	Gigabit-per-second optical links.
	Signaling techniques for packing maximum signals in limited bands.
	Spread-spectrum modulation.
	Data compression.
	Multi-access satellites.
	Multiple-user communication theory
	Wide-bandwidth, low-noise receivers.
	Complex high-rate signal processing.
	Small, light, efficient components.
	Mass-produced spaceborne components.
Radio Sensors	Microwave frequencies in all bands up to optical frequencies.
	Complex high-rate signal processing.
	Multi-feed, multi-frequency, wideband, steerable, shaped-beam antennas. Large front-to-back ratios.
	Ultra-stable, low-cost spaceborne oscillators.
Deep Space Links	Microwave bands at S, X, K_u.
	Large spaceborne antennas.
	Large ground antennas and arrays
	Large transmitter power.
	Low-noise spaceborne receivers.
	Efficient channel coding.
	Data compression.
	Data rates to 10 megabits per sec.
	Ultra-stable low-cost spaceborne oscillators.
	Small, light, efficient components.
Interstellar Communication ● Search for extraterrestrial life	Arrays of large ground antennas.
	Ultra-wideband microwave sys.
	Ultra-low system noise temp.
	Complex wideband signal processing.

In addition to the mainstream forecast activity, a Communications Technology Seminar was conducted. The invited speakers (listed in E below) were asked to speak informally on communication

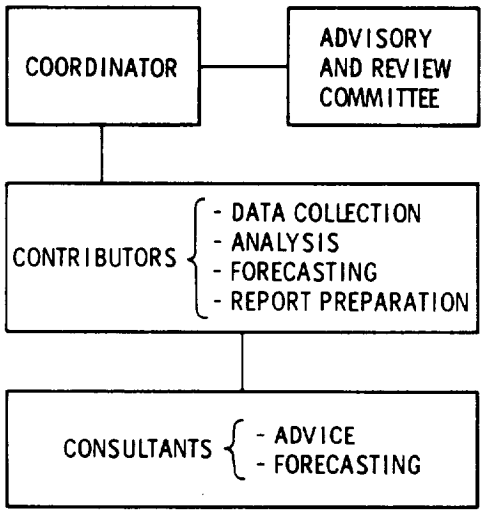
technology and to interact with a panel comprised of the speakers and senior technical management. An audience included those participating directly in the forecast. Prior to the meeting, the panel was provided a list of issues to focus the session, to some extent, on the subject matter being addressed in the forecasts.

The purpose of the seminar was threefold:

(1) To solicit opinions on future communication technology, providing a broader view.
(2) To solicit opinions on the forecast methodology: Were the right approaches being taken?
(3) To provide a forum where the forecasters could interact with well-known and respected leaders in the field.

A major contribution of the seminar was the generation of a good perspective of what is to be expected in communications developments for the next 25 years. The seminar predictions are reflected in the Summary and Implications subsection of this section.

The forecast team was organized as depicted below:



C. FORECASTS

The Transferring Information forecasts are organized under eleven major headings on the following pages as shown below:

(1) Microwave Transmitters

FC 3-26. Klystron RF Power
FC 3-27. TWT RF Power
FC 3-28. Solid-State Power-Frequency Characteristics

(2) Microwave Space Receivers

FC 3-29. Device Noise Temperature at S-Band
FC 3-30. Device Noise Temperature versus Frequency

(3) Microwave Antennas and System Noise Temperature

FC 3-31. Gain of Large Earth-Based Antennas at S, X, and K_u Bands
FC 3-32. Gain of Large Earth-Based Antennas at 95 GHz
FC 3-33. Gain, Mass, and Cost of Geostationary Earth-Orbital Antennas at S, X, and K_u Bands
FC 3-34. Gain, Mass, and Cost of Large Spacecraft Antennas at S, X, and K_u Bands
FC 3-35. Gain and Cost of Spacecraft Antennas for Selected Lunar and Mars Missions
FC 3-36. System Noise Temperature of Earth-Based Communication Stations
FC 3-37. System Noise Temperature of Geostationary Earth-Orbital Communication Systems

(4) Signal Design and Processing

FC 3-38. Coding in the Year 2000
FC 3-39. Coding Gain
FC 3-40. Bandwidth Compression Gain

(5) Optical Communication

FC 3-41. Synchronous-to-Synchronous Satellite Communication Data Rate (CO_2 Laser)
FC 3-42. Low-Altitude Satellite-to-Synchronous Satellite Communication Data Rate (CO_2 Laser)
FC 3-43. Synchronous-to-Synchronous Satellite Communication Data Rate (Nd:YAG Laser)
FC 3-44. Low-Altitude Satellite-to-Synchronous Satellite Communication Data Rate (Nd:YAG Laser)
FC 3-45. Synchronous-to-Synchronous Satellite Communication Data Rate (Nd:YAG, Doubled, Laser)
FC 3-46. Deep-Space-to-Near-Earth Laser Data Relay Communication Data Rate

(6) Near-Earth Communication

FC 3-47. Transfer Rate, Synchronous Orbit to Earth (Microwave)
FC 3-48. Transfer-Rate, Synchronous Orbit to Small Earth-Terminal
FC 3-49. Transfer-Rate, Synchronous to Low Earth-Orbit (Microwave)
FC 3-50. Commercial Satellite Transmission Costs
FC 3-51. Commercial Terrestrial Communication Capability (Per Unit of Equipment)
FC 3-52. Commercial Terrestrial Communication Costs

(7) Deep-Space Communication

FC 3-53. Deep-Space Communication Rates

(8) Interstellar Communication – The Search for Extraterrestrial Life

FC 3-54. Interstellar Search Range
FC 3-55. Interstellar Communication System Implementation Cost Estimate

(9) Near-Earth and Deep-Space Communication Stations

(10) Radio Sensors

(11) Radar Astronomy

FC 3-56. Ground-Based S-Band Planetary Radar Sensitivity
FC 3-57. Ground-Based X Band Planetary Radar Sensitivity
FC 3 58 Orbiting S-Band Planetary Radar Sensitivity
FC 3-59. Orbiting X-Band Planetary Radar Sensitivity

1. Microwave Transmitters

a. Introduction. Microwave transmitting devices are forecasted here for space application. The discussion is limited to those present-day devices known to qualify favorably for use in a space environment--linear-beam tubes and solid-state devices.

The forecast is based in part upon surveyed opinions of twenty-eight designers and technical managers in the microwave transmitter industry, which are summarized in the following figures and narrative, and in part upon experience with microwave transmitter developments at JPL.

The following static transmitter parameters are assumed as minimum requirements for future spacecraft use:

Frequency (f)	2 to 100 GHz
RF power	10 W to 1 MW (saturated)
Gain	30 dB or greater
Bandwidth	(f x 0.01)
Modulation	Phase-shift-keyed (PSK)

b. Background. A survey of the past shows that some thirty years elapses from the time a new microwave energy reaction phenomenon is discovered until devices utilizing it mature. The spark-gap transmitters invented by Marconi in 1895 came into full usage during the late twenties. The triode invented by De Forest in 1906 did not produce powerful radio transmitters until the mid-thirties. The Klystron invented by Varian in 1936 did not reach high power until the mid-sixties, and the traveling-wave tube (TWT) invented by Kompfner in 1942 did not mature until the mid-sixties. The transistor of Shockley, et al., introduced in 1947 is only now reaching interesting power levels at microwave frequencies. The maser/laser invented by Townes in 1950 is still in the process of technical growth and will probably not mature until the eighties. The most recent reaction, a combination of two earlier ones, is the electron-beam semiconductor discovered by Stanford researchers in 1967, in which an electron beam impinging on a solid-state diode gives a gain of 30 dB. This device should mature at a somewhat faster pace because of previous knowledge of the reaction.

c. Present Status. The designs of present spacecraft transmitters are largely limited to linear-beam tubes. Their characteristics are discussed by category below and illustrated in accompanying figures.

(1) Power and Frequency Limits. These are shown in Figure 3-2, which also illustrates the minor improvements expected by industry if research funding becomes available in the future.

(2) RF-Power and Frequency Characteristics. Figure 3-3 shows that, of the multitude of existing tubes at all power and frequency levels, only a few have been qualified for flight use, and these at relatively low power and frequency. Considerable monetary support will be required in the future to extend flight qualification along either the power or frequency axes.

(3) Cost. Figure 3-4 shows estimates by industry of flight-qualification costs for those devices yet to be selected for space utilization.

(4) Efficiency. All linear-beam tubes today have nearly reached their peak efficiencies. Only minor improvements (15%) are expected in the future, and those only if sizeable research support is provided. Efficiency degrades with increasing RF power and frequency. At nominal power (100 Watts), efficiency declines from 55% at 2 GHz to 18% at 100 GHz. At nominal frequency (8 GHz), efficiency degrades from 50% at 100 Watts to 35% at 10 kilowatts.

(5) Life. Transmitter lifetime is a primary concern for all space missions. The operating life of an electron tube is dictated by the current drawn per unit area of its cathode and by its cathode operating temperature. At S-band frequencies, tube elements are comparatively large. Larger cathodes can therefore be used with lower current loading and lower temperature, which give greater life at higher power. As frequency increases, the elements become smaller, requiring smaller cathodes, which must be driven to higher current loading and temperature for equivalent power levels. Thus, it is seen in Figure 3-5 that both lifetime and power become progressively smaller as frequency increases from 2 GHz to 60 GHz.

(6) Size and Weight. Size and weight increase proportionally with rf power. Examples of weight are: 1 kg at 10 W, 2 kg at 100 W, and 5 kg at 800 W. At 1 kW and above, a heat exchanger is required, bringing the total transmitter weight to 27 kg at 1 kW, 90 kg at 10 kW, and 270 kg at 100 kW. Examples of size are 1,700 cm^3 at 10 W, 5,100 cm^3 at 100 W, and 14,200 cm^3 at 800 W. At 1 kW and above the tube plus heat exchanger size is 0.15 m^3 at 1 kW, 0.17 m^3 at 10 kW, and 0.48 m^3 at 100 kW. State-of-the-art heat exchangers can dissipate 775 watts/m^2.

(7) Power Supplies. Each spacecraft transmitter requires a flight qualified power supply, whose cost for development and flight production approximates that of the linear beam tube which it powers. The weight of each power supply is nearly equal to that of its driven tube.

d. Forecasts. Linear-beam tube research and development flourished during the 1960s, producing numerous higher-powered and higher-efficiency devices. Funding for research and development, however, has declined severely during the first half of the 70s and will fall to nearly zero in the early 80s. Users will find that presently developed tubes can satisfy nearly all of their requirements and "standardization" will be practiced by heavy government users, such as the military, in an attempt to lower escalating system costs. Power and frequency projections for linear-beam tubes are shown in Forecasts FC 3-26 and FC 3-27 which illustrate the effects of diminishing research support.

At medium microwave power, solid-state devices are steadily taking over the market with their attractive prices and simplicity. As a result of substantial and growing research and development, the market will shift in their favor. The region above a few hundred watts in power and above 10 GHz in frequency, however, will belong to the tube manufacturers for at least another decade because of present limitations in power and frequency for solid-state devices. The power and frequency characteristics of solid state devices with year as a parameter are displayed in Forecast FC 3-28.

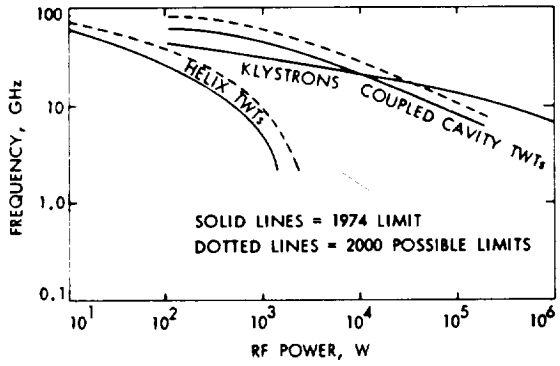


Figure 3-2. Maximum power-frequency characteristics of linear beam tubes

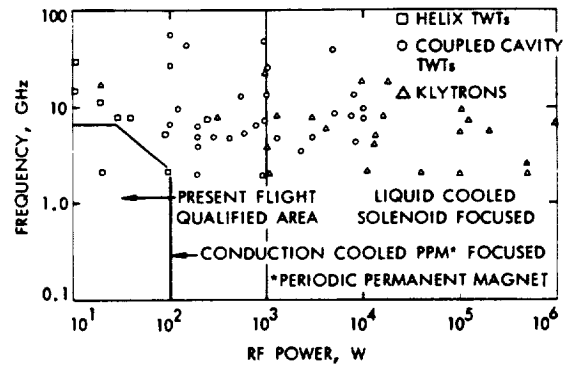


Figure 3-3. Power-frequency characteristics of presently available tubes

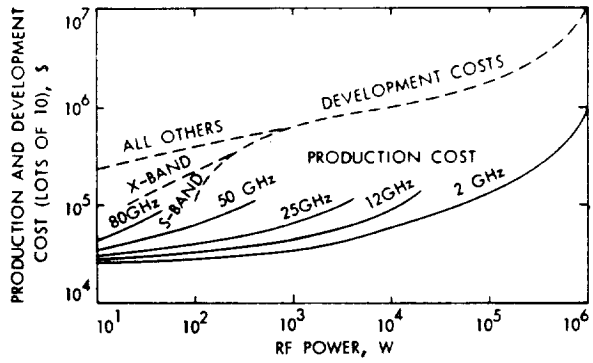


Figure 3-4. Electron tube cost versus rf power (flight quality)

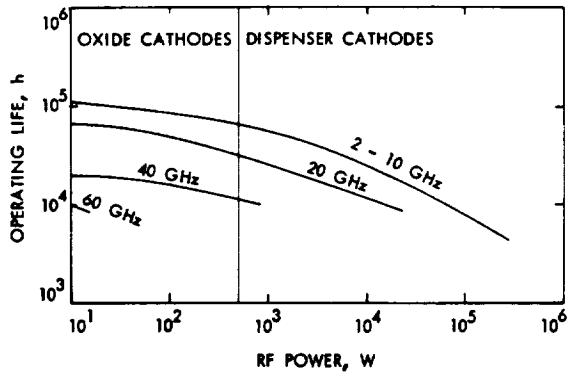
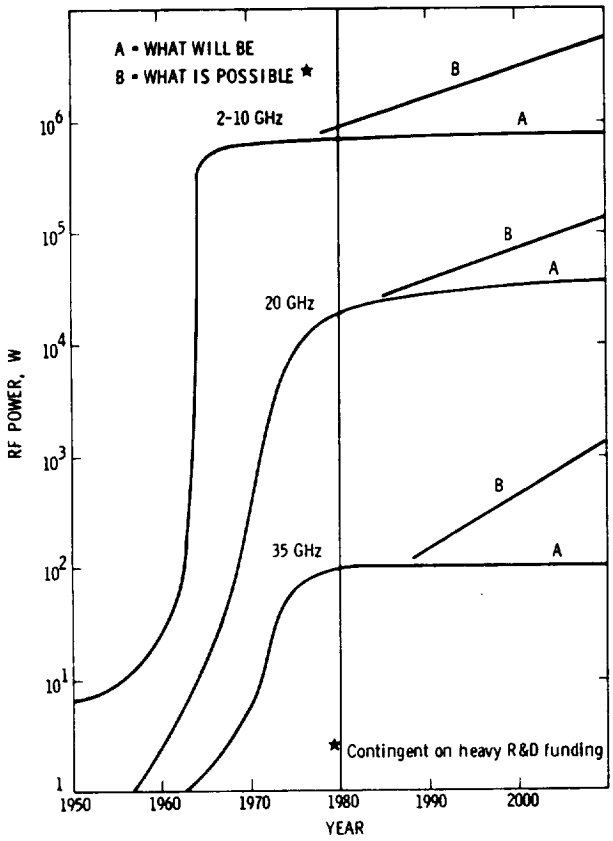
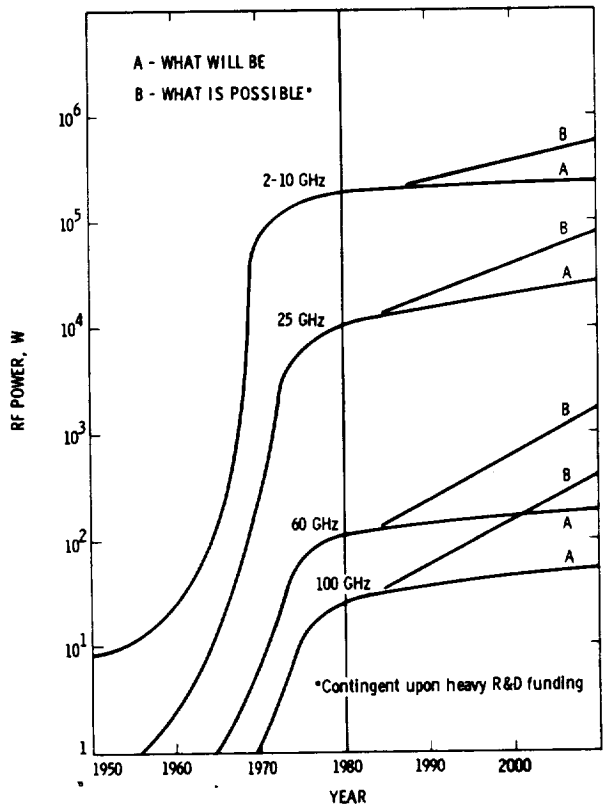


Figure 3-5. 3-dB life versus rf power for linear-beam tubes

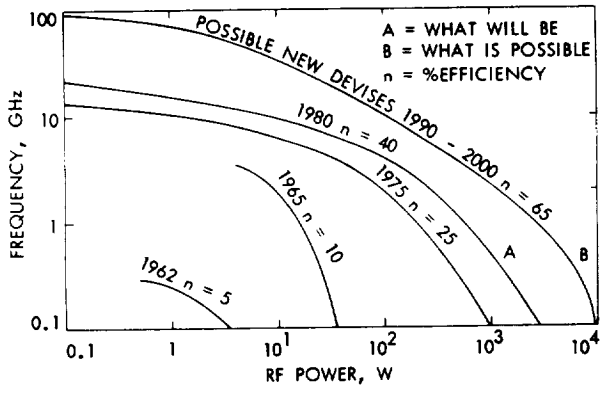
FC 3-26. Klystron RF Power



FC 3-27. TWT RF Power



FC 3-28. Solid-State Power-Frequency Characteristics



DISCUSSION

During the next decade, continued development of present microwave solid-state devices will increase their frequency and power capabilities and lower their noise figures. As we have learned from the past, however, technology is an ever-evolving phenomenon and it can be expected that the present solid-state concepts will give way to newer and better ones. Bulk effects will be discovered which will increase solid-state power performance. Even now, traveling-wave effects are being found and explored for higher solid-state gain (Ref. 3-37).

Earth and near-Earth communication links will rely substantially on solid-state technology by the mid-80s, but NASA deep-space missions will be committed to the tube if more ambitious exploration demands higher frequencies, power, and efficiency. The requirements of solar-system exploration will, in general, be satisfied by present 50- to 100-W tubes; consequently, there will be little research and development activity. Were stellar exploration to be attempted in the 1990s or thereafter, a whole new communication concept would have to be available. Either a multi-megawatt spacecraft transmitter or a larger antenna array (of the size proposed in the Cyclops study – Ref. 3-38) would be required to cover the 375-dB space loss over the distance to the nearest star.

FC 3-27 (Contd)

The production of electromagnetic radiation power has progressed through four prime energy reactions in the past 75 years, evolving from spark discharges of the old gap transmitters to the electron-beam interactions of linear-beam tubes to the hole-electron flow of solid-state devices and to the atomic resonance of lasers. What is of interest is that no prime radio frequency reaction has been discovered in the past 25 years! An innovation is seemingly overdue, and with our accumulating technical wherewithal. It is likely to come before the present decade is past – in view of the present emphasis on energy research. Energy production will reach the status of a national goal and the research surrounding this activity will receive wide public funding support. The next radio-frequency reaction phenomenon will be discovered either directly or as a side-effect of this tremendous nationwide scientific activity. Energy of one form is required to produce energy of another form, and the level of energy research destined for the next ten years will bring forth many useful power reactions. It is expected that among these will be a new rf transmitter powered by a simple energy source.

In summary, we can expect the use of tubes to decline and the use of solid-state devices to rise; both will be replaced by a new radio-frequency concept which will reach maturity in the 1990s.

2. Microwave Space Receivers

a. Scope. The primary forecast parameter is noise temperature for receivers operating at frequencies ranging from 2 GHz (S-band) to 100 GHz. Forecasted, also, are the expected trends in cost, size and weight, and power consumption of space receivers and transponders.

b. Background. Spaceborne receivers have several functions. Aside from their use in the communication link, they are also used as key elements of spacecraft navigation systems providing Doppler and range information. Receiver signals are also frequently used by scientists to establish characteristics of numerous near-Earth, solar, planetary, and interplanetary media such as coronas, plasmas, atmospheres, ionospheres, and charged particles.

One of the most important measures of spacecraft radio performance is the receiver noise temperature. This parameter is predominantly determined by the receiver "front end," consisting of the antenna feed cable, diplexer, preselector, rf amplifier, and down-converter. All of these components play a role in determining receiver noise temperature, depending on whether or not low-noise rf amplification is used. The loss mechanisms of the passive components add up directly to the noise temperature of the receiver in the absence of prior rf amplification. However, when the system employs an rf amplifier in its front end, the noise temperature and gain of the amplifier modify the overall noise figure according to the well-known Frii's formula (Ref. 3-39).

The basic space receiver design is somewhat independent of the uplink carrier frequency. The noise temperature, however, is strongly dependent upon uplink frequency because the circuit loss mechanism is proportional to frequency. As frequency increases, the only significant changes in receiver design are in the local oscillator chain to provide the higher-frequency down-conversion signal and the possibly higher-frequency and/or wider-bandwidth intermediate frequency if the higher frequency is chosen for its higher data-transfer capability.

To date, little emphasis has been placed on lower noise temperature for deep-space applications because of the substantial increases in ground effective-radiated-power in recent years and the questionable reliability of the various low-noise amplifiers.

c. Forecasts. FC 3-29 shows the technology trend of various amplifying devices (assuming zero passive losses) at S-band for the next 25 years (Ref. 3-40), along with the history of the Mariner spacecraft receiver-system noise temperature (Ref. 3-41).

Low-noise amplifiers are of several types. Among these are bi-polar transistors, field effect transistor amplifiers, tunnel diode amplifiers, cooled and uncooled parametric amplifiers (paramps), and masers.

Of those low-noise amplifiers listed above, only the solid-state bi-polar or field effect transistor amplifiers and the uncooled parametric amplifiers provide the necessary characteristics for deep-space missions for the better part of the next 25 years. In order to project the use of either maser or cryogenically cooled paramps, it is necessary to assume major advances in the closed-cycle cooling system with respect to size, weight, cost, reliability, and power consumption (Refs. 3-42, 3-43 and 3-44). See also the discussion on page 5-58 of this report.

The noise temperature of the uncooled paramp is inversely proportional to the pump frequency. Therefore, it is essential to generate a higher frequency pump oscillator to achieve lower noise. An even higher pump frequency is required for a higher frequency paramp than for a lower frequency one when a similar noise performance is desired. The current state-of-the-art is capable of generating 60-GHz pump sources and varactors with cutoff frequencies as high as 600 GHz. It is projected that the current level of effort will push the pump source to 300 GHz and the varactor cutoff frequency to 1000 - 2000 GHz. The trend will result in a 20°K noise temperature for the uncooled paramp at S-band by the year 2000.

Forecast FC 3-30 shows the noise-temperature-frequency characteristics of the low-noise amplifiers as of the present time and the expected characteristics for the year 2000 (Ref. 3-40).

Several factors will influence the expanded use of low-noise amplifiers in future deep-space missions: (1) power increases in ground station effective radiated power due to economic factors; (2) maturing technology; (3) missions to the edge of the solar system and beyond; and (4) large required uplink data rates of future deep-space and near-Earth missions.

Other characteristics of space receivers are discussed by category below.

(1) Frequency. The design of the preamplifier and the local oscillator frequency will have to be changed to adapt the basic receiver to higher uplink carrier frequency.

(2) Implementation. Significant future advances are expected to result from the extensive use of integrated circuits and of digital techniques in the basic phase-lock loop and at the highest practical intermediate frequency. Both of these advances will reduce weight, volume, and cost while increasing reliability and performance (Refs. 3-45, 3-46, and 3-47).

(3) Size and Weight. The size and weight of the uncooled paramp are currently 800 cm^3 and 6.5 kg, respectively, and they are projected to reduce to 100 cm^3 and 0.4 kg by the year 2000. The size and weight of the transistor amplifier are 15 cm^3 and 60 g now and their size is expected to be reduced to 4 cm^3 and 15 g in the

same period. The weight and volume of current space receivers (to be flown on Mariner Jupiter-Saturn) are 1.8 kg and 1550 cm^3, respectively. They will decrease to 0.4 kg and 250 cm^3, respectively, in the next 25 years as the degree of monolithic and hybrid integration complexity increases, even in the face of increased functional complexity. The exciter weight and volume increments are 0.8 times and 0.9 times, respectively.

(4) Cost. The recurring costs of the uncooled paramp and the transistor amplifier are now $25,000 and $7,000, respectively, and they are expected to be reduced to $10,000 and $3,000 in the next 25 years. The cost of space receivers is projected to come down to $45,000 from its present value of $150,000 (1975 dollars per unit, nonrecurring vendor selling price) without including the low-noise amplifier. The cost will be further reduced by a factor of two for procurements in quantity (16 units versus 4 units).

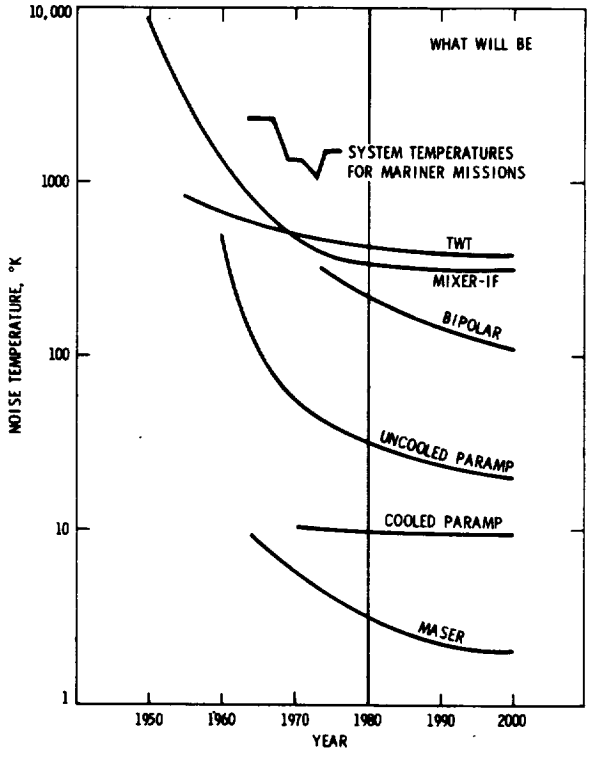
Since most space receivers are a part of a transponder (receiver and exciter operating in a coherent turnaround mode), a cost increment for the exciter has been estimated at 0.7 times the receiver cost.

(5) Power. Advanced circuit-design techniques and the availability of efficient devices will reduce the power drain of current space receivers, which is on the order of 3 watts, to the 1-2 W range in the next 25 years. The power required for future receivers is primarily dependent upon the amount of future complexity and the achievable speed-power product of future digital devices.

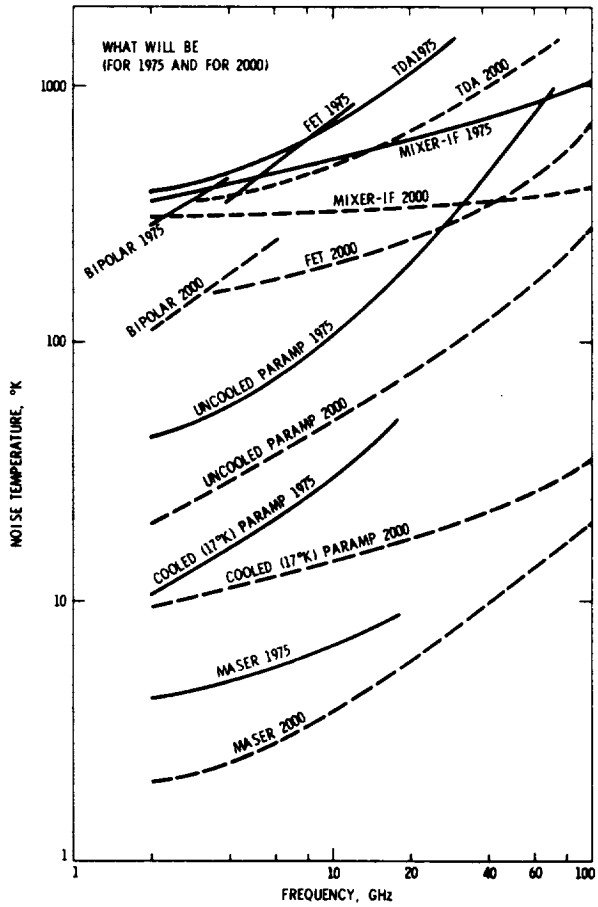
(6) Reliability. The reliability of the uncooled paramp is estimated to improve from 35 to 5 failures per million hours of operation in the next 25 years, whereas that of transistor amplifiers will fall from 6.5 to 2 failures per million hours. The reliability of the remaining parts of the receiver is believed to be much higher than that of the low-noise amplifiers.

TRANSFERRING INFORMATION FORECASTS (contd)

FC 3-29. Device Noise Temperature at S-Band



FC 3-30. Device Noise Temperature versus Frequency



3. Microwave Antenna and System Noise Temperature

a. Scope. Large antenna aperture and system noise temperature are emphasized in this forecast for Earth and space station and spacecraft applications. In addition, antenna requirements are included for two applications of communications technology which are and will continue to be significant drivers of antenna development: (1) radio instrument sensing and (2) satellite communication.

b. Background. Significant resources will be allocated over the next 25 years for antenna development where designs are being driven by diverse technology applications ranging from satellite communications and radio instrument sensing to interstellar communication, particularly radio mapping and the search for signals from extraterrestrial civilizations. The antenna characteristics forecasted for radio sensing instruments listed in Table 3-2 provide an example of the type of varied requirements existing, that will result in special classes of antennas. The requirements for communication satellite antennas are similar to radio sensing requirements emphasizing antenna beam shaping, accurate pointing and strict sidelobe control. Antenna patterns will be shaped to match national geographic areas within irregular border limits. Integrated small element arraying and lens technology will be used extensively, providing flexible electronic steering and multibeam operation.

A significant challenge faces antenna developers in generating lower-cost designs for achieving extremely large antenna apertures (on the order of 3 km in effective diameter) for use in deep space, especially interstellar communication. One promising solution would place in Earth orbit, large single structures (as forecasted in FC 3-33) to achieve the required aperture. Another solution, which may become cost competitive using large scale integration (LSI) technology, would array millions of integrated antenna elements (dipoles) to achieve the required aperture and also provide a multibeam capability.

c. Forecasts. Forecasts for several representative classes of microwave antennas are presented in FC 3-31 to FC 3-35. System noise temperature for large antenna facilities is forecasted in FC 3-36 and FC 3-37.

Table 3-2. Radio instrument antenna requirements

Radio Instrument	Antenna Size, m	Nominal Frequency, GHz	Antenna Position
Scatterometer		13.9	Fixed
Ocean Wind Sensor	23	13.9	
RMS Ocean Waveheight Sensor	8.5	30	
Rainfall, Rainrate Sensor			
Earth Orbit*	9	3	Scanned
	2.7	10	
	0.9	30	
Geostationary Orbit	400	3	
(10-km resolution)	120	10	
Soil Moisture and Crop Identification			
(1-km resolution)*	90	3	Scanned
	27	10	
	9	30	
(10-km resolution)*	9	30	
	2.7	10	
	0.9	30	
Imaging and Sounding Radar			
50-m planet resolution	1 x 25	1.6, 10, 13.9	Fixed
5-m Earth resolution	1 x 2.5	1.6, 10, 13.9	
Radar Altimeter*	1 - 2	13.9	
Microwave Limb Sounding			
Molecule observed - O_2	1.2 - 4	60	Scanned
- O_2, CO	0.6 - 2	117	
- H_2O, O_3, N_2O	0.4 - 1.3	184	
- O_3, CO, N_2O	0.3 - 1.0	230	
Earth Observations* Microwave Radiometry (1 km resolution)			
Soil moisture*	400	0.61	Scanned
Subsurface	173	1.413	
Ocean Salinity	91	2.695	
Sea-Surface Temperature	37	6.6	Scanned
Sea State / Heavy Precipitation	23	10.69	Scanned
Water Vapor	12	20 - 22	Scanned
Light Precipitation	6.6	37	
Storm over Land	4.7	53	
Water-Ice Boundaries	2.6	94	
Storms over Land	2.0	118	Scanned

*800-km orbit is assumed.

DISCUSSION

Large reflector antennas will be used for microwave remote sensing with feed requirements that are more diverse than those for communication. For Earth observations, multifrequency concentric beams are desired so that resulting radiometric images can be co-registered and inversions made to determine surface parameters. At present, there are limited solutions to this problem. For microwave limb sounding, the surface accuracy of the reflectors and stability of the feeds are more critical because of the higher frequencies.

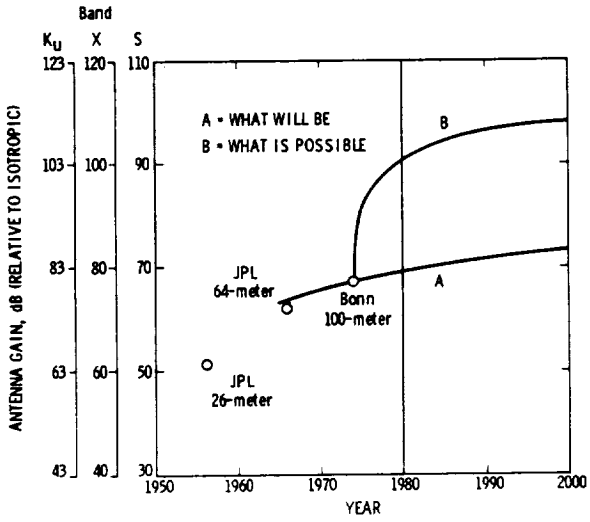
Interleaved multifrequency phased arrays with dual-frequency, dual-polarization, and beam-switching capabilities will be developed for future synthetic array imaging radar systems. Since the resolution of the image is related to the antenna size, independent of wavelength, future systems which desire multiband, multifrequency, multipolarization capability will be practical only if those functions can be performed economically in the same physical area. At present, research on this problem is limited and designs are not available.

Table 3-2 DISCUSSION (Continued)

Many of the antennas in Table 1 must scan with various track limits depending upon the application. For most of the Earth-observation radiometric systems, the main lobe must be tilted off nadir approximately 45°. Many sensors will be placed aboard the same satellite for simultaneous measurements and no one antenna can satisfy all sensor requirements. Most microwave sensing satellites will therefore require several antennas, each serving possibly several functions. Radio frequency, interference, and scanning blockage problems must be dealt with between radiometers and active radar sensors. Serious study of the multiple-antenna integration and interference problems will need to be conducted to assess the impact upon packaging, erection, scanning and blockage, and unobstructed operation for each antenna over the coverage sector required.

TRANSFERRING INFORMATION FORECASTS (contd)

FC 3-31. Gain of Large Earth-Based Antennas for Earth-to-Space Communications at S, X, and K_u Bands



DISCUSSION

It is assumed that the large apertures forecast here will be achieved by arraying 100-meter dishes, each with an equivalent rms surface tolerance of 0.08 cm. Degradation in overall gain resulting from the arraying will be small.

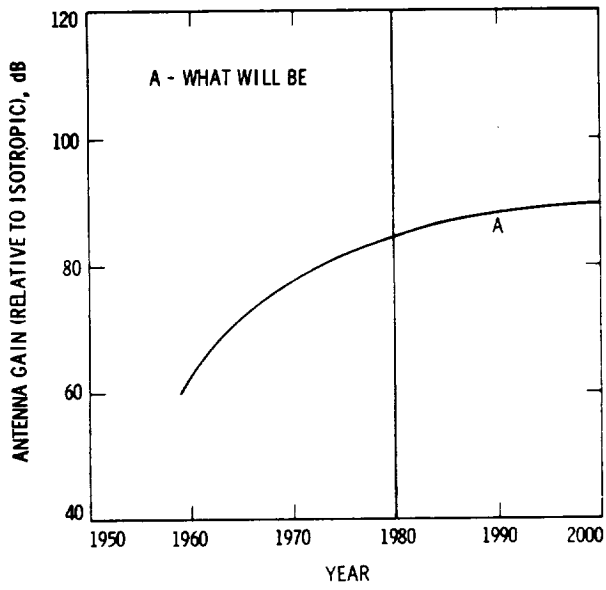
The "what will be" curve reflects a slow growth at a rate of one new antenna every eight years, the approximate time required between implementation of the first 26- and the first 64-meter antennas of the Deep-Space Network.

The "what is possible" curve assumes a commitment to an antenna array with the capabilities called for in the Project Cyclops study (Ref. 3-2). Antennas would be added at the rate of 60 per year until, at approximately 1200 100-meter antennas, the effective diameter would be on the order of 3 km.

The 100-meter radio-astronomy antenna in Bonn, Germany, would cost approximately 16.5 million 1975 dollars. The estimated cost of the 100-meter antenna considered here would be 57 million 1975 dollars because of its more rigid tracking and environmental specifications.

The assumed aperture efficiency of 63% for each antenna is compatible with what is achievable today for a large antenna at a zenith angle of 45°.

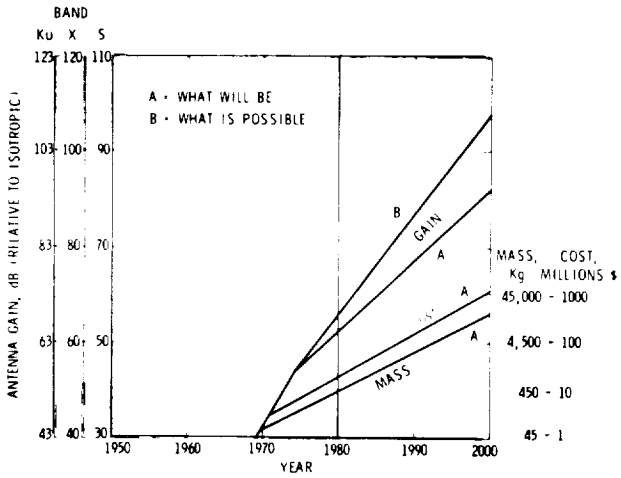
FC 3-32. Gain of Large Earth-Based Antennas for Earth-to-Space Communications at 95 GHz



DISCUSSION

The "what will be" curve is an extrapolation of the gain growth curve from 1958 to 1974. A "what is possible" curve would be strictly a function of dollars based on the technical and cost estimates below. It is then assumed that the projected gain increase will be achieved by arraying antennas with diameters of 12 meters, the maximum permitted by today's state-of-the-art for the surface tolerance of 0.01 cm required for 95 GHz operation. The "what will be" curve requires that one new antenna be added every 3.5 years. The estimated cost of each antenna is 500,000 1975 dollars.

FC 3-33. Gain, Mass, and Cost of Geostationary Earth-Orbital Antennas for Space-to-Space Communication at S, X, and K_u Bands



DISCUSSION

For the above projections (Ref. 3-12) it is assumed that the antenna would be carried into low Earth-orbit by the Space Shuttle and then into synchronous orbit by a Space tug. Preliminary calculations indicate that, for each Shuttle payload, two additional payloads will be necessary to provide transportation by an expendable tug.

It has been assumed that the maximum size of the antenna is limited to what can be carried in one Space-Shuttle load: the maximum mass will be 30,000 kg, the maximum size will be that defined by a cylinder 18.3 meters long and 4.6 meters in diameter. The cost curves above include antenna development and fabrication costs only and do not include transportation or erection costs.

The projected antenna performance is based on the assumption that an in-space surface evaluation and adjustment system for the reflector surface will be developed.

The system will accomplish quick and continuous evaluation of the reflector surface, then determine and mechanically implement the necessary adjustments.

Such antennas could provide an aperture efficiency of 55% and a surface tolerance of 0.08 cm rms. The "A" curve assumes a 0.7 km diameter by the year 2000. The "B" curve assumes a 3.0 km diameter. FC 5-31 of this report forecasts a maximum achievable diameter of 1 km by CY 2000 and a "will be" of 0.1 km. This would give gains 5 to 8 dB lower than shown above. The disagreement is unresolved but is within the uncertainty range for the forecast.

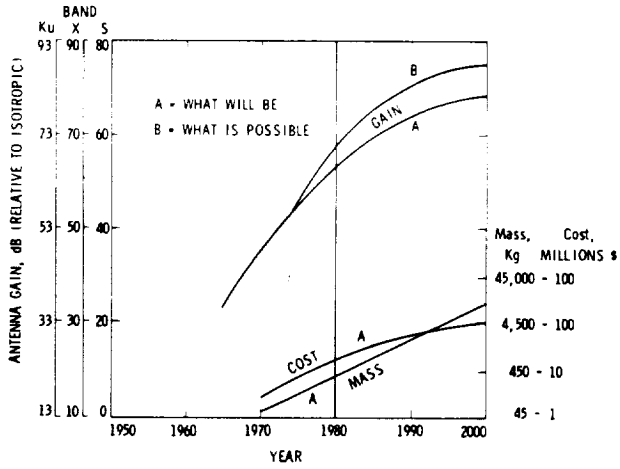
Attitude control capability for structures in the order of 1 to 3 km in diameter is forecasted as "what is possible" by the year 2000 (see FC 5-41). Certain elements of the space attitude control system will need intensive development above what is planned for this capability to be available by the year 2000.

Although the basic design of the geostationary antenna assumed a lightweight semi-rigid gravity gradient stabilized fixed antenna (Ref. 3-48), it was assumed that slow, three-axis slewing at a fixed rate could be accomplished with the same design. Fine steering would be accomplished by an electronic array feed. This would allow the antenna to be used to track distant spacecraft at approximately 0.25 degrees per minute.

The achievable antenna gain at 95 GHz is assumed to be the same as at K_u band. This is based on the assumption that the lower frequency antenna can be scaled with a constant ratio of rms surface tolerance to diameter. Historically this has been true; however, there is controversy over the validity of the assumption in this particular case. Pessimistic estimates are about 20 dB lower than those forecasted.

Although the 95 GHz antennas will be smaller (95 GHz/15 GHz) the cost will be about the same for K_u band because of the difficulty of achieving the very small surface tolerances. The mass, however, will be reduced by about the 2.4 power of the inverse of the frequency ratio, or about 0.007 of the value shown on the curve.

FC 3-34. Gain, Mass, and Cost of Large Spacecraft Antennas at S, X, and K_u Bands



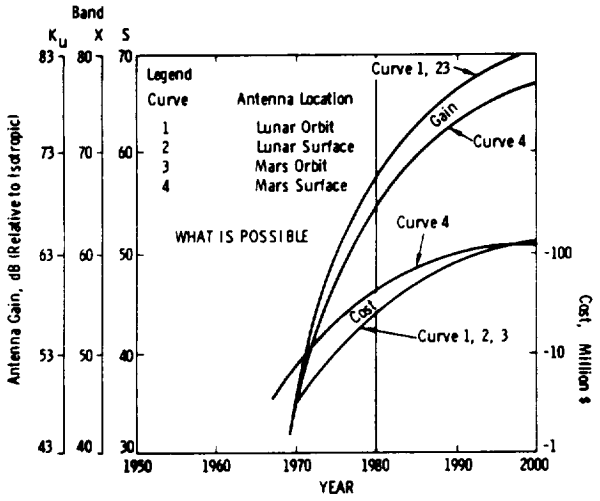
DISCUSSION

Large spacecraft antennas enable data to be transmitted at high rates over large distances. Because the beamwidths of such antennas are narrow, accurate beam steering is needed. Gross steering will be accomplished mechanically, but fine beam-steering will be done electronically with a multiple-feed phased array. The antennas will have to be sufficiently stiff structurally that they will not undergo excessive distortion while being steered. It is assumed that the spacecraft will be sufficiently far from massive objects that gravitationally-induced distortions will be negligible during antenna use. It is further assumed that three-axis stabilization will be employed. Recent work done for the Large Space Telescope indicates that stabilization accuracies of 0.001 arc second are now possible.

By the year 2000, the maximum antenna diameter for frequencies up to 15 GHz will be 180 m. The antenna gain prediction is based on an aperture efficiency of 55%. It is assumed that no surface-shape adjustments will be made after unfurling and that the rms surface tolerance will be 0.08 cm.

The achievable antenna gain at 95 GHz is assumed to be the same as at K_u band, with the same assumptions discussed in FC 3-33.

FC 3-35. Gain and Cost of Spacecraft Antennas for Selected Lunar and Mars Missions



DISCUSSION

Spacecraft orbiting the Moon and Mars are subjected to gravitational and thermal environments similar to those of deep-space probes, except that the orbiters can experience thermal variations from solar occultation. On the Lunar and Martian surfaces the antenna systems will be in gravitational fields respectively one-sixth and 0.38 that of Earth, and will undergo large changes in temperature. On Mars, the landed systems will in addition be exposed to winds over 300 km/hr in an atmosphere approximately one-hundredth that of Earth. All systems must be capable of holding their parabolic shapes under the above environmental conditions and while being mechanically slewed to maintain pointing direction.

It was assumed that each antenna system will be placed in low Earth-orbit by a Space Shuttle transportation capability for final assembly. A Space tug is required to carry the antenna to its final destination. Each antenna system was limited to one Shuttle level low-orbit payload; two additional payloads are assumed for transport of expendable tug components to low Earth-orbit.

The cost curves above include antenna development costs only and do not include transportation costs.

The weight of the antenna system includes those of the reflector, the feeds and feed supports, the gimbal mechanisms, and the contour evaluation and adjustment systems necessary to maintain antenna shape.

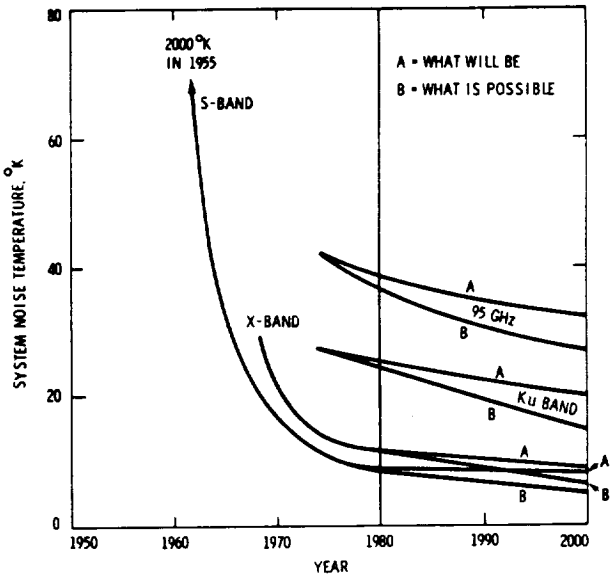
The maximum Shuttle payload space available was assumed to be 18.3 meters in length and 4.6 meters in diameter. The maximum antenna diameter compatible with these constraints is 180 meters.

Additional assumptions are: three axis stabilization will be used for orbiting spacecraft; fine-beam steering will be electronic; the maximum operating frequency will be 15 GHz; and the aperture efficiency will be 55%.

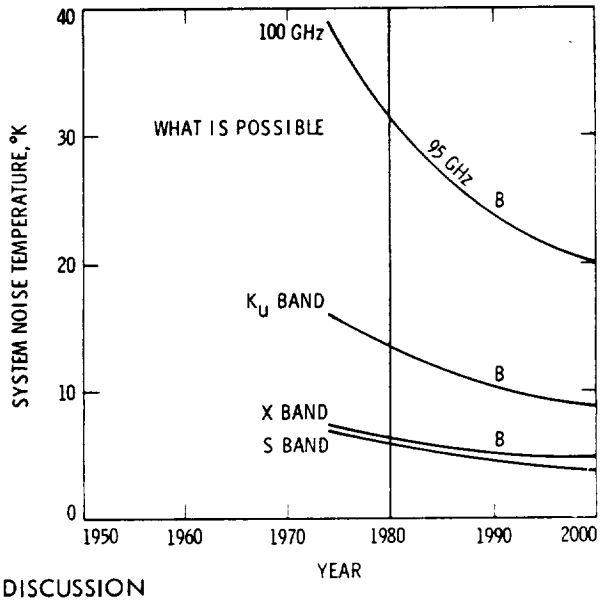
The achievable antenna gain at 95 GHz is assumed to be the same as at K_u band, with the same assumptions discussed in FC 3-33.

The achievable antenna gains at 95 GHz are assumed to be the same as at K_u band with the same assumptions discussed in FC 3-33.

FC 3-36. Zenith System Noise Temperature of Earth-Based Earth-to-Space Communication Stations



FC 3-37. System Noise Temperature of Geostationary Earth-Orbital Space-to-Space Communication Stations



DISCUSSION

The reduction in system noise temperature will come about from improved masers.

Noise temperatures of Earth-based systems are greater than those of orbital systems because of atmospheric effects. These are more pronounced at higher frequencies.

It is assumed that the Earth orbiting antenna is not looking at the Earth, or any other "hot" body.

4. Signal Design and Processing

a. Introduction. This forecast is concerned with signal design and signal processing. Signal design includes three intimately related areas: coding/decoding, modulation/demodulation, and bandwidth compression. Signal processing, as it relates to information transfer, includes any transformation of natural or artificial signals into information sets which are useful and meaningful to the user.

The success of signal design depends upon the capability of signal processing. Sophisticated and efficient decoding algorithms and demodulation schemes may be of only academic interest if they require unattainable signal-processing speed and capacity. Conversely, improved signal-processing techniques stimulate the development of better signal designs.

The benefits of signal design and processing do not always lie directly in power gain or bit-rate increase, the typical rewards of advances in transmitters, antennas, etc., but rather in more efficient ways of using electronic signals. For example, in channels with multipath characteristics, brute-force increase of power does not improve channel efficiency because the limiting performance factor is the ratio of multipath interference to direct signal power, which remains virtually unchanged with power level.

b. Forecasts.

(1) Coding/Decoding. Over the past twenty-five years, coding research has been fruitful, producing results that have become indispensable in communication. Coupled with advances in such fields as high-speed computers and miniaturization of electronics, new coding techniques can be expected to make greater contributions to the increased efficiency and reliability of advanced communication systems.

On the basis of the rate of progress over the past twenty-five years and certain reasonable assumptions, a forecast can be made of what the achievable performance will be by the year 2000 (FC 3-38). A more optimistic prediction might show these gains occurring 10 to 15 years sooner. This projection is based upon several subsidiary expectations:

- Recent new theoretical results (e.g., Justesen codes and Goppa codes) will bear practical fruit (Ref. 3-49).
- A sophisticated technique for converting "hard-decision" decoding algorithms into "soft-decision" algorithms for block and convolutional codes will soon exist.
- Ground hardware advances will allow increased symbol/bit rates, say in the range of 5 to 10.
- The speed of logic circuitry will increase.
- Support in coding research will continue.

Some or all five of these expectations will need to be fulfilled for substantial coding gains to be achieved.

FC 3-39 projects the coding gain over that of the phase shift keyed (PSK) system as a function of time out to the year 2000. As shown, approximately 4-5 dB can be achieved with better codes and less expensive decoders.

(2) Modulation/Demodulation and Bandwidth Compression. The technological outlook for modulation/demodulation during the 1980 to 2000 time period probably does not involve the discovery of new techniques, but rather the application of existing efficient modulation/demodulation schemes to future communication channels. Of major interest will be methods of implementation and performance analyses to produce effective trade-offs among transmission bandwidth, data rate, signal-to-noise ratio, and error probability. Unlike coding theory, in which new codes are continuously sought (to get closer to the Shannon limit), digital modulation techniques are characterized by transmission of amplitude, phase, or frequency as information or combinations of these. To date most of the more efficient combinations of amplitude, phase, and frequency have been studied as modulation techniques and their performance has been analyzed over the present channels of interest. Most recently, work on multiple-amplitude PSK has led to transmission at increased data rates without expansion of bandwidth relative to systems which transmit either phase or amplitude alone as digital information. Since an increased data rate requires increased signal-to-noise ratio at a constant error probability performance, these systems use power to conserve bandwidth. Forecast FC 3-40 projects bandwidth-compression modulation gain. To date, most of the bandwidth conservation systems on which this forecast is based have not been built, but a need is foreseen to conserve bandwidth in the near future for near-Earth communications.

Revived interest in the fading channel (e.g., as caused by the solar corona) raises the problem of providing a modulation/demodulation technique which can be detected either coherently or noncoherently, the former when phase information is available and the latter when it is destroyed by channel disturbances. In this light, continuous-phase frequency-shift keying (CPFSK) appears to be a viable candidate since its coherent performance is near that of PSK and its noncoherent performance is no worse than that of noncoherent frequency-shift keying. If, in addition, bandwidth conservation becomes important on such channels, one might consider a new modulation technique, namely, continuous phase amplitude frequency-shift keying (CPAFSK), whose performance in coherent transmission should be compared with that of the corresponding multiple amplitude phase-shift keyed signal set.

(3) Signal Processing. In addition to standard telemetry signal detection and decoding, some common applications of signal processing are the transformation of radar data into topographic maps, the identification of mineral-bearing geological formations by SONAR-like techniques, spectral analysis of stellar radiation for scientific purposes, and interferometric observation of signals from radio stars for earthquake analysis and prediction. The underlying tools involved are correlation, filtering, and spectral transformation.

The algorithms that are followed to carry out these transformations place high demands on data storage and arithmetic capabilities. In present-day signal processing, these transformations are largely implemented via digital computers. Indeed, digital signal processing is an important driving factor, along with such others as image processing and data compression, for digital computer advances.

Thus, a forecast for signal processing must be based on projections for digital logic.* Forecasts for ground-based and space-borne computers are presented in Section IV-C-1 (Hardware Characteristics).

Prediction of digital logic and computer capabilities over any significant period of time is itself extremely risky. During the recent past, major increases in processing capability has occurred by repeated changes of the technology base from which it is fabricated, i.e., from vacuum tubes to transistors to integrated circuitry logic of varying form and density. At any instant of time, projections based upon improvements of the then current technology would have indicated a slowing rate of improvement or a ceiling on capability that was effectively circumvented by the changed technology base. In this light, improvement in processing power, per dollar expended, is perhaps conservatively estimated to be continued at an order of magnitude increase per decade. This improvement appears in a number of dimensions, most notably in the higher speed of logic devices, the increased complexity and packing density of logic devices and much higher per-unit reliability of devices. These factors today combine to make feasible many applications which were inconceivable a decade ago, such as digital radar imaging processing and data processing required for detection of microwave signals from extra-terrestrial civilizations.

It appears reasonable to assume that the overall trend of improvements will continue unabated at the above rate for the remainder of this century, although we lack knowledge of the technologies which will surface to permit such growth. Thus, by the year 2000 three orders of magnitude improvement in available processing capability is expected. If we consider, as state-of-the-art today, a Fast-Fourier-Transform Unit which can develop in real-time a 1024 point Discrete Fourier Transform of a 100 KHz signal, a comparable unit by the year 2000 should be able to provide a 10^5 point transform of a 10^6 Hz signal, or perhaps a 10^4 point transform of a 10^7 Hz signal, at no increase in cost over today's unit. By the year 2000, the amateur geologist should be able to easily acquire a pocket instrument with the same capabilities as today's state-of-the-art Fourier Transform Unit; just as he can today obtain a hand-held calculator with a power which noticeably exceeds that of many early computers. It is futile to speculate on all the applications which will surface as a result of the year 2000 capability. Those we can see today are extensions of today's experience. Those which will dominate the year 2000 are impractical or inconceivable today, such as:

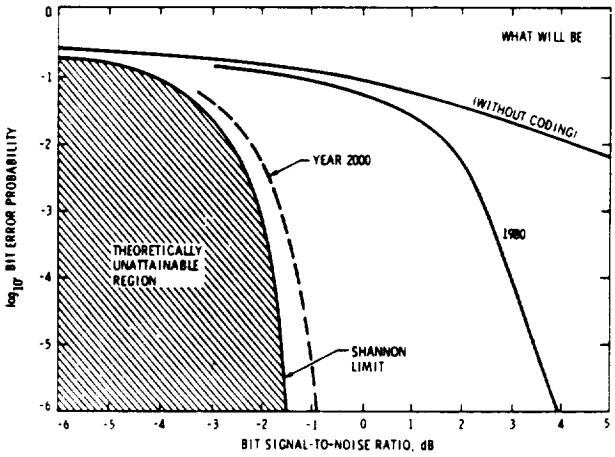
(1) Personnel communications via random access satellite links.

(2) Achievement of large antenna aperture with arrays of billions of small dipole elements.

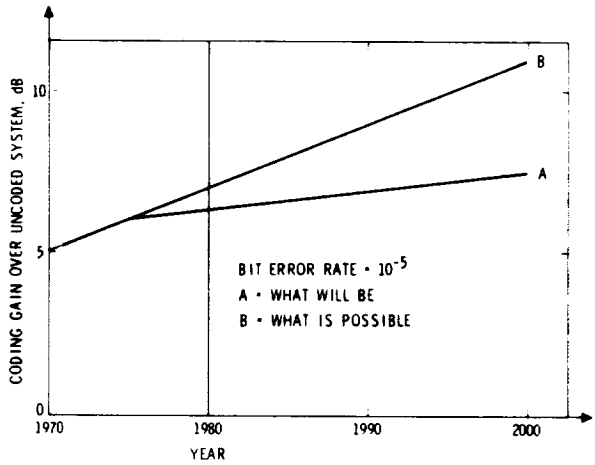
(3) Processing 10^9 Hz bandwidth to 1 Hz bandwidth resolution in near real-time.

*Should we err in predicting signal processing in this fashion, it will be to underestimate the capabilities that will develop because of other processing technology advances such as what is being cited for optical processing in Ref. 3-50.

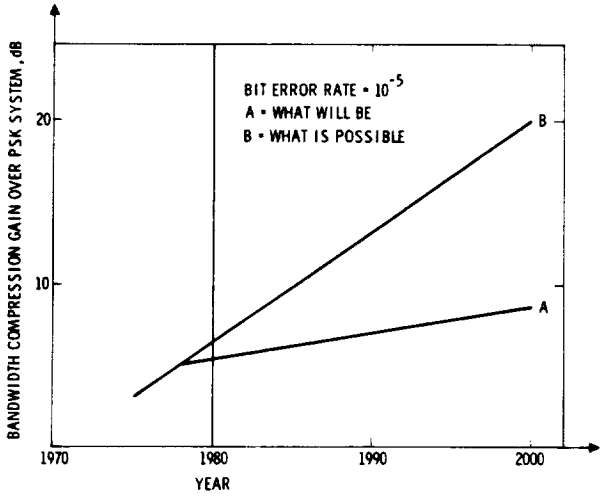
FC 3-38. Coding in the Year 2000



FC 3-39. Coding Gain



FC 3-40. Bandwidth Compression Gain



5. Optical Communication

a. Background. Optical communication systems (Ref. 3-51) based upon laser devices as transmitters are presently being developed for satellite-to-satellite and satellite-to-Earth data links. The optical systems very closely resemble microwave communication systems, but have an additional device whose function is to steer the beams of the transmitting and receiving antennas. Normal spacecraft stabilization techniques can be used if the transmitting/receiving telescopes are aimed in approximately the right direction. The beam steering systems will then lock onto the incoming signals and track out the spacecraft motions. A block diagram of a laser communication system is shown in Figure 3-6. The laser beacon in the receiver is necessary to provide a signal for the transmitter beam-steering system.

The main advantage offered by laser communication systems is a high data-rate capability at modest size and weight. Furthermore, the narrow beamwidths permit an extreme amount of space diversity, virtually eliminating the problem of spectrum crowding. The most serious disadvantage of laser communication systems is the low efficiency of the laser transmitter (2% to 15% depending upon the laser chosen). Efficiency is defined here in the usual way: transmitter power output/raw power into the communication system.

At the present time, there are only a few wavelengths available for use in laser communications. Their number is determined entirely by the types of lasers that have high efficiency: the carbon dioxide laser operating in the 9-11 μm portion of the spectrum, with an efficiency of up to 15%; and the Neodymium:YAG laser operating at a wavelength of 1.064 μm, with an efficiency of 2%. These are the only lasers considered in the forecasts. Clearly, as time advances, other lasers will be discovered with more desireable properties than the ones considered here.

The pacing factor in the development of space laser-communication systems is the availability of funding to space-qualify the systems. Laser communication at a rate of 10^9 bps has been demonstrated in the laboratory. The U.S. Air Force and NASA's Goddard Space Flight Center are jointly planning a satellite to be launched by 1979 for the purpose of demonstrating the capability of this type of system. The future growth of these systems will be influenced by the amount of money put into improving the various system components. Many of the devices are performing near their maximum limit, and improvements will be costly.

Laser communication is still in its technological infancy, with new developments and inventions occurring frequently. It is very likely that the devices and systems discussed here will be superseded before the year 2000. The usual problems that have plagued engineers for all time are reflected in this field: lasers need to be more powerful, more efficient, more tunable, have lighter weight and longer life, etc. These areas will get considerable attention in the future without much prodding. There are several technologies which deserve special attention, and into which significant effort should be invested:

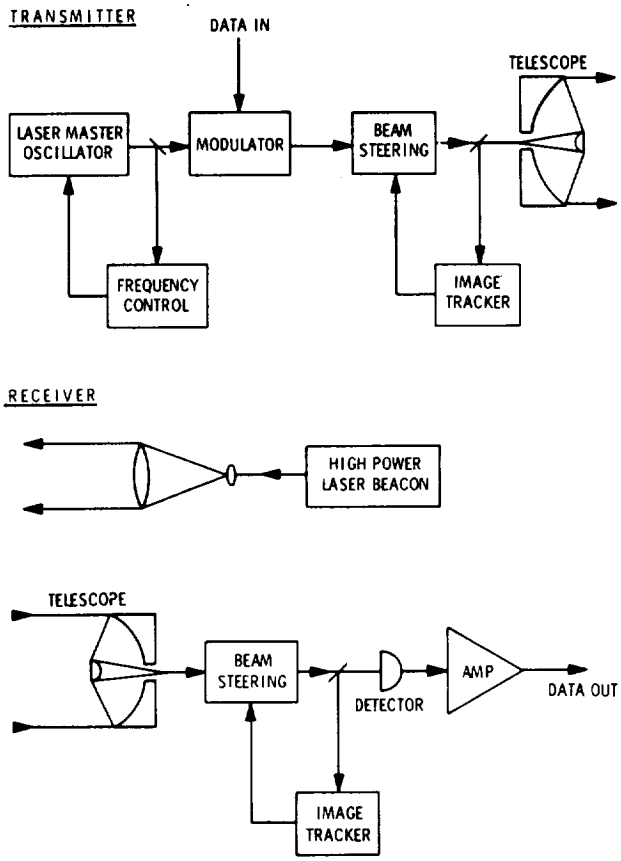


Figure 3-6. Block diagram of an optical space communication system

(1) Lasers. Emphasis should be placed upon chemical and direct electrical pumped lasers as a means of improving device efficiency and lifetime. Tunable devices should be sought. Improvements in frequency stability, control, and measurement must be made.

(2) Modulators. New modulation schemes that do not have severe bandwidth limits should be investigated. The evolving integrated optics technology may provide suitable techniques for attaining higher frequency response from optical modulators.

(3) Detection Systems. Detectors with faster response times must be developed. Present technology limits detector response to 0.1 ns. Integrated optics may provide an answer. Room temperature detectors for use in the infrared spectrum should be sought.

(4) Optical Materials. Many lasers and laser-related systems are limited in their operating lifetime and power levels by the destruction of optical materials at high power levels. Research into the fundamentals of the interaction of high intensity light with materials and surfaces may provide the insight needed for significant improvements.

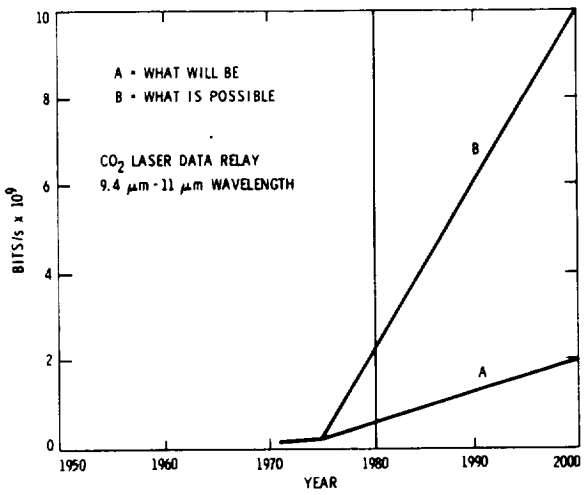
(5) Data Storage and Handling Systems. The data rate capabilities of the optical communication systems discussed in this forecast are high

enough to strain those of present data storage systems. New data storage techniques must be developed to keep pace with the improved communication ability. Optical storage techniques and integrated optical systems may provide solutions. See forecasts of optical memories (FC 5-12 through 5-16).

b. Approach. The emphasis here is placed upon optical communication use in the near-Earth region of space. The laser systems considered are for synchronous-satellite-to-synchronous-satellite and low-orbiting-satellite-to-synchronous-satellite communication. Comparison of the capabilities of laser and microwave systems for deep space applications does not show a distinct advantage of one over the other. Considerations of system cost, complexity, and spectrum availability and mission-dependent factors will have a major influence in determining which type of system would be selected for deep space missions.

c. Forecasts. The following forecasts were made by the groups presently developing laser space communication systems at Goddard Space Flight Center and at Wright-Patterson Air Force Base.

FC 3-41. Synchronous-to-Synchronous Satellite Communication Data Rate (CO_2 Laser)

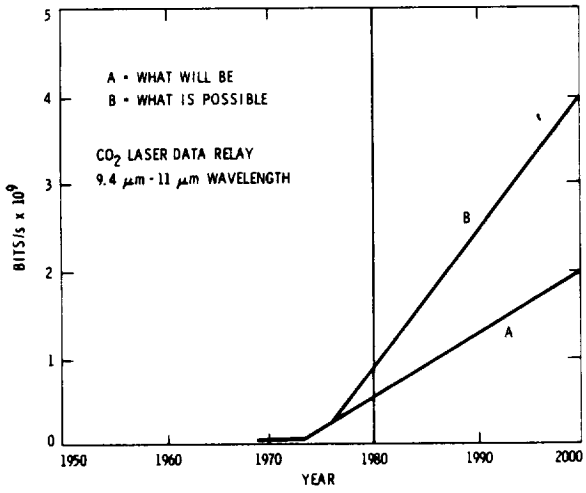


DISCUSSION

The systems utilize 25-cm-diameter transmit/receive antennas at a range of 7.4×10^7. The "what will be" system, curve A, assumes a 2-watt, 10%-efficient CO_2 laser, and a receiver with a 2-GHz bandwidth and a noise of -160 dBm/Hz. The "what is possible" system, curve B, assumes a 10-W, 15%-efficient CO_2 laser; a receiver with a 10-GHz bandwidth and a noise of -163 dBm/Hz; and an M-ary coding on the signal.

System Support Requirements		
	"What Will Be" System	"What is Possible" System
Power	250 W	600 W
Weight	25 kg	75 kg
Size	0.7 m^3	0.7 m^3

FC 3-42. Low Altitude Satellite-to-Synchronous Satellite Communication Data Rate (CO_2 Laser)

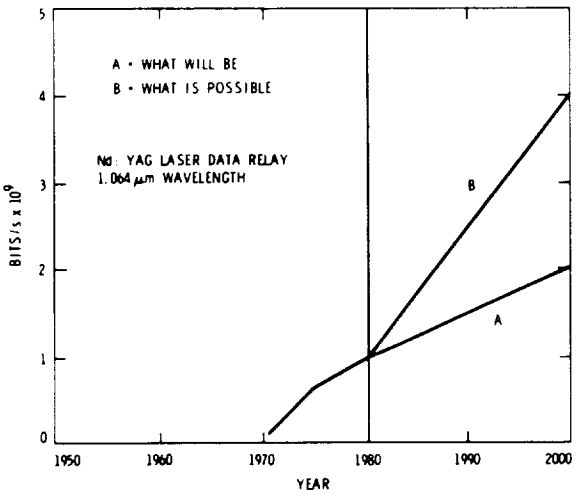


DISCUSSION

The low-altitude Earth-orbiting satellite carries a laser system for communication up to the synchronous satellite. The synchronous satellite carries only a beacon laser to aid the two-way lockup of the optical systems. The antenna diameters are 25 cm, with an average operating range of 4.7×10^7. The "what will be" system, curve A, assumes a 2-W, 10%-efficient CO_2 laser, and a receiver with a 2-GHz bandwidth and a noise of -160 dBm/Hz. The "what is possible" system, curve B, assumes a 10-W, 15%-efficient CO_2 laser; a receiver with a 10-GHz bandwidth and a noise of -163 dBm/Hz; and an M-ary coding on the signal.

System Support Requirements		
	"What Will Be" System	"What is Possible" System
Power	250 W	175 W
Weight	68 kg	60 kg
Size	0.4 m^3	0.7 m^3

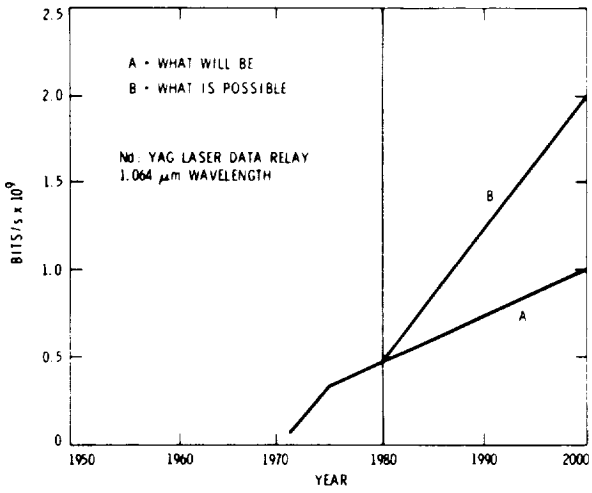
FC 3-43. Synchronous-to-Synchronous Satellite Communication Data Rate (Nd:YAG Laser)



DISCUSSION

The system utilizes a 40-cm-diameter transmit antenna and a 60-cm-diameter receive antenna, combined optically into the same telescope. An operating range of 9×10^7 is assumed. The lasers are mode-locked, and the modulation scheme is the pulsed temporal format type. The receivers use non-coherent detection with a maximum likelihood demodulation. The "what will be" system, curve A, assumes a 0.4-W, 2%-efficient laser; and the "what is possible" system, curve B, assumes a 0.8-W, 10%-efficient laser.

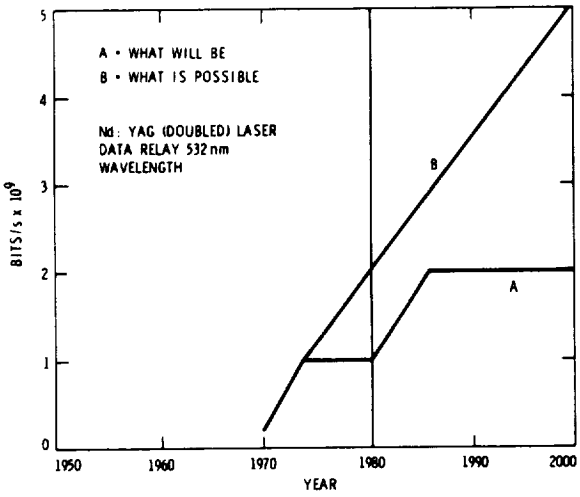
FC 3-44. Low-Altitude Satellite-to-Synchronous Satellite Communication Data Rate (Nd:YAG Laser)



DISCUSSION

The system utilizes a 20-cm-diameter transmit antenna on the low-altitude satellite and a 60-cm-diameter receive antenna on the synchronous satellite. An average operating range of 4.5×10^7 is assumed. The system is used only one-way, from the low-altitude to the synchronous satellite. The synchronous-satellite laser is used as a beacon to aid in the two-way lockup of the optical systems. The lasers are mode-locked, and the modulation scheme is the pulsed temporal format type. The receivers use a non-coherent detection with a maximum likelihood demodulation. The "what will be" system, curve A, assumes a 0.4 W, 2% efficient laser; and the "what is possible" system, curve B, assumes a 0.8 W, 10% efficient laser.

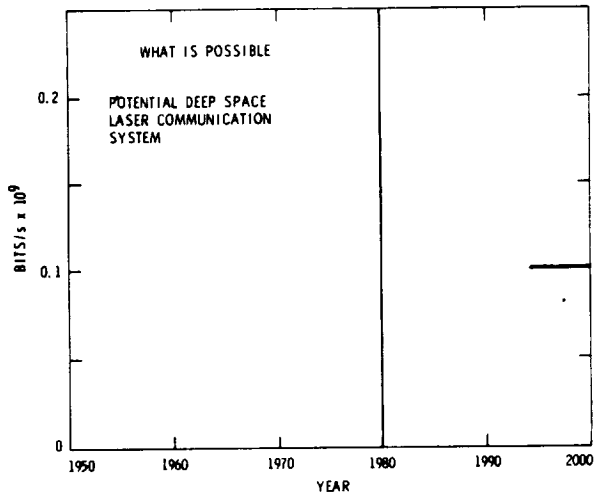
FC 3-45. Synchronous-to-Synchronous Satellite Communication Data Rate (Nd:YAG, Doubled, Laser)



DISCUSSION

The forecasts project expected improvements as seen now with presently increasing rates and funding levels by extrapolation out to the year 2000 (Curve A). Increased funding levels and requirements, and especially increasing capabilities are reflected in Curve B. The trends are a best estimate of what may be expected with a Nd:YAG frequency-doubled laser where no significant improvements in the laser material are assumed. Improvements in these areas will have to be made if the data rate is to be increased significantly beyond that indicated in curve B. We do not consider these to be forthcoming.

FC 3-46. Deep-Space-to-Near-Earth Laser Data Relay Communication Data Rate



DISCUSSION

Lunar Based Transmitter:

Pointing Accuracy:	0.1 μrad
Beam Divergence:	1 μrad
Wavelength:	Visible
Range:	5 AU
Required Laser Power:	50 W

Space-or Lunar-Based Receiver:

Distant-Spacecraft Laser-Transmitter Power: 1 W
Distant-Spacecraft Pointing Accuracy: 1 μrad
Distant-Spacecraft Beam Divergence: 5 μrad
Wavelength: Visible
Range: 5 AU
Photon Bucket Diameter Required: 43 m

6. Near-Earth Communication

a. Background. Telecommunications has made continuous progress since its inception. The advent of the synchronous communication satellite has extended this technical growth into a new, higher region of performance. Indicative of this steady growth (Figure 3-7) is the sequence of major technical innovations since the start of telegraph service about 1840 (Ref. 3-52). The expansion in capability (bits/second) has been remarkably constant, averaging a factor of ten every seventeen years.

b. Forecasts. Since 1965, the growth in satellite transmission capability has also been roughly constant, averaging a factor of ten every three years (see FC 3-47). This growth reflects increasing satellite physical size (more power, transponders, weight) and the use of new technology, such as higher frequency transmitters, more efficient antennas, and improved modulation techniques. The future projections indicated in the forecast largely depend on the resources allocated to technology development. The "what will be" curve assumes an R&D program continuing at current levels through 2000. The "what is possible" curve is premised on a considerably expanded R&D program (perhaps 10-to-20-fold increase). The accelerated pace of growth to 1982 reflects the exploitation of all available but unused technology. The pace thereafter slows because of technical difficulties in making the necessary increases in bandwidth. Extensive use of multiple-beam antennas and data compression is expected.

Besides the above application, which requires large sophisticated ground stations, technology is emerging which will make practical another use. This is the satellite-to-"cheap"-receiver application for which most of the equipment complexity is in the satellite, not on the ground. This type of system could be used for remote-station data collection, personal communication anywhere in the area of coverage, direct broadcast television to the home, and disaster-warning information beacons. The projected capability for this link is shown in FC 3-48. The '60 cm' curve represents the home broadcast use; the '15 cm' curve is for a hand-held receiver for individual use. As we approach the year 2000, this trend will provide, in order, alert/paging (less than 1 kbps), voice (16-64 kbps), and broadband video (10 Mbps and above) transmission.

Satellite-to-satellite links will be used in the future. FC 3-49 shows the projected transfer rates between a low-altitude Earth-orbiter (such as a Shuttle-launched experiment payload or an Earth-resource satellite) and a synchronous

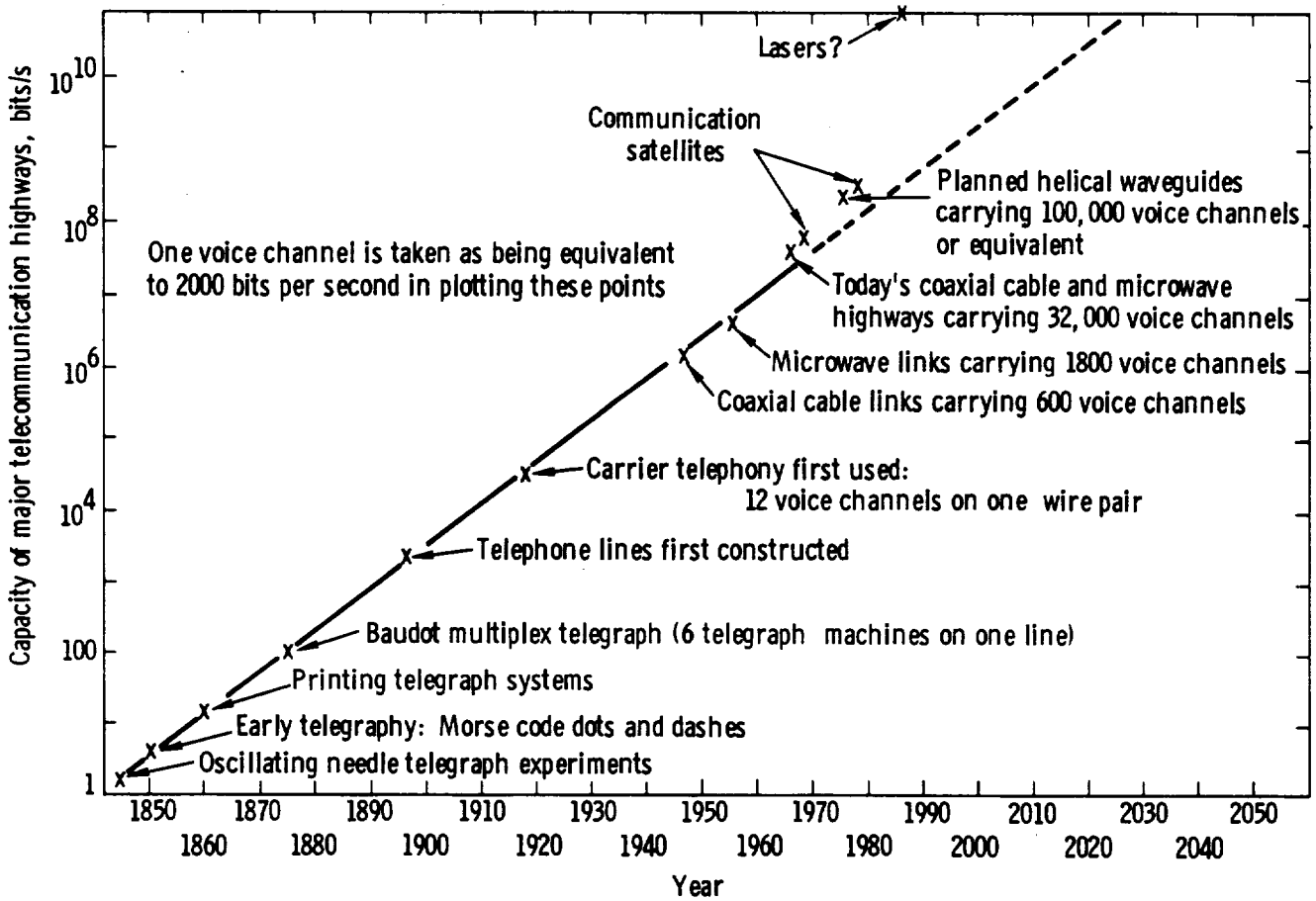


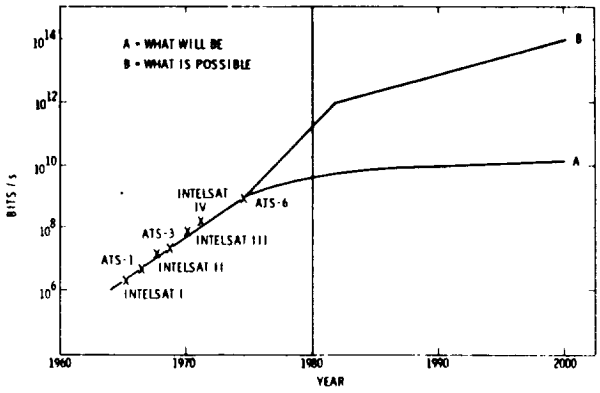
Fig. 3-7. The sequence of inventions in telecommunication (Reprinted from Martin, Ref. 3-52)

satellite (such as tracking and data relay satellite, TDRS). Growth here is primarily determined by the orbiting craft's data requirements. These are not expected to exceed 10^9 bps by 2000, but could go to 10^{10} bps. Synchronous-to-synchronous satellite links may also find use in the future. Since the synchronous-satellite-to-ground technology FC 3-47 covers this link also, at least for microwave technology, it need not be forecasted separately.

The costs of synchronous satellite communication exclusive of ground station costs (FC 3-50) are taken from a Lockheed study (Ref. 3-53). The continued reductions in unit cost result from the efficiency of the new technology described above, decreased cost of other spacecraft subsystems, and lower transportation costs because of the Shuttle. The "what is possible" curve reflects the early application of advanced bandwidth-saving technology and multiple-access techniques.

As regards long-haul terrestrial communications, Forecasts 3-51 and 3-52 show the performance and cost forecasts, respectively. As for satellites, new technology can be expected to provide enlarged capacity at lower unit cost. Optical fiber technology is projected to be in limited use on a commercial basis sometime after 1985. The costs shown do not cover the local distribution and terminal multiplexing circuits.

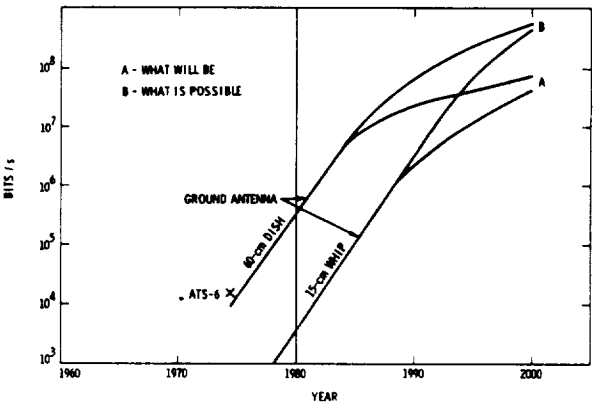
FC 3-47. Transfer-Rate, Synchronous Orbit to Earth (Microwave)



DISCUSSION

The following assumptions have been made: The "what will be" curve has developments in millimeter bands, multiple-beam/shaped beam antennas; frequency allocations will not change. Materially "what is possible" curve requires new frequency allocation; 10^{14} bps at 2000 is realized by 50-channel link (multibeam antenna), each at 40 GHz (20 Gbps), and 100:1 data compression; the curves flatten and approach limits fixed by the carrier frequency.

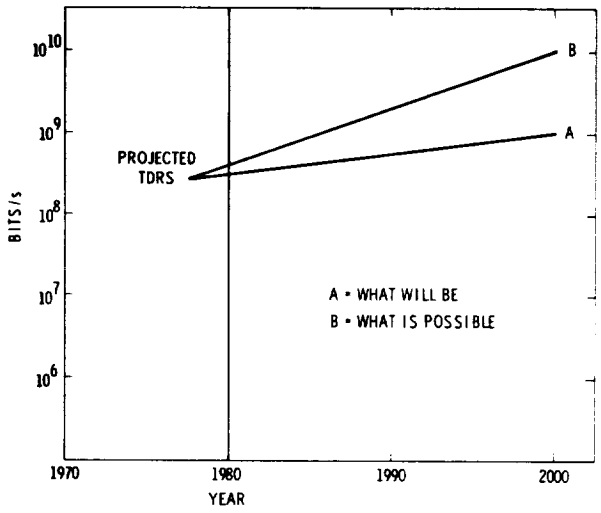
FC 3-48. Transfer-Rate, Synchronous Orbit to Small Earth-Terminal



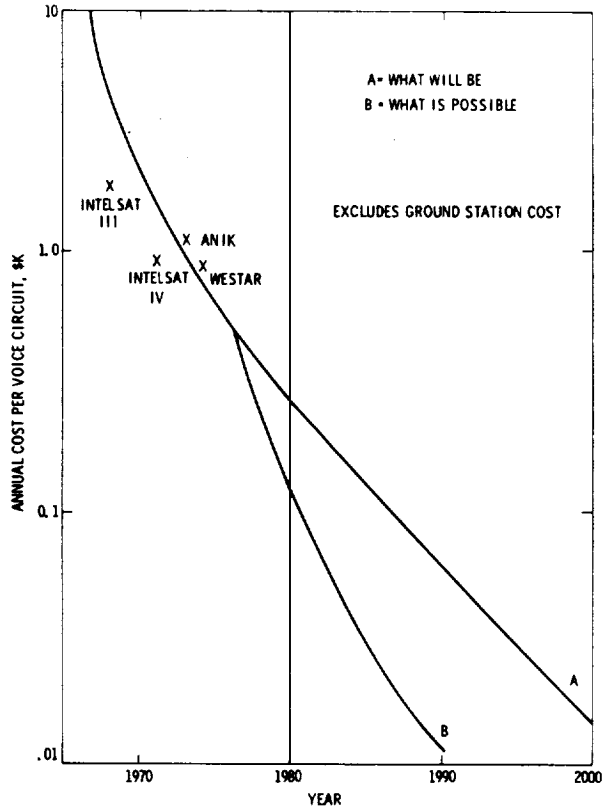
DISCUSSION

The following assumptions are made: The frequency allocation is a strong factor after 1985; the curves flatten and approach limits fixed by the carrier frequency. Initial points calculated at 1 GHz carrier frequency.

FC 3-49. Transfer-Rate, Synchronous to Low Earth-Orbit (Microwave)

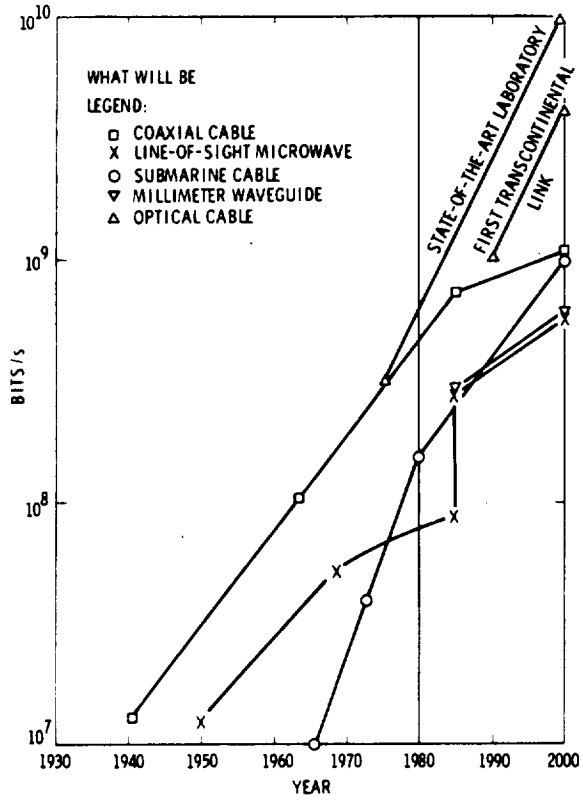


FC 3-50. Commercial Satellite Transmission Costs

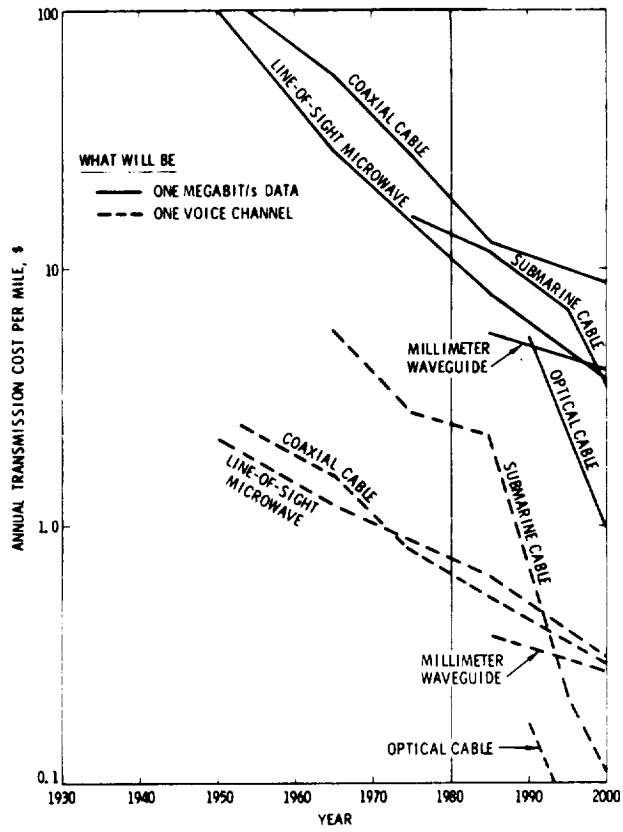


Source: Reference 3-50

FC 3-51. Commercial Terrestrial Communication Capability (per Unit of Equipment)



FC 3-52. Commercial Terrestrial Communication Costs



7. Deep-Space Communication

a. Introduction. This projection of deep-space communication capabilities is based upon current and forecasted device technologies and assumes a largely unconstrained deep-space-mission budget. The forecast is surprise-free in that it does not in any way attempt to show the impact of breakthroughs. It is thus a "what is possible" projection. To forecast "what will be" would require assumptions concerning the resources allocated to deep-space missions and mission cost trends. It would also be necessary to answer questions of this kind: Will 10^8 1975 dollars buy a Pioneer-class mission in 2000 or an orbiting Mars station? The answer depends upon the inflation rate, productivity, technological breakthroughs, the political climate, and many other factors over the intervening 25 years. In 1950 it would have been possible to project computers with 1975 capabilities, but it is not likely that their cost would have been estimated to be 300 1950 dollars. Since NASA draws from industry and military technology as well as that developed in-house, mission costs will be influenced by virtually all technology research and development budgets.

b. Background. Deep-space telecommunications systems are very much driven by the types of missions planned. For example, if during the next 25 years the exploration of Venus were to be limited to a few atmospheric probes and perhaps one radar mapper, then brief and occasional bursts of data at 50 Mbps would be sufficient to meet data-transfer requirements. However (to consider an extreme example) if Venus were to be biologically converted to a psuedo-Earth planet and used for food production, the communication requirement would be many hundreds of megabits continuously, with bandwidth conservation and multichannel systems for monitoring, control, and data return.

The forecast to be presented is a system synthesis of device forecasts using maximum data-rate as the primary driver. It is not constrained by considerations of frequency, bandwidth allocation, or availability of flight power sources. It is assumed that an X-band (8-GHz) Earth-based network will be available until the year 1985, and K_ℓ-band (30-MHz) orbiter-based broadband receiver terminals from 1985 to 2000. The technology base for the spacecraft will lag that technology that will be available at time of encounter - by five years for the inner planets, ten years for Jupiter and Saturn, and fifteen years for Pluto and beyond. In other words, capability at encounters for long-duration missions such as those for the outer planet missions will not reflect technology advances at that period of time but will reflect lesser, possibly outmoded technology, used at the time of launch.

Assumptions have also been made regarding the maximum data rates at given carrier frequencies. It seems reasonable to expect modulators capable of switching the carrier by $\pm 180^\circ$ in phase. The primary question, from a communication point of view, is how many carrier cycles to allow per bit of transmitted data. The current capability of 1.5 subcarrier cycles per bit may prove to be unattainable for the carrier, so a 5-cycle-per-bit value has been assumed, which allows for 1.6×10^9 bps at X-band and 6×10^9 bps at K_ℓ-band.

c. Forecast. From a systems standpoint, the most critical parameters of the telecommunication receiver are its noise temperature (sensitivity) and reliability. Missions to the inner planets will not require as low a noise temperature or as long a life as those to the outer planets and beyond, which will need lifetime of as much as ten years or longer as well as large receiver sensitivity – even for modest uplink command rates. On long-distance missions, spacecraft will need some degree of on-board intelligence to provide rapid response to problems and to make the required decisions. They will be largely self-navigating and will compress collected data, communicating relevant data only at moderate rates, or dumping data at high rates infrequently. Low-rate loading of on-board computers will occur at periodic intervals during the long cruise periods. Large-scale-integration technology will lead to the use of arrayed integrated-circuit parametric amplifiers, radiatively cooled and distributed on an antenna as are current solar cells on panels. This distributed receiver will provide a higher reliability with a graceful degradation failure mechanism rather than the catastrophic failure mode associated with discrete components. The spacecraft receiver will also relay to Earth data received from probes, floaters, and landers.

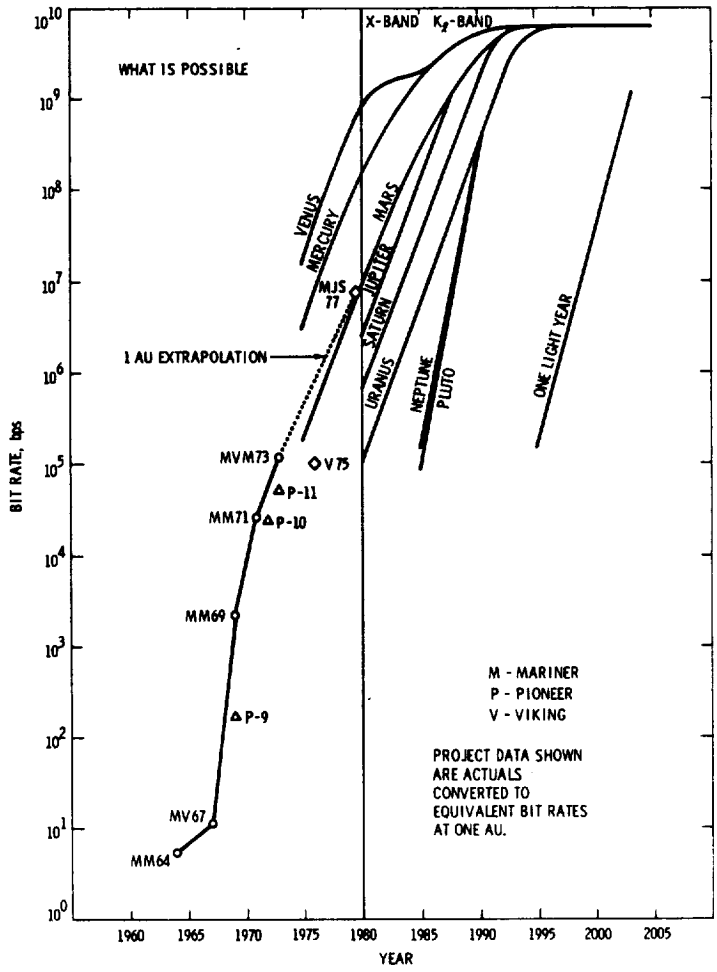
As forecasted in FC 3-26, FC 3-27, and FC 3-28, a wide range of transmitters will be available by the year 2000, ranging from solid-state or travelling wave tube power amplifiers to more exotic solar-pumped microwave or laser transmitters in the 100 - 10,000 watt range. The requirements on spectral purity and stability for the small transmitters will be very tight because of navigation requirements and the use of bandwidth conservation.

Microwave antennas less than 30 meters in diameter will probably be adequate for the inner planets, but for the long-distance missions, large antennas will be required with diameters on the order of 180 meters. Multifrequency multibeam antennas will be used for combined radio sensing, probe data relay, radiometric tracking, and standard telemetry and command communication.

For some missions to inner planets, data will be transferred at gigabit rates to Earth for processing.* This method will provide for very-high-resolution multispectral radar and optical imaging. Earth processors will have real-time processing capabilities up to gigabit rates. As with the devices described for deep-space missions, outer-planet missions will exploit on-board processing up to gigabit rates.

*The Earth terminal for deep-space links will have the characteristics described in subsection 9 below.

FC 3-53. Deep-Space Communication Rates



DISCUSSION

Although the above curves showing bit rate vs time are useful to the telecommunications engineer, their significance can be made more dramatic by presenting the information in another way. To gain insight into the transfer capability forecasted by the above curves, consider that, by the year 1995, it would be possible to send a 3-dimensional telecast, in color, of a football game played anywhere in the solar system to any point on Earth. If one 10^9 bps is assumed for the hypothetical 3-dimensional real-time system, then the true capability would be 6 games simultaneously from Pluto. Commercial television at 10^8 bps as we now know it could be achieved from Venus in 1977 and from Mercury by 1979 while both were at their maximum distances from Earth. The actual rate achieved by the Mariner 10 spacecraft in 1973 was 10^5 bps at Mercury with 1969 technology.

As shown on the curve, historical data were examined and converted to a common base, as all actual data rates were increased or decreased to place these missions at a 1-AU range. These data were then plotted and extrapolated to compare with the forecasts derived from device forecasts. As shown, this 1-AU extrapolation lines up well with the data-rate forecast at Mars distance; close to 1 AU.

8. Interstellar Communication - The Search for Extraterrestrial Life

a. Introduction. The search for extraterrestrial intelligence has, over recent years, gained increasing support as a legitimate scientific undertaking and has begun to attract considerable public interest as well. Accordingly, one aspect of the communication technology forecast was an attempt to determine what possible or probable advances over the next 25 years would lend themselves to the detection of microwave signals emanating from extraterrestrial civilizations.

The most comprehensive and current engineering evaluation of the problems confronting extraterrestrial life detection is contained in the report of the Project Cyclops Design Study (Ref. 3-38), carried out in the summer of 1971 under NASA sponsorship. The objective in the forecast presented here is to ascertain what projected new technology or device capabilities might affect the results of the Cyclops study, as documented, and alter the basic design approach.

The Cyclops design calls for a large, 3-km diameter equivalent-aperture phased array consisting of 100-meter antenna elements, with a system noise temperature of 20°K. Prospects for reduction of the noise temperature are good:

Zenith Noise Temperature, °K	
1971	20
Demonstrated	13
With concerted effort in 1975	11
Will be achieved by year 2000	7.8

Lowering of the noise temperature reduces the array aperture and, hence, the total cost:

System Noise Temperature, °K	Required Array Diameter, km
20	3
11.2	2.3
7.8	1.8

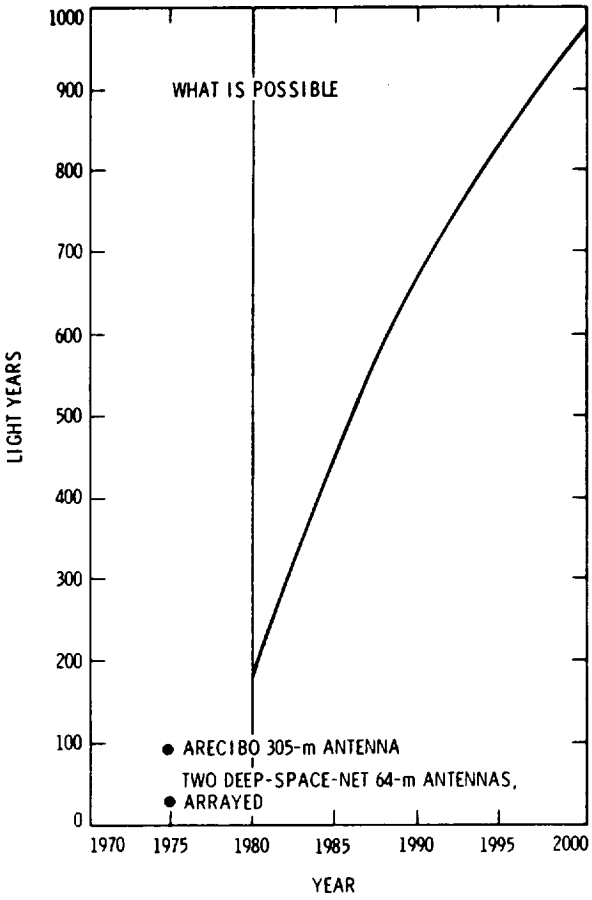
Relative to the cost estimates of the Cyclops study, the net effect of the lower system noise temperature of 7.8°K would be a savings of approximately 4 billion (1975) dollars.

The emergence and application of LSI technology, advancing rapidly at the time of this forecast, could alter the data processing approach assumed and, hence, the cost, since data processing will be a major contributor to the total cost of a search program like that proposed by the Cyclops study.

The projected capability to erect large (up to 3×10^3-meter diameter) antennas in space could also have significant implications for the basic Cyclops design approach. Initial estimates indicate a possible reduction of as much as 40% in antenna costs relative to those of an Earth-based array (see FC 3-33).

b. Forecasts. Interstellar communication forecasts of search range and implementation cost are on the following page.

FC 3-54. Interstellar Search Range



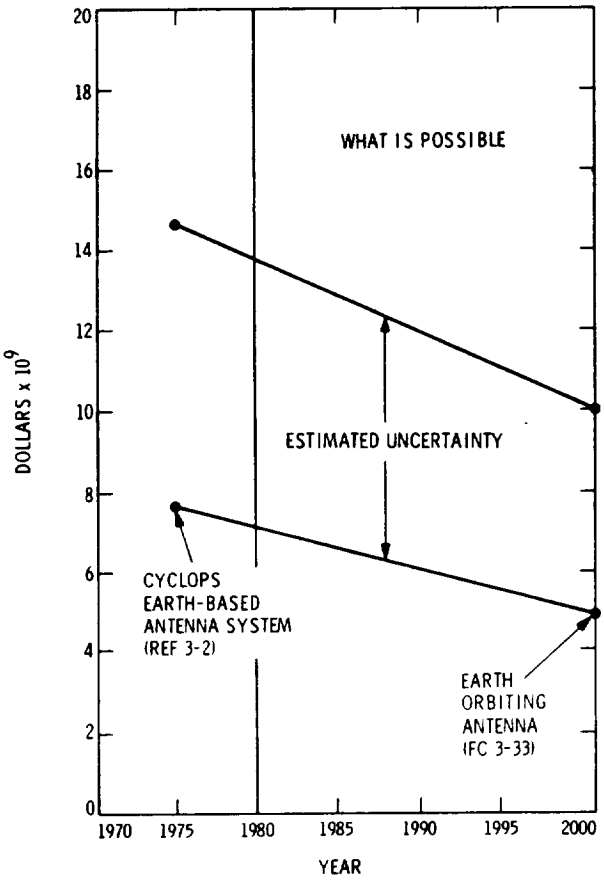
DISCUSSION

The interstellar range is the distance from Earth over which signals can be transmitted from an extraterrestrial civilization and be detected, assuming the transmission conditions given in the Cyclops study (Ref. 3-38): an omnidirectional transmission of a highly monochromatic signal at 10^9 W. The "what is possible" curve forecasts the search capability on the basis of a Cyclops-type system:

(1) A 3-km-diameter effective-antenna aperture would be achieved by arraying 1191 100-m antennas.
(2) A processor would be implemented which could search in real time for highly monochromatic signals over a 100-200 MHz bandwidth with 0.1 - 1.0 Hz resolution.
(3) Implementation of this system would begin in 1980 at an antenna fabrication rate of sixty 100-m antennas per year, continuing until the year 2000.

In 1981, after the first year of construction, sixty 100-m antennas would be available to begin the search with a range of approximately 225 light years. The estimated search capabilities in 1975 are for existing radio tracking/astronomy facilities: the Deep-Space Tracking Network in California, Spain, and Australia, and the Arecibo antenna in Puerto Rico. Their interstellar search capability is determined by comparing their receiving antenna apertures and system noise temperatures at L-band against the Cyclops specification, assuming each facility uses a Cyclops-type signal-processing capability.

FC 3-55. Interstellar Communication System Implementation Cost Estimate



DISCUSSION

This figure forecasts implementation costs for a Cyclops interstellar search system. Ninety percent of the cost is for development and construction of the antenna array. The 1975 cost estimates are for an Earth-based array. The year 2000 cost estimate forecasts a significant cost reduction in achieving large antenna aperture with the use of single, large antenna structures in geosynchronous Earth orbit as forecasted for the year 2000 in FC 3-31 through FC 3-37.

The lower 1975 cost-estimate bound (1975 dollars) is taken from the Cyclops report (Ref. 3-38) and assumes reduced 100-m antenna construction costs, due to mass production, by a factor of 0.4, and a single 100-m antenna cost = \$1,470 d^2, where d is the diameter in meters. The larger 1975 cost estimate bound was derived in a Cyclops study critique (Ref. 3-54) and assumes a mass-production factor of 0.7 and a single 100-meter-antenna cost = \$1,156 d^2.

9. Near-Earth and Deep-Space Communication Stations

a. Scope. This forecast is concerned with space communication stations, or terminals, that track, transmit to, and acquire data from spacecraft in Earth orbit or in deep space.

b. Forecast. For Earth-satellite data-acquisition and tracking, a decreasing number of Earth stations will be in use. The major tracking and data acquisition load will be borne by satellites. A tracking and data relay satellite system (TDRSS) is planned to begin operation in the early 1980s.

The TDRSS will consist of two geosynchronous relay satellites, 130 degrees apart in longitude, and a ground terminal centrally located in the continental United States. The payload of each tracking and data relay satellite is the telecommunication service system which relays communication signals between low-altitude Earth-orbiting user spacecraft and the TDRSS ground terminal. A "bent-pipe" design concept is used, in which received data are turned around in real time and retransmitted.

The forward telecommunication link, from the ground terminal to the TDRSS to the user, will carry command data, tracking signals, and voice transmissions. The return link, from the user to the TDRSS to the ground terminal, will carry telemetry data, return tracking signals, and voice. Both the forward and return links will consist of a space-to-space link between the TDRSS and the user satellite and a space-to-ground link between the TDRSS and TDRSS ground terminal.

The following types of service will be available:

(1) Multiple-access. The system is designed to support simultaneous, real-time, dedicated telemetry from low Earth-orbiting spacecraft with data rates up to 50 kbps during the entire portion of orbit visibility to TDRSS, a minimum of 85 percent of the orbital period. The command service is time-shared and supports one user at a time.

(2) Single-access. The system is designed to serve users requiring real-time turnaround at data-rates up to 50 kbps, and users requiring forward link rates of one to two kbps.

The types of forward links available will be as follows:

(1) Multiple-access. This system will be time-shared by all users; all of whom will operate at the same frequency, separated by unique codes.

(2) Single-access S-band. Users of this time-shared system will be discriminated by frequency and PN code.

(3) Single-access K-band. Users of this time-shared system will be discriminated by polarization, coding, and beam pointing.

The types of return links available will be as follows:

(1) Multiple-access. Each link will be dedicated to a specific user and can provide support for the entire visible part of the user's orbit. All users will operate at the same frequency and be discriminated by unique codes.

(2) Single-access S-band and K-band. Users will be discriminated by frequency, code, and beam pointing. This will be a time-shared system and will not normally provide continuous support to any user.

(3) Single-access K-band. Users of this system will be discriminated by polarization, code, and beam pointing. This is a time-shared system and will not normally provide continuous support to any user.

With the implementation of the TDRSS, the post-1979 Earth satellite tracking and data acquistion network will consist of two subnets: the TDRSS subnet, consisting of the satellites and the ground terminal, and the ground site subnet, with locations at California, Madrid, Orroral, Alaska, Merritt Island, Rosman, Bermuda, and Tananarive.

By the year 2000, the TDRSS system will be expanded to meet increasing satellite tracking and data acquisition and relay needs. Data will be acquired and relayed at gigabit rates. While most communication will continue at K-bands, greater loads and larger bandwidth needs will force use of higher bands. Satellite-to-satellite links will be optical.

The probable configuration for deep-space communication stations on Earth for the 1985 period will be two 64-meter antennas plus one 26-meter antenna at each of the stations at Goldstone, California; Madrid, Spain; and Canberra, Australia. Standard coherent telemetry, command, and two-way tracking will be available along with noncoherent processing at a central location via a 10-MHz bandwidth ground-communication-facilities link. Increased use of differenced radiometric tracking data will reduce sensitivity to ionospheric and tropospheric effects on frequency and time standards for all tracking declinations. S-band uplinks will be used at all stations. Goldstone will also have an X-band uplink. Both S- and X-band downlinks will be available at all stations with an added K-band capability at Goldstone. Network monitoring and control will be largely automated by 1985.

Two optional configurations are forecasted for the network for the year 2000. One would configure four 128-meter antennas plus two 64-meter antennas at Goldstone, California. Stations in Australia and Spain would utilize two 64-meter antennas in an arrayed configuration. The addition of a 64-meter antenna in South America would provide a North-South baseline in conjunction with Goldstone for high-accuracy very-long-baseline interferometry (VLBI) in addition to the now-available East-West baseline. Very-wideband ground-communication capability (50 MHz) would permit central processing in California, minimizing the equipment required at each station.

Up to 1.6 MW of X-band power would be available on a 128-meter antenna at Goldstone. Noncoherent downlink capability would also be provided in addition to standard coherent telemetry. With 1.6 MW of uplink power at X-band, and with an assumed 9-meter spacecraft antenna for reception, an uplink data rate of 100 bps would be possible at 1/2 light year. In addition, with 1.6 MW of uplink power, radar detectability for radar astronomy should be realized for all the outer planets and their satellites. See subsection 11.

A second network configuration option for the year 2000 calls for an automated station with a 300-meter antenna in an inclined synchronous Earth orbit above the continental United States, providing a North-South baseline. In addition, 64-meter antenna arrays would be located at Goldstone, California, and on the East coast of the USA. Wideband communication would again allow central processing. High-accuracy VLBI would be available with a 35,000-km baseline.

Relative to an Earth-based system, the differenced radiometric or interferometric tracking data types would enable the positions of a spacecraft relative to the center of mass of a target body to be determined to an accuracy of approximately 50 km per AU (150 million kilometers) by 1985, representing an angular accuracy of 0.1 second of arc. This accuracy would be improved by placing the planetary ephemerides on an extragalactic radio-source coordinate system with a technique called "delta differential very-long-baseline interferometry" (ΔVLBI), using the Earth-based VLBI system. With the planetary ephemerides referred to this system, accuracy would approach 5 km per AU (0.01 arc second) probable and 0.5 km per AU (0.001 arc second) possible by the year 2000. Extending the VLBI baseline through use of a station in synchronized Earth orbit or in Lunar orbit would probably not improve tracking accuracy over that of an Earth-based system since the determination and maintenance of station location would become a dominant error source for the increased baseline. It should be noted that extending the VLBI baseline from Earth diameter to 400,000 km through use of a Lunar-based station would provide an estimated possible angular accuracy approaching 10^{-4} arc second. See Forecast FC 5-34.

By the year 2000, deep space communication stations may be the Earth terminals for links with Lunar bases, orbiting stations in deep space or with a landed Mars exploration party. For a Mars communication link three communication relay satellites in synchronized orbit around Mars would make possible continuous communication with a landed party on Mars from Earth. For this discussion, it is assumed there is an orbiting transportation vehicle in addition to the orbiting communication satellites. S-band uplink and downlink channels would be used between Earth and orbiting spacecraft at a 200 to 300 kbps data rate. Separate S-band two-way links would also be used for each relay satellite when it is in view from Earth. A two-way, UHF channel at 200 to 300 kbps would be used between the orbiting spacecraft and the landed craft. In addition, separate two-way UHF channels will exist between the relay satellite and the landed craft. Finally, an S-band two-way channel would permit the landed craft to communicate directly with Earth with a 10 to 20 Mbps uplink and 2-to-3-Mbps downlink data rates. Continuous coverage by the Earth terminal would be provided by either antennas spaced 120° around the Earth or by Earth orbiting stations.

10. Radio Sensors

a. Forecast. Technology requirements for radio sensors (altimeters, radiometers, scatterometers, synthetic-array and real-aperture imaging radars) will be major drivers for development of communication devices and system capabilities at the extreme limits of frequency, bandwidth, peak power, and receiver sensitivity.

Active and passive microwave instruments operating in a single band with limited spatial resolution have been used in space, to date, primarily as experimental instruments. An increasingly large number of applications-oriented satellites are expected to make Earth and planet geoscience observations with multiband, active and passive radio instruments with multipolarization, large spatial resolution, large scan rates, complex signal processing, and large data rates. These missions pose significant problems for antenna design and integration, interference prevention, and transmitter/receiver design. The present outlook for microwave remote-sensing satellites indicates the need for a number of large antennas, each with multiple feeds, to be integrated on one spacecraft. Perhaps the best current example of significant multiple-antenna integration requirements is offered by the SEASAT program, for which synthetic aperture imaging radar, scatterometer, radar altimeter, and optical and microwave radiometer sensors will operate simultaneously making ocean-surface measurements. In addition to antenna requirements, higher-power space-qualitied transmitters will be developed to improve the performance of altimeters, scatterometers, and imaging radars. Transmitters will be developed with nanosecond pulse widths and kilowatt peak power at L to K_u bands. Low-noise receivers in the rf bands from 20 GHz to 1000 GHz will be developed for improved microwave radiometer sensitivity. By the year 2000, a receiver noise temperature of 20°K can be obtained at 20 GHz. For the higher bands, a noise temperature of 20°K will be available at frequencies to 300 GHz and a noise temperature of 50°K at 1000 GHz is expected by the year 2000. Microprocessing will be used extensively in radio sensors for the following functions:

(1) Adaptive, optimum pulse tracking using maximum likelihood estimation techniques for altimetry.

(2) Decompression, correlation, pre-summing and clutterlock compensation for radar imaging.

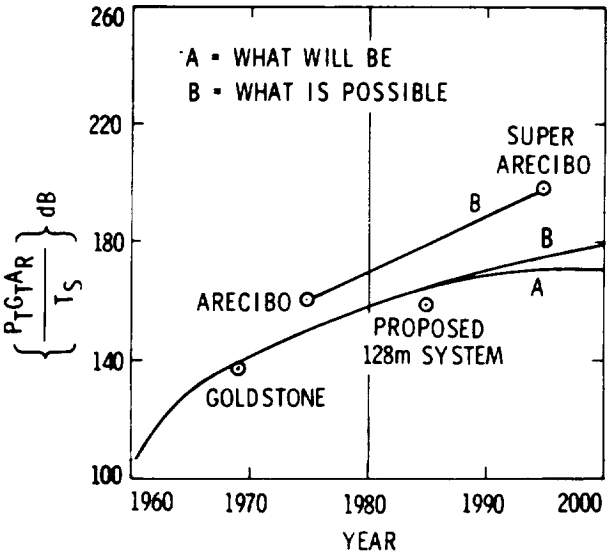
(3) Analog to digital conversion at megabit to gigabit rates for buffering, formatting, adaptive filtering, and data processing for all sensors. Signal bandwidth will be as large as 100 MHz. Processing and communication data rates will be as high as 1000 Mbps.

11. Radar Astronomy

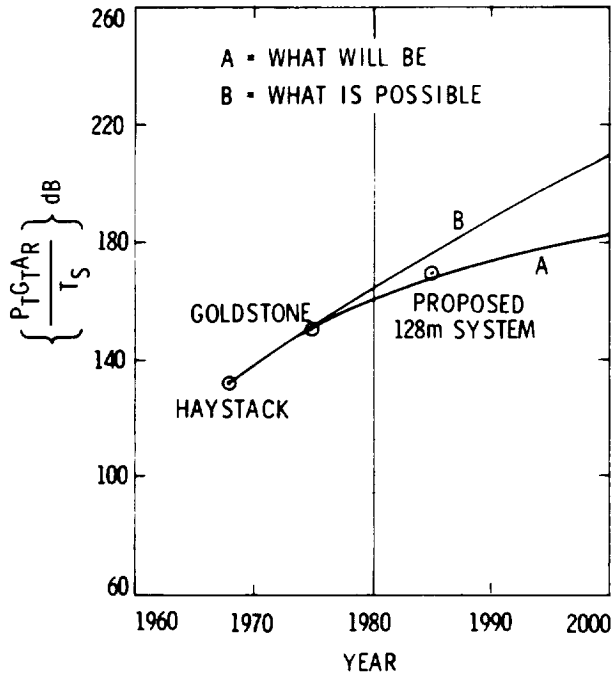
a. Introduction. The radar astronomy forecast considers systems which are either ground-based or Earth-orbiting, operated either as monostatic or multistatic systems, from the point of view of overall system sensitivity. The performance curves are constructed from the forecasted data for antennas, transmitters, and receivers. Points of reference are shown for several existing and proposed radar systems. Data for these points were obtained from figures given by Evans and Hagfors (Ref. 3-55) and from a more recent report by Jurgens (Ref. 3-56). Also considered is the possibility of using an Earth-orbiting microwave power-generating station as a radar transmitter. Such a system would permit radar studies of all presently known bodies in the solar system.

b. Forecasts. The forecast figures present the radar sensitivity factor, $P_T G_T A_R / T_S$, expressed in dB as a function of year, where P_T is the transmitter power in watts, G_T is the gain of the transmitting antenna, A_R is the effective collecting area of the receiving antenna in meters squared, and T_S is the receiver system temperature in degrees Kelvin.

FC 3-56. Ground-Based S-Band Planetary Radar Sensitivity



FC 3-57. Ground-Based X-Band Planetary Radar Sensitivity



NOTE:

The Goldstone facility is located in the Mojave Desert in Southern California. The Goldstone curve is based on use of the 64 m antenna capacity at Goldstone. The Arecibo facility is located in Puerto Rico. The Arecibo curve assumes the use of the Arecibo 300 m antenna capability.

DISCUSSION

These forecasts have been prepared using Forecasts 3-33 for S-band antenna gain, FC 3-26 and FC 3-27 for microwave power, and FC 3-29 and FC 3-30 for receiver-system noise temperature. Other points show the capabilities of the present Arecibo and Goldstone systems as well as a proposed 128-m fully steerable system with a 1.6-MW transmitter and a receiver-system temperature of 10°K (Ref. 3-56). Further capability could be achieved by receiving with multiple arrays of large antennas, but multiple transmitting arrays seem unlikely unless the problems associated with phase synchronization over many sites in real time can be solved.

Also plotted is a point (Super Arecibo) which represents the largest sensitivity that appears possible with a single Earth-based instrument. This is a 900-m-diameter antenna with an Arecibo-type structure employing an 8-MW transmitter consisting of a cluster of four 2-MW transmitting tubes. The receiver system temperature would be 25°K.

The growth in sensitivity is usually stepwise in large increments, not smooth. The large steps assume massive efforts in transmitting tube and receiver technologies and very large antenna systems designed specifically for deep space communication, radio and radar astronomy, or military applications. Further increases in radar sensitivity will require a continued commitment to technological improvement. In a few cases, systems designed for other applications may be useful for astronomical purposes. For example, fast digital-processing machinery and large-scale integrated-circuit technology will progress because of the large market for such items. A 300-m-diameter antenna requires a definite commitment, i.e., it will be brought about by a large demand for such an item.

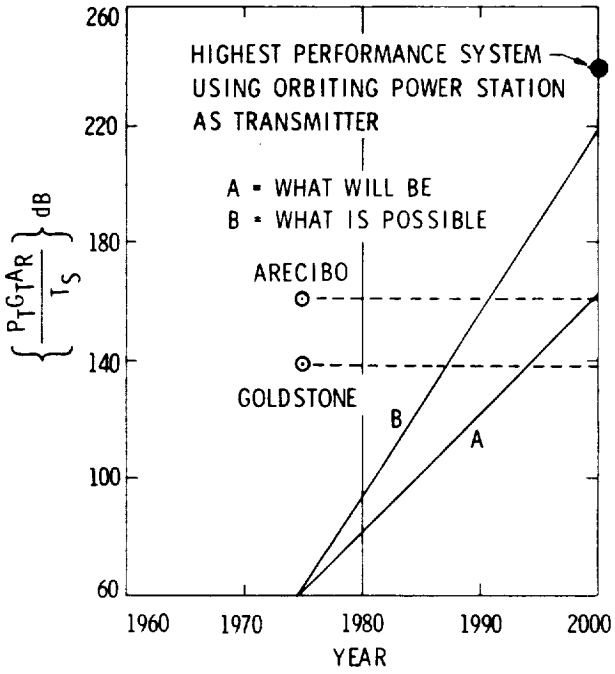
The curves have been prepared assuming gradual growth in some cases, averaging through large steps in growth in other cases, and by assuming various large commitments at certain points.

In order to make a reasonable increase in radar sensitivity, a commitment for a system would have to be made as much as 10 years in advance of the time when the system is to be operational.

The two X-band curves assume growth rates in transmitter power of either 0.52 dB/year or 0.26 dB/year as well as receiver improvements averaging -0.1 dB/year and -0.05 dB/year for the upper and lower curves respectively. The upper curve assumes a transmitter power of 8 MW distributed over the array by the year 2000 and only 1.8 MW for the lower curve. A point of reference is shown also for the Haystack radar system.

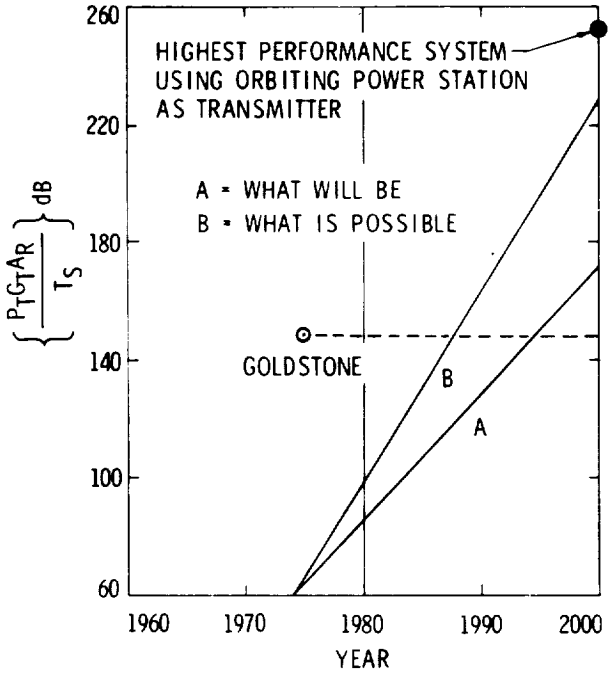
Radar sensitivity is defined in the text (see b. Forecasts above).

FC 3-58. Orbiting S-Band Planetary Radar Sensitivity



NOTE:
ORBITING S-BAND PLANETARY RADAR SYSTEM SENSITIVITY FACTOR AS A FUNCTION OF YEAR.

FC 3-59. Orbiting X-Band Planetary Radar Sensitivity



NOTE:
ORBITING X-BAND PLANETARY RADAR SYSTEM SENSITIVITY FACTOR AS A FUNCTION OF YEAR.

DISCUSSION

An Earth-orbiting planetary radar system may not be practical until greater sensitivity can be achieved in orbit than on the ground. Presently, the sensitivity factors, $P_T G_T A_R / T_S$, for the Goldstone radar system are 138 dB and 148 dB at S-band and X-band, respectively. The anticipated growth in ground-based capability may be on the order of 1 to 1.5 dB per year over the next 30 years. If an orbiting system were built at the present time, using the technology now available, it would have a sensitivity factor of only 72 dB; assuming a 10-m antenna with 55 dB gain, a 50 W transmitter, a collecting area of 37 m^2, and an uncooled parametric amplifier having a system temperature of approximately 40°K.

The task of forecasting the growth rate of orbiting-radar sensitivity is difficult because power increases in high power transmitters is rather nonuniform and highly dependent upon military applications. The available forecast data on large orbiting antennas indicates that the growth rate due to increased antenna size and lower temperatures of receiver systems alone could be between 3.7 and 4.8 dB per year. We can assume that a cluster of perhaps four 2-MW klystrons could be operating in a space environment by the year 2000 – this would give a growth rate of about 2 dB per year. With average growth rates, the orbiting-radar sensitivity could not surpass the ground-based radar sensitivity until after 1990. This is assuming that Goldstone represents the baseline capability. If it is assumed that Arecibo is the baseline, this capability would not be reached until the year 2000. Therefore, there is little reason to consider forecasting usage of this application prior to 1990.

If the sensitivity factor is calculated from the respective forecast data (FC 3-58 and FC 3-59) directly, the results, for S- and X-band respectively, show that unfurlable antenna systems will become increasingly larger – to a diameter of as much as 1 to 3 km – and that, by the year 2000, it will be possible to operate a cluster of four 2-MW klystrons in a space environment. An uncooled parametric amplifier is assumed for the receiver, and a system temperature in dB of roughly 16.5-.14T, where T is in years past 1975. The lower curves, which are based on curves presented in the antenna forecasts, assume a power generating growth rate of only 1.0 dB per year in contrast to 2.0 dB per year for the upper curve. The present sensitivities of the Goldstone and Arecibo instruments are shown for reference. It is clear that if such large antenna structures can be designed for orbiting systems, considerable improvement in radar sensitivity can be realized by the year 2000. Perhaps as much as an 80-dB improvement over the Goldstone system is possible. Radar astronomy has always borrowed facilities from other scientific projects to carry out its experiments. The upgrading of the Arecibo instrument was the first example in which the incentive for the expenditure was justified primarily by the increased radar capability that could be achieved. A further example is discussed in the following paragraphs.

The highest performance planetary radar system at the year 2000 will result from the combined development of space-power generation and the ability to manufacture large unfurlable-antenna systems having adequate precision to operate between the S- and X-band wavelengths. Microwave power generating capability near 10^{10} W is assumed (Ref. 3-57). Slight modifications of the proposed microwave power transmitting system for radar applications are required since it is designed to focus the radiation to a point on the Earth where a pilot transmitter is located to serve as a phase reference for the orbiting antenna array. A new reference in the direction of the target would have to be established. This could be located on a second small satellite having a laser ranging system to accurately locate and lock the pilot satellite to the orbiting array. Fine steering of the beam could be accomplished by moving the pilot transmitter instead of steering the physical array. The ability to transmit binary-phase-coded signals would have to be added to permit other than pure continuous wave operations. Such a system would add the transmitting capability to reach distant stars (Ref. 3-58). The total $P_T G_T$ product for such a system could be 187 dB at S-band or 199 dB at X-band. Here a transmitted power of 10^{10} watts and a modified version of the illumination distribution over the aperture has been assumed to maximize the antenna gain; i.e., the smooth Gaussian distribution is not essential as a low side-lobe level is not required. A 1- km diameter array might have an aperture efficiency greater than 70%, giving a total effective area of 0.5×10^5 m^2 and gains of 87 dB at S-band and 99 dB at X-band.

The satellite power stations are to be in synchronous orbits; however, for the purposes of radar astronomy, more distant orbits may be desirable to minimize the problems of pointing at an astronomical source. Optimum locations might be at the Lagrange points L4 and L5 of the Earth-Moon system, provided that these regions are not filled with debris. At their distance the rotation rate is only once in 30 days, which makes the steering easier and permits adequate time for the entire system to reach thermal equilibrium as the rotation proceeds. Gravitational forces are also less so that distortions of the figure are less likely than for the synchronous orbit.

A second antenna of the unfurlable design having a maximum diameter of 3350 m could be used as a receiving station, yielding 67 dBm^2 of effective collecting area. A conservative receiver design might incorporate a simple uncooled parametric amplifier having a total system temperature near 25°K. A more complicated maser design could reach a temperature as low as 8°K if a closed cycle refrigeration system can be designed for space operation. The conservative receiver design gives a system product, $P_T G_T A_R / T_S$, of 240 dB at S-band and 252 dB at X-band. An improvement of roughly 102 dB over the present Goldstone radar system at either S- or X-band can be achieved by this system.

The difference between the losses over the paths to Pluto and Venus is about 91 dB; thus the orbiting radar system would be able to produce maps of Pluto, similar to the present maps of Venus obtained with the Goldstone radar system, with 10 dB to spare. The detection and mapping of all numbered asteriods would become a relatively easy task. The larger satellites of Jupiter and Saturn would be at least 25 to 35 dB more detectable than Pluto. Essentially all presently known members of our solar system would come within the detection capability of such a radar system.

D. SUMMARY AND IMPLICATIONS

Extremely large communication capacity is now available and will continue to grow, at lowering costs, for Earth, Earth-orbit, and deep-space information transfer. In many instances, the information rate exceeds processing and storage capacity and the needs of most users at the present cost of information transfer. For example, satellite communication technology stands ready to provide gigabit data rates once cost effective uses are found and facilities exist for effective data processing and dissemination. As costs are further reduced, there will be increased application of this high-rate transfer technology, but for the present, and probably to a large degree until the year 2000, a significant portion of Earth communication can be accommodated effectively over existing telephone-line systems.

Source encoding (data compression) and onboard processing by "smarter" spacecraft will slow the need for growth in data transfer rate as well as in ground data storage and processing capacities. However, the availability of large information rates at relatively low cost for some applications will be exploited by inexpensive spacecraft with simple data-acquisition systems relaying data, at a high rate, to central processing stations. An example is the planned SEASAT satellite real-time relay of imaging radar data to Earth for processing.

All deep-space communication and a majority of satellite and Earth links will continue to use microwave bands up to approximately 30 GHz. Communication by optical cables for Earth point-to-point links will grow rapidly over the next 25 years.

Technology will exist for lower cost, more reliable Earth communications by the year 2000, making possible high rate higher quality mobile communication for airplanes, boats, rescue, and remote sensing; two-way megabit home-communication by cable; and electronic mail and personal communication via satellite. The use of digital terminals in business offices will be widespread when their cost is on the order of that of typewriters. They will be used in homes when their cost is still lower.

Satellite communication capability over the next 25 years will exceed gigbit data rates over microwave and optical links. Three types of satellite links will be in use: satellite-to-satellite, satellite-to-low-Earth-orbit, and satellite-to-Earth. Satellite optical links will communicate to a multitude of Earth receiving stations, widely separated geographically and connected to a central-processor site with optical and microwave ground links. Satellite communication will continue to lower the cost of communication, making it largely independent of communication distance.

Satellite communication growth will not continue unabated without problems. The following factors will tend to retard the use of satellite communication technology:

(1) Lagging data-processing speed and storage capacity in relation to available channel capacity.

(2) Inefficient distribution and assimilation of the large quantities of data involved.

(3) The large capital investment in established Earth-communication facilities such as the telephone system and existing satellite-link Earth terminals with their constraints.

(4) Problems associated with integration of satellite technology into the world society – data security, transmission infringements of national borders, interference with established users of frequency bands, etc.

(5) Competition of satellite communication with low cost, high-data-rate Earth optical communication. Such optical systems are especially suitable for low-cost, centralized communication and represent a means of transmitting local community-oriented news. Satellite links, by their nature, provide greater geographic coverage and therefore are more nationally or internationally oriented.

Deep-space communication systems (Earth-to-deep-space probes or to planetary probes, flybys, orbiters, and landers) will exploit satellite technology to achieve higher rates at higher frequencies. Satellite data rates and frequency requirements have historically led and will continue to lead those of deep-space missions, placing an earlier demand on these technology developments. Deep-space communication technology advances will be most prominent in the development of large, lightweight, deployable antennas; small, integrated, solid-state transmitters and receivers; lower receiver noise temperatures; ultra-stable time sources; and probe links.

Communication stations situated on Earth for satellite tracking will be largely phased out and replaced by geo-synchronous satellites communicating into one Earth station. For deep space tracking stations, relay of data acquired from remote stations located around the world will be relayed to a central station by satellite. On one hand, microprocessing technology will provide for automatic, complex processing at the data acquisition site; while on the other hand low-cost, wide-band, high-rate satellite data capability will allow for direct transmission of the raw signal from the data acquisition site to a central station for processing. One or two large Earth-orbiting antennas could replace antennas on Earth which are located at longitudes approximately 120° apart for continuous deep-space coverage.

It is likely that a major attempt will be made in the next 25 years at detection of electromagnetic signals emanating from other civilizations in interstellar space. These signals at microwave, infrared, visible or ultra-violet wavelengths reach Earth either as incident radiation or representing a direct attempt at communication. On Earth, emphasis will be placed initially on the detection of these radiations from space. For a search

in the microwave band out to 1000 light years from Earth, an antenna collecting area as large as 3 km is required. Wide-band and low-noise receivers and processors will need to search megacycles of bandwidth, resolving the received spectrum to 1 Hz, in order to detect signals which are expected to be highly monochromatic in nature with sidebands carrying possibly the most information-packed message in Earth communication history!

Large-scale integration of semiconductor devices (LSI) and microprocessing will have a significant impact on communication technologies not historically linked to semiconductor or computer technology. For many applications, communication systems will consist of an integrated transmitter, receiver and antenna. The antenna will be composed of an array of small dipole elements, each tied to its respective receiver and transmitter amplifier. Thus, antenna, receiver, transmitter, processing, and control functions will be integrated into one microprocessing system. Physically they will be formed into thin polygonshaped plates whose area represents the antenna collecting area. Microprocessing will compensate for antenna structure shape deformation, point and shape multi-antenna beams, and adjust polarization. As LSI technology advances continue, arraying millions of integrated dipole elements may become a less expensive method of achieving large antenna apertures required for radio astronomy and interstellar communication. Microprocessors will also provide inexpensive large-scale data-processing capability (correlation and fast-Fourier transformation, etc.) for signals with large bandwidths requiring narrow-frequency resolution.

LSI and microprocessing technology will consolidate on a chip once established and traditional functions that were identifiable as unique black boxes in the communication link. Established technical disciplines and organizations structured to match the once traditional discrete functions will require alteration to accommodate the trend toward systemizing. Broader technical backgrounds will be required of development organizations. Antenna engineers will need to be well versed in computer and semiconductor sciences as well as in electromagnetic wave theory. Where in the past, individual subsystems were developed and then integrated into systems, total system packages will be fabricated encompassing transmitter, antenna receiver, processing, and control functions.

By the year 2000, large structure technology may allow placement in Earth orbit of antennas on the order of 3×10^3 meters in diameter and for deep-space probes, antennas as large as 2×10^2 meters in diameters. Shuttle and a tug transportation capability for transfer to a higher orbit or into deep space are assumed.

The ultimate limits for communication channel parameters such as antenna gain and transmitter power are set by cost. Increasingly large levels in antenna gain and transmitter power can be achieved by arraying single elements. Near-theoretical limits of receiver noise temperature and channel coding efficiency will be achieved by the year 2000 – to the point of diminishing return. The emphasis in coding development will shift toward reducing bandwidth requirements, avoiding interference and providing security. The major limit to data rate is carrier frequency and bandwidth allocation. For any carrier frequency the ultimate data rate in bps is the carrier frequency itself, but this places a prohibitive bandwidth requirement of twice this frequency beginning at 0 Hz. Bandwidth allocation at a particular carrier frequency band is then the limit to data rate.

Technology requirements for radio and radar sensors (altimeters, radiometers, scatterometers, synthetic array or real-aperture imaging radars) will be a major driving force in the development of communication devices and systems capabilities at the limits of frequency, transmitter power, receiver bandwidth, and signal processing capability. Some representative developments will be:

(1) Transmitter power of kW peak power levels at S, X, and K bands, and above with nanosec pulse durations.

(2) Multiband receivers with extremely low noise temperatures at all frequency bands including those above 100 GHz up to infrared frequency bands.

(3) Antennas with unique beam shaping to provide required Earth or planet coverage. Antenna beams will be electrically steered. They will exhibit strict sidelobe control and provide for selectable polarization. Antennas will cover all frequency bands up to and above 100 GHz. At L-band frequencies antennas as large as 20 to 30 m^2 will be developed.

(4) Complex signal processing for real-time radar imaging to 5-m resolution.

A number of external factors will influence the direction of communications technology. Positive drivers include:

(1) Resource shortages. Communication could reduce transportation needs and, thus, energy needs as well.

(2) Emerging wealthy countries – for example, oil-producing nations, which may desire their own communication satellites or other space projects for prestige.

(3) Increasing widespread awareness of our cosmic environment. A belief that other extraterrestrial civilizations exist in the universe could result in a major search for extraterrestrial life.

Among the negative drivers are these:

(1) Government regulations and changes in regulations.

(2) Breakup of major communication research organizations.

(3) Inflation and a worsening economy, resulting in nearsightedness and its impact on long-range planning.

(4) Decreased government-sponsered research and lack of an adequate well-planned long-range research program (on/off support).

(5) Lack of cultural acceptance; technology advances can be construed as infringements on individual freedoms and receive unequal world-wide acceptance, depending on culture. Computer assistance in our personal lives, while readily accepted by more disciplined societies may be rejected in other cultures.

Two information-transfer applications which are limited by present communication technology and present significant development challenges are: 1) The search for electromagnetic signals from extraterrestrial civilizations will require lower-cost large antenna apertures; wideband, complex data processing; and low-noise wideband receivers. 2) The development of a personal communication system will require small, reliable, inexpensive two-way radios and wideband, high capacity random access satellite reception, switching, and relay capability. Development of a system design which utilizes a realistic bandwidth allocation will pose a significant challenge.

E. PARTICIPANTS[1]

The Coordinator expresses his appreciation to those who so willingly and enthusiastically contributed to this study. Their original contributions are preserved on microfilm (see Section F). Appreciation is also extended to others not listed below whose many conversations helped focus the activity on the important areas treated in this report.

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F. INDEX OF MICROFILMED FORECASTS

The following forecasts, concerning the transfer of information, are available at the Jet Propulsion Laboratory. This information may be retrieved by calling Mr. George Mitchell at (213) 354-5090 and giving the document number (1060-42) and volume number (Vol. III), followed by the correct page reference numbers as listed below:

Title	Page No. (1060-42, Vol. III)
1. Microwave Transmitters	
a. Space Transmitters	3-200 — 3-226
b. Ground Transmitters	3-227 — 3-239
2. Microwave Spaceborne Receivers	3-240 — 3-252
3. Microwave Spaceborne and Ground Antennas and System Noise Temperature	
a. Spaceborne and Ground Antenna (Large Element) and System Noise Temperature	3-253 — 3-297
b. Large Spaceborne Deployable Antennas (Single Element)	3-298 — 3-341
c. Microwave Antennas (Small Element Array)	3-342 — 3-353
4. Signal Design and Processing	
a. Coding, Modulation, and Optical Communications	3-354 — 3-374
b. Signal Processing	3-375
5. Optical Communications	3-376 — 3-410
6. Earth/Near Earth Communications	
a. Near Earth Communications	3-411 — 3-417
b. Earth Communications	3-418 — 3-424
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a. Near Earth Stations	3-425
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Section IV. PROCESSING AND STORING INFORMATION

W. M. Whitney

A. SCOPE

Processing covers the operations performed on information, excluding those involved in transfer, from the time it is received from instruments, sensors, or a communication link, until it is delivered to the next link, to a storage medium, or to a human user in some form such as a printed record, a display, or an audio signal. Source encoding for efficient data and information transfer is included, but channel encoding for faithful transmission is not, the latter being addressed in Section III, Transferring Information. The interface between humans and machines is included here because its special problems have more to do with the disparate processing characteristics of source and receiver than with the mechanism of transfer.

The storing of information, its preservation for later retrieval and use, may be necessary at any stage of acquiring, transferring, or processing, and for periods of time that may vary from nanoseconds to years. For several reasons, the forecasts for storing and for processing have been combined in this section. First, they share common technologies. As the density of storage elements continues to increase, economic considerations are promoting the use of similar or compatible manufacturing techniques for both logic and memory, leading toward their physical integration. Foreshadowing the increasing gate density and decreasing cost of large-scale integrated circuits is a trend toward system architectures that are based upon separate computing elements, each having its own memory for local functions and communicating with other processor-storage elements for global ones. Second, as the requirements for storage and high-rate data handling grow, it seems unlikely that monolithic high-capacity memories, tied to processors through a relatively small number of registers or accessed serially in the manner of present tape systems, will remain practical; more probably, different storage schemes, based on distributed, parallel storage structures, each requiring local processing to facilitate more "intelligent" search and storage procedures, will be developed. Finally, by whatever means Nature has accomplished the storage function in living systems, it seems to be intimately linked to processing. Thus, looking ahead to larger and more capable information-management systems, we have chosen to combine processing and storing here, even though the distinction is presently a real one and may remain so for some years to come.

In view of the fact that many of the capabilities being forecast in this section depend upon advances in microcircuit technology, the reader is advised to review Part Five, Section III, in relation to Hardware Characteristics (see below).

B. ORGANIZATION AND APPROACH

Progress in the processing and storing of information can result from advances in any of the computer and information sciences and their related engineering disciplines. The scope of these fields, taken together, is enormous, covering such diverse subjects as computational complexity theory, microelectronic circuit design, machine perception, computer architecture, control theory, display, programming languages, data structures, artificial intelligence, and psychological factors in the human use of machines, to name only a few. Preparation of separate forecasts for all areas of possible future relevance to processing and storing technology would have required an effort far beyond the scope of the present study.

It is believed, however, that such an exhaustive survey is not necessary. The intent in "A Forecast of Space Technology" is not so much to forecast individual lines of work as to look for related developments or converging trends most likely to be of significance for space activities during the next quarter century. The search is conducted in this section by examining a few areas that seem to make contact with a variety of present disciplines and potential space applications. Selection of the areas was based on the notion that processing-storing systems can be characterized by their physical structure and properties, by the methods by which they are prepared and used, and by the purposes to which they are directed. Three comprehensive secondary categories or functions were defined and nine groups of forecasts developed that relate to and expand upon the functions. These are discussed below. The numbers refer to the subdivisions of "C. Forecasts."

(1) Designing and Building Machines — combining concepts of machine structure and organization with proven technology to produce reliable working systems. One group of forecasts is presented in this category:

1. Hardware Characteristics. Quantitative projections are made for Earth-based and spaceborne processors and storage systems. Peripheral hardware, although it is a necessary part of any large computer installation, is not covered.

(2) Instructing and Using Machines — preparing or programming machines so that they can

perform the tasks required of them; and using them interactively or as autonomous or semiautonomous agents in task execution. Five groups of forecasts are presented:

2. Human-Machine Communication. The focus is on the characteristics of the interface through which a human user instructs or programs a machine, interacts with it during execution, and accepts information from it. Software production is treated as one aspect of human-machine communication.

3. Data Compression. This forecast covers the on-board collection, processing, and encoding of measurement information. Emphasis is on concise representation of image information so that communication channels and data-storage facilities are efficiently utilized.

4. Teleoperators. A teleoperator is a human-machine system that enables human sensory, motor, and cognitive faculties to be augmented and extended to remote sites for the conduct of complex operations. Although such machines are employed in tasks that, strictly speaking, involve the "management of matter," they are discussed here because the primary problems in their design and use relate to information and control functions.

5. Robots. A robot, in this forecast, is considered to be a machine that can perform certain tasks requiring coordination of sensing and control automatically, without step-by-step human direction. The human is not totally removed from the control loop, but rather exercises a supervisory function and interacts with the machine at a relatively high command level.

6. Automation of Space-Related Information Processing. This forecast is concerned with the increasing use of the computer in NASA work.

(3) Automating Cognitive Processes – finding ways of representing data, knowledge, problems, and goals in machines and developing numerical or symbolic procedures that facilitate or supplant human information processing and storing functions. Three groups of forecasts are presented:

7. Picture Processing and Scene Analysis. Theory and capabilities of methods of processing pictorial information are discussed and related to applications of interest to NASA.

8. Natural-Language Understanding. This forecast is concerned with the understanding and use of natural language by computers, an ability fundamental to providing a more comfortable accommodation between human beings and machines.

9. Problem-Solving Systems. Potential applications of automated problem-solving in space activities include robots, human-machine interaction (e.g., question-answering systems, language understanding), and automated software production. The status of work in this area and future prospects for advances are addressed.

All information processing done by machines, simple "number-crunching" as well as symbol manipulation, can be regarded as "automated cognition." Advances in numerical procedures or their underlying theory have not been forecasted. Faster, more accurate, more efficient computational algorithms seem likely to have wide application throughout society, especially in the light of the advances forecast in "1. Hardware Characteristics" below (Forecasts 3-60 and 3-61) and the advent of inexpensive microprocessors made possible by semiconductor developments projected in Part Five. Their development, however, seems not to promise qualitative changes in computer capabilities. Considerable emphasis in categories (2) and (3) is placed on the automation of some of the highly complex information-processing procedures carried out by living systems. These are generally not understood, and thus have been found difficult to reduce to algorithms, but their successful simulation would have enormous impact on the role of computers in space applications and in all of human life. These procedures usually combine the following functions:

(1) Sifting through very large quantities of data to reduce their volume and extract information relevant to some purpose.

(2) Applying heuristic procedures to limit or accelerate search in the exploration of decision trees too large to be followed to conclusion.

(3) Building, maintaining, and accessing large information bases whose application and content may change.

(4) Controlling many concurrent procedures with competing requirements and changing priorities.

Studies concerned with understanding these and other functions like them and mechanizing their fully automatic performance are among those loosely collected under the designation AI – artificial intelligence (or MI – machine intelligence). In a recent forecast and technology assessment of Coles et al. (Ref. 3-59) the following categories are listed for AI: language understanding, problem-solving, perception (visual), modeling, learning and adaptive systems, robots, and games. Together the forecasts presented under categories (2) and (3) provide a representative view of status and prospects in those aspects of machine cognition thought to be most applicable to space information systems over the next 25 years.

Finally, a few comments are offered concerning the approach followed in developing forecasts for this section. The primary impetus for innovations in computer hardware technology comes from military and commercial requirements. With some notable exceptions, the role of the civilian space program has been largely to modify and apply what has come into existence at an earlier time in Earth-based systems. It was determined that extensive forecasting of processing and storing hardware had already been conducted and the results were available in the literature. The principal problem in preparing the forecasts in these areas was to sift through the material, condense it, relate it to space applications, and present the results in a consistent and coherent framework.

In those areas forecasted under categories (2) and (3) it has been harder to find prior published work that is compatible with the approach and level of treatment adopted for this study. While there are many good measures of hardware performance, few exist to characterize progress in the applications of computers. The disciplines of information and computer science are relatively young, and there is as yet no comprehensive underlying body of theory that unifies concepts and quantifies them (as does communication theory for information transfer). Existing forecasts, of which there are few, are understandably descriptive rather than quantitative, and use consensus or intuitive methods to predict the future time at which some specified capability is likely to be achieved. No way of improving on these methods has been found in the course of this study. Thus, the forecasts that relate to computer programs are descriptive, and combine the experience and judgment of the forecasters with similar insights obtained from the literature.

C. FORECASTS

1. Hardware Characteristics (Forecasts 3-60 to 3-66)

a. Introduction. Forecasts of the characteristics of electronic computing hardware for spaceborne and Earth-based systems are presented here under the two major categories of processors and mass storage media. The emphasis is on the future computing capability of spaceborne systems. Computer peripherals (input-output devices) and data-communication equipment are excluded.

A detailed technical forecast of computer hardware technology is a difficult task requiring a deep understanding of a wide variety of computer architectures and operating principles. To develop an independent forecast for this study would have been a formidable undertaking. Fortunately, the future of computer technology has received considerable attention during the past five years and several excellent forecasts have been published. These have been the primary sources for the material assembled here. The reference consulted most extensively was the book by R. Turn (Ref. 3-60).

The main parameter used as a measure of computer processor performance is instructions or operations per second, determined from a sum of the weighted execution times for a set or "mix" of instructions. For mass memories the parameter is capacity in bits. More meaningful indicators of performance that would relate directly to NASA missions are not available from the references consulted. The forecasted capabilities of future hardware systems must be measured in terms of their relative gains in performance over those of the existing systems identified in the forecasts.

b. Background.

(1) Processors. Electronic computing machines, which had their beginnings in the late 1940s, have progressed through a series of stages or "generations." Two generation scales of components and computers that have been identified for Earth-based systems are given in Tables 3-3 and 3-4 (Ref. 3-60). From a study by E. C. Joseph (Ref. 3-61) of the computer generations and the work by K. E. Knight (Ref. 3-62), the following trends have been identified for Earth-based systems:

(1) Performance has increased by a factor of 100 each 10-year period over the past 30 years since introduction of ENIAC. (See Fig. 3-8.)

(2) Physical size, power consumption, and cost have decreased at about the same rate during the past 30 years.

(3) Reliability has increased about 10 times each new component generation.

(4) Memory capacity has increased about 20 times each new component generation.

The growth of spaceborne systems has been less dramatic, and new features have lagged their introduction in Earth-based systems by as much as 10 years. Some of the important trends are these:

(1) Performance has increased about 5 to 10 times in a 15-year period (Ref. 3-60).

(2) Physical characteristics (weight, size, and power) have not changed significantly during the past 10 to 15 years because spaceborne computer systems have been allocated the same or greater physical resources on space vehicles; but the efficiency in terms of performance capability per weight, size, or power has been improved by several orders of magnitude (Refs. 3-63 and 3-64). The density is approximately that of water.

(3) Main memory capacity has increased about 16 times from 4 k to 64 k words (Ref. 3-61).

(4) Each successive component generation has permitted development of a more capable and complex computer with greater reliability than that of the previous generation. Reliability improvements have resulted in an increase of mean-time-to-failure from several hundred hours to thousands of hours.

(5) Special-purpose designs have been developed to meet power-size constraints and reliability requirements.

Table 3-3. Component generations

Generation	Component	Application
0	Relays and vacuum tubes	Used to build one-of-a-kind computers, such as Harvard-IBM and ENIAC. Time period: up to 1953.
1	Vacuum tubes	Commercial computers, such as UNIVAC I, IBM 701, IBM 704, and IBM 709; 1951-1958.
2	Transistors	The beginning of solid-state component technologies. Examples of applications are Philco 2000, IBM 7090, CDC 6600, and the supercomputers STRETCH (IBM 7030) and UNIVAC's LARC; 1958-1969.
3	Solid-state integrated circuits (IC's)	Examples of applications are the IBM 360 series, Burroughs 6500, and UNIVAC 1180; 1967 to the present.
4	Solid-state medium-scale integration (MSI) and large-scale integration (LSI)	Here entire subsystems are manufactured as monolithic units. Examples of applications are the ILLIAC IV computer and the developmental Navy AADC (All Application Digital Computer).

Source: Ref. 3-60.

Both block and functional redundancy have been used to achieve the long lifetime requirements.

(6) There is a trend toward decentralized or distributed computing system architectures, now in the development stages. Examples are the Navy's All Applications Digital Computer (AADC), the Air Force's Universal Digital Avionics Module (UDAM), and NASA's Unified Data System (UDS).

Typical characteristics of a present-day composite operational spaceborne computer system (Refs. 3-60 and 3-63):

(1) Speed: 10^5 operations/sec

(2) Memory:

Capacity - 10^4 to 10^6 bits
Cycle time - 1.5 to 2.5 microseconds
Technology - plated wire

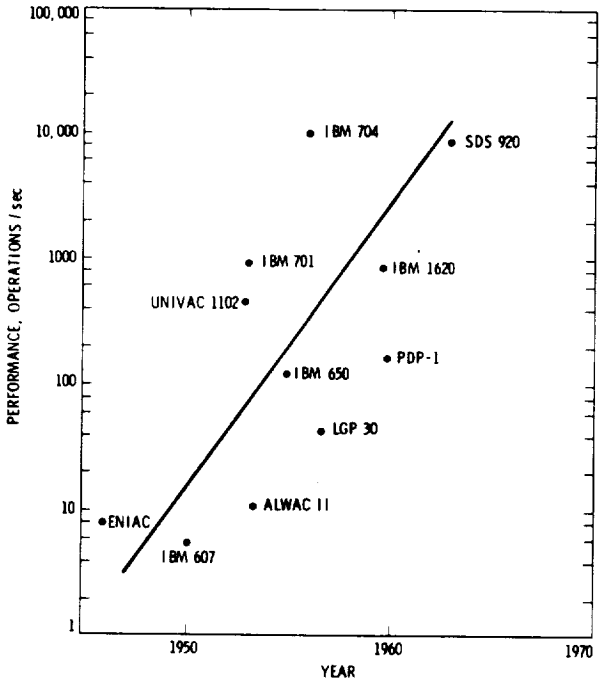
(3) Power: 22 watts

(4) Weight: 4.5 kg

Table 3-4. Computer generations

Generation	Computer Type	Application
1	Special purpose	Introduced in 1951-52 for scientific or business computations; single job operation; about 100 simple instructions, a few index registers; machine language, subroutines, utility routines, symbolic assemblers.
2	General purpose	Introduced in 1958-60 for general data processing; about 100 complex instructions, independent and simultaneously operating I/O, high-speed main memory and a mass memory, batch-processing type of operation; higher-level languages, software monitors, macro-assemblers, executives.
3	Computer systems, families of computers	Introduced in 1963-65 for general information processing, multiprogrammed and time-shared operation, remote terminal interactive and job-entry systems; multiprocessing and real-time teleprocessing systems; operating systems, many higher-level languages, modular programs, reentrant subroutines, conversational systems.
4	Networks of computer systems	Introduced in 1970-72 for on-line information processing; multiprocessing, new architectures, direct higher-order language processing; mini- and micro-computers; extendible languages, meta-compilers, subprograms in hardware; microprogrammable computers.

Source: Ref. 3-60



NOTES:

1. THIS CURVE IS DEVELOPED FROM REF. 3-64
2. PERFORMANCE = $\frac{M_x}{t_c + t_{I/O}}$ WHERE,

   M_x IS FUNCTION OF MEMORY CAPACITY AND WORD LENGTH

   t_c IS FUNCTION OF MIX OF OPERATIONS AND OPERATION TIME

   $t_{I/O}$ IS FUNCTION OF INPUT-OUTPUT RATES AND CHARACTERISTICS

Fig. 3-8. Performance of Earth-based computers

(2) Mass Storage. The mass or "bulk" storage media are those used for storing programs as adjuncts to the main random-access memories of processors or for preserving vast amounts of data that are to be retrieved in times on the order of hours, days, or years later. The various types of mass storage systems are the following (Ref. 3-60):

(1) Magnetic-tape storage units.

(2) Rotating devices, fixed and moving head-magnetic drums and disks.

(3) Extended magnetic core.

(4) Electro-optical memories - laser memories, optical memories.

(5) Solid-state memories - charge-coupled devices, magnetic-domain wall motion devices ("bubbles").

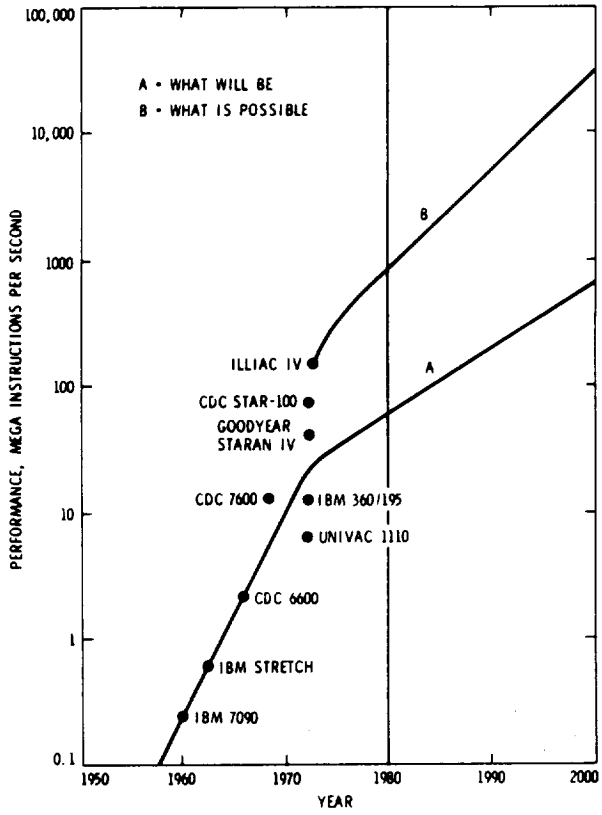
Characteristics of contemporary mass-memories that are operational or under development are given in Table 3-5 (Refs. 3-60 and 3-65).

c. Forecasts. Forecasts of the characteristics of electronic computing hardware for spaceborne and Earth-based systems are presented here for the two major categories of processors (FC 3-60, FC 3-61, FC 3-62, and FC 3-63) and mass-storage media (FC 3-64, FC 3-65, and FC 3-66).

Table 3-5. Characteristics of present mass-memory systems (Refs. 3-60, 3-65)

Storage Device	Capacity, bits	Access Time, sec	Data Rate, M bits/sec	Cost/Bit, cents
Magnetic tape (730 m reel)	4×10^8	72	0.075 - 1.2	5×10^{-5}
Magnetic disk (one drive)	2×10^9	0.06	2 - 12	0.005
Magnetic tape cartridge system (IBM 3850)	4×10^{12}	3 - 8	7	5×10^{-4}
Magnetic drum	$10^7 - 10^8$	0.016	3 - 6	0.1
Extended core	2×10^7	$10^{-5} - 10^{-6}$	0.1	1.5
Laser (read only)	$10^{10} - 10^{12}$	0.15 - 5	4 - 10	$10^{-3} - 10^{-4}$

FC 3-60. Performance of Earth-Based Computers



DISCUSSION

This forecast is derived from Ref. 3-60. For curve A:

$$\text{Performance} = \frac{1}{0.7t_a + 0.3t_m + 2K_m t_{mc}},$$

where t_a = add execution time,

t_m = multiply execution time,

t_{mc} = memory cycle time,

K_m = degree of look-ahead by the control unit,

K_m = 1 indicates no look-ahead,

K_m = 0 indicates totally transparent memory

For curve B, the same equation is used except that a 64-unit array processor system is assumed (as for ILLIAC IV) which increases the performance by a factor of 64.

The Tse computer (Ref. 3-66) is a special-purpose design currently in the early development stages that provides array processing and is projected to achieve three to four orders of magnitude increase in performance over current designs by 1980. The efficiency of this type of architecture depends on the availability of parallelism in algorithms such as is provided in image processing. By the mid-1980s image processing speeds of 10^{12} bits per second may be achieved.

Minicomputers and systems using microprocessors will replace medium- to large-scale systems for some dedicated applications and will also be applied in both local and remote federated computer systems. These systems will provide a rate of increase in total U.S. computing power greater than the factor of 1000 per decade projected in 1966 by W.H. Ware (Ref. 3-67). Clearly, the trend is toward providing individuals with personal computers possessing the power of some present day minicomputers.

Current research and development concerned with implementing software with hardware may yield reduced software development costs through simplified verification and validation of programs, increased computational speed, reduced storage requirements, and simplified programmer/hardware interfaces.

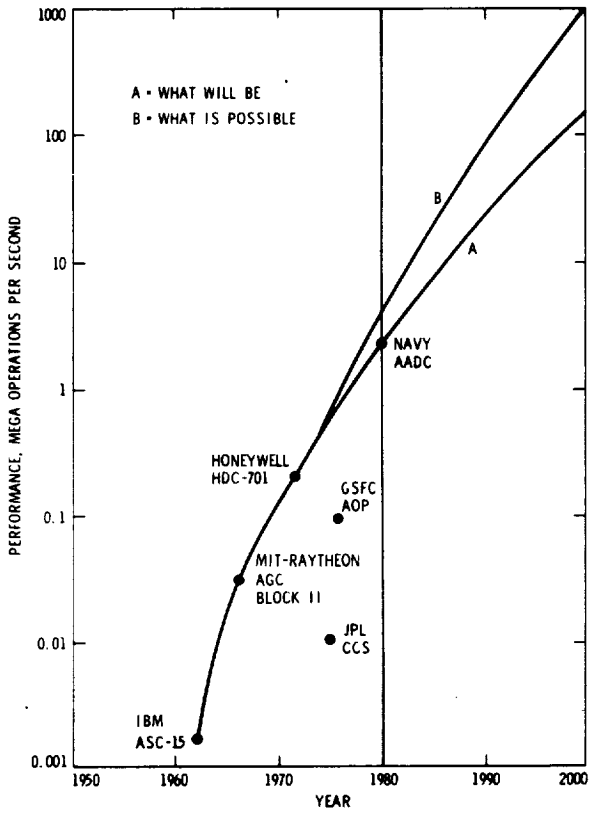
Other research and development efforts on future computer systems, related to achieving higher levels of reliability, are expected to provide the following features (Ref. 3-68):

(1) Automatic program recovery and data protection in case of transient malfunctions (especially external interference).

(2) Self-repair by self-diagnosis and replacement of failed modules in case of permanent failures.

(3) Fail-soft operations ("graceful degradation") after spares have been exhausted, reducing total computing capacity gradually and extending the useful life of the system.

FC 3-61. Performance of Spaceborne Computers



DISCUSSION

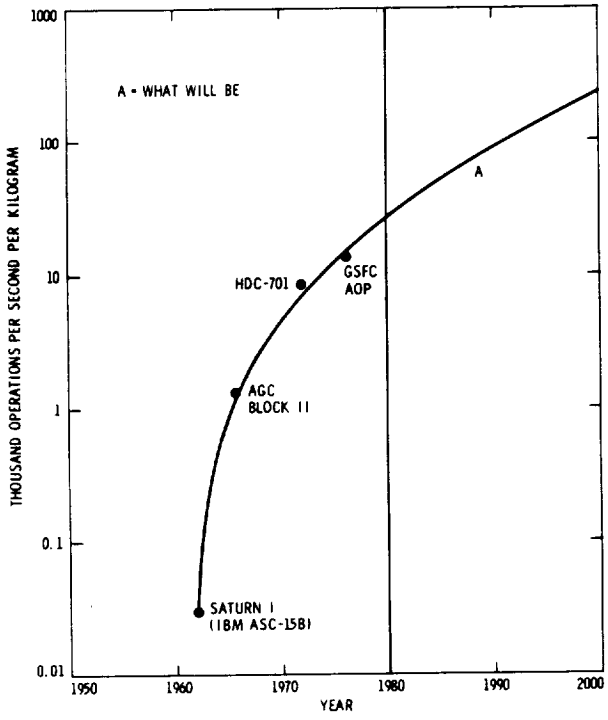
This forecast is derived from Ref. 3-60. The performance or computing speed for spaceborne processors is determined by substituting the appropriate parameters into the equation presented in the discussion for Forecast 3-60.

With the development of space-qualified microprocessors, expected by 1980, the trend will be to decentralize the on-board computing. Individual processors will be used to replace hardwired logic in more and more of the instruments and subsystems. This form of distributed computing is comparable to the current Earth-based federated computer systems in which processors are dedicated to performing largely independent functions but can intercommunicate via data buses (Ref. 3-60). Distributed computer configurations using identical microprocessors will offer increased capability at a lower cost in both hardware and software.

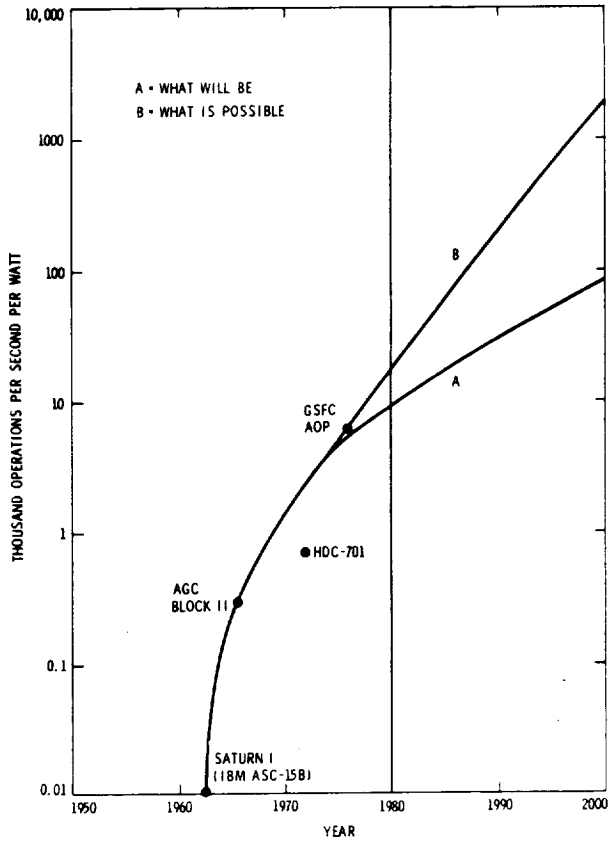
The use of a single, highly complex and expensive computer to perform a large number of computing tasks has been characterized by high costs in software development, verification, and simulation. With a network of identical processors, all performing largely independent functions and operating at less than their full capacity, the software can be developed on an independent function-by-function basis using common software tools at a substantial reduction in effort and complexity.

The distributed computer system also offers an increase in overall system reliability. The loss of a single processor would not cause a complete system failure as it would in a centralized computer system. Simple block redundancy would also be more easily implemented on a selected basis. The application of more complex forms of system architecture to provide higher levels of fault tolerance, as in the JPL STAR computer (Ref. 3-68) is not expected to occur until the late 1990s.

FC 3-62. Performance of Spaceborne Computers per Kilogram



FC 3-63. Performance of Spaceborne Computers per Watt

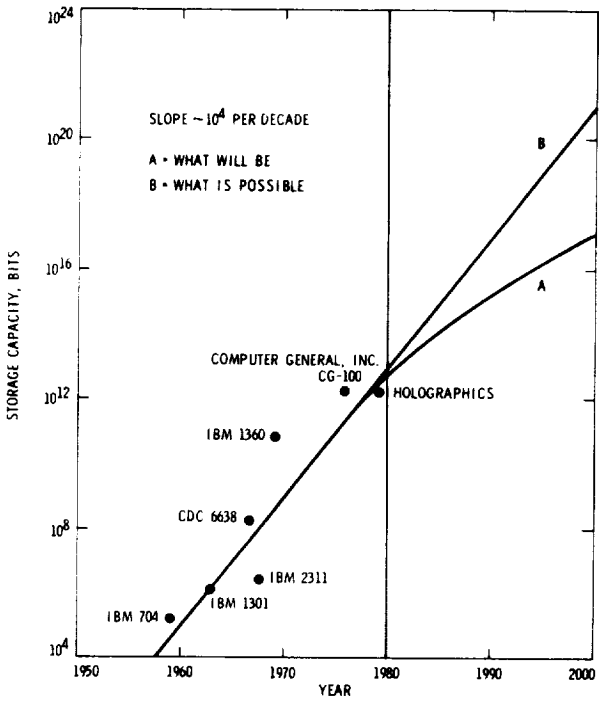


DISCUSSION

A projection of the physical characteristics of spaceborne computers is best presented in terms of the performance per kilogram or per watt. These two forecasts are based on an extrapolation of the following data:

	Performance thousand ops/sec	Weight, kilogram	Power watts
Saturn I (IBM ASC-15B	1	34	150
AGC Block II	30	26	100
HDC-701	200	23	270
GSFC AOP	80	6	14

FC 3-64. Capacity of Earth-Based Mass Storage Systems



DISCUSSION

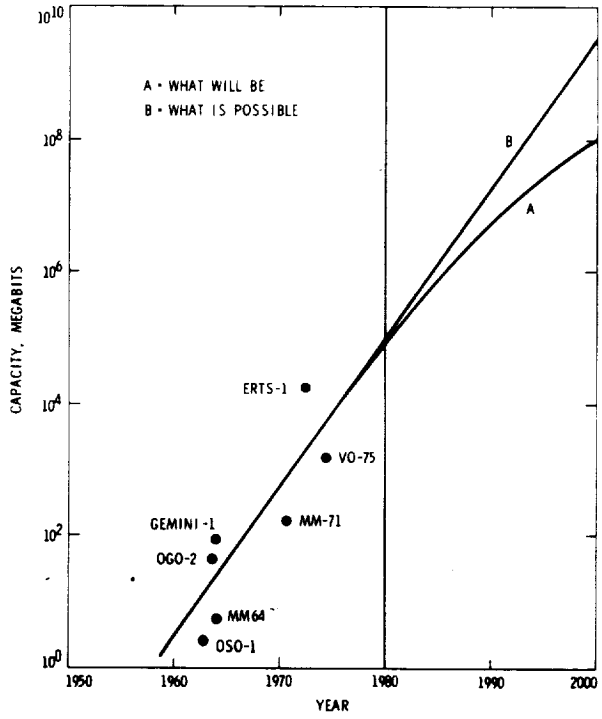
This forecast is adapted from Ref. 3-69. The projected capacity of 10^{21} bits by the year 2000 is considered to be very optimistic in view of the characteristics of mass storage systems which are still in research and development stages. Read/write memories with capacities up to 10^{13} bits using laser-holographic techniques would appear to be practical by 1990. Increases in capacity by several orders of magnitude beyond 10^{14} bits would seem to require significant technological breakthroughs in storage media as well as more sophisticated approaches to the organization of memory and the representation of data and information.

Although tape and disk systems will continue to be used for many archival storage requirements, the memory technologies of magnetic domain walls (bubbles), charged-coupled devices (CCD), and electro-optical techniques will replace tape systems, since the access times of the solid-state memories are several orders of magnitude less than those of rotating device memories. Typical characteristics projected for mass memory systems in the 1990s (Ref. 3-60) are as follows:

Type	Capacity bits	Access Time, μs	Transfer Rate, M bits/sec
Bubble memory	10^9	2	1.5
Read/write laser	$10^{11} - 10^{13}$	0.1 - 10	50
CCDs	10^9	0.5	6

The introduction of these memories is expected to have a significant impact on the architecture of computer systems, especially minicomputer systems in either stand-alone or time-shared configurations (Ref. 3-70).

FC 3-65. Capacity of Spaceborne Mass Storage Systems

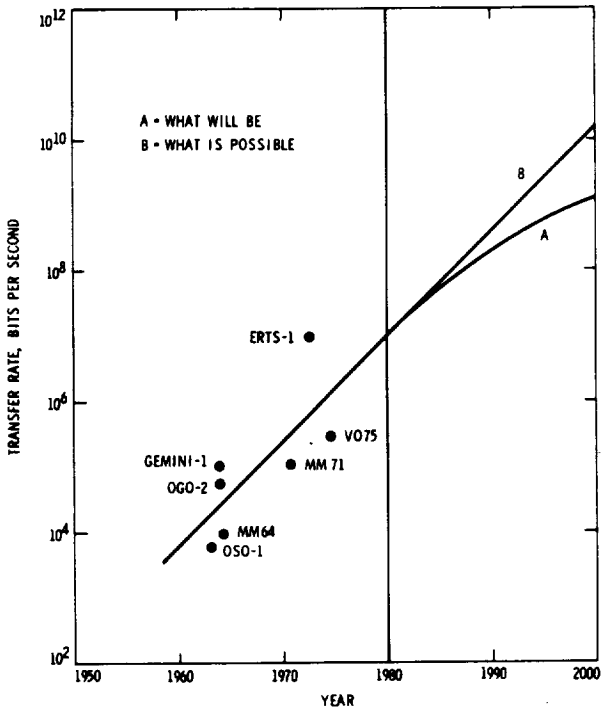


DISCUSSION

Up to the present, magnetic tape systems have been used exclusively for spaceborne mass storage and will probably continue to be used for data storage requirements of 10^9 to 10^{11} bits in the 1980s, but substantial improvements in lifetime and reliability will be necessary for the longer duration missions. Solid-state memories, using magnetic-bubble, CCD, or MNOS technologies, will be available for buffer applications by 1980 but are not expected to compete with magnetic tape systems until about 1990. The bubble memory technology is considered to be the most promising because it offers the advantages of higher bit density, lower power consumption, nonvolatility, nondestructive readout and radiation resistance.

The continued demand to increase mass storage capacity for on-board processing requirements could result in the same growth rate in capacity as experienced in the past, paralleling the growth rate of Earth-based mass storage systems.

FC 3-66. Transfer Rate of Spaceborne Mass Storage Systems



DISCUSSION

This forecast for mass storage is based on the same technology as that discussed in the previous forecast. The transfer rate for the indicated magnetic tape-recorder systems is for a single track; thus for the Viking Orbiter (VO75) tape-recorder system, which has eight tracks, the total data rate could be nearly an order of magnitude greater.

The projected transfer rates should be much more easily achieved than the corresponding storage capacities.

2. Human-Machine Communication (Forecast 3-67)

a. Introduction. This forecast is concerned with how human beings communicate with information systems and employ them to do work. Specifically, a projection is made of the productivity of human beings in preparing—or instructing—machines to do their tasks, and the outlook for easing the problems of human-machine interaction is discussed.

The information system or machine is regarded as a black box which interfaces with human beings in a collaborative way to do work. The major barriers to the effective use of such systems by people can be associated with the interface between them, across which data, instructions, or results of other kinds (for example, process-control actions) must flow. The purpose of this discussion is to characterize the interface problems and to discuss the prospects for their alleviation.

The human-machine interface is essentially a communication interface. Humans communicate data, machine instructions (or programs), requests for processing and information retrieval (either directly or in the context of a question), intermediate results, and all other information required by the computer to complete its task. Computers communicate the results of processing operations (which may include process-control actions as well as data reduction), any information requested, and other messages that they have been programmed or instructed to produce.

The barriers to congenial human-machine communication arise not from the information-transfer process but rather from the translation necessary to accommodate the highly disparate characteristics of receiver and source. Humans are noisy, narrow-band "devices," but their nervous systems have many parallel and simultaneously active channels (Ref. 3-71), and they are accustomed to using several of them simultaneously in communication. For example, they watch facial expressions while listening to words. Relative to humans, computing machines are very fast and very accurate but they are limited to performing only one or a few elementary operations at a time. Humans are flexible, capable of operating contingently on the basis of newly received information. Machines are "single-minded" and highly constrained by their preprogramming. Humans are used to speech for output with concomitant hand motions for text generation (printing, writing, typing, etc.) and facial and body expression. They speak redundant languages organized around unitary objects and coherent actions and employing 20 to 60 elementary symbols. Machines can accept multiple simultaneous inputs but recognition is as yet difficult and primitive for all but a few input modes. The languages that they employ are nonredundant, based in the final analysis on only two elementary symbols, and their structure is simple and formal. Machines can generate text and speech much faster than can be assimilated by humans, although this mismatch reflects primarily the traditional text output of machines; information "encoded" in forms other than printed text — for example, displays — can be assimilated much more rapidly by humans. In general, the communication interface between humans and machines can be characterized by the degree of adaptation and effort required of the human to effect a good symbiosis (Ref. 3-72). Table 3-6 (Ref. 3-73) presents some of the data rates characteristic of human communication modes. Table 3-7 summarizes the rate at which people can assimilate information.

Table 3-6. Representative human data rates (Ref. 3-73)

Communication Mode	Data Rate, words/sec	Remarks
Oral reading		
Random words	3.0 - 3.8	Selected from 2500 most familiar monosyllable words
Random words	2.1 - 2.8	Selected from 5000-word dictionary
Spontaneous speaking	2.0 - 3.6	
Handwriting	0.3 - 0.4	
Handprinting	0.2 - 0.5	
Typing	1.6 - 2.5	Skilled
Typing	0.2 - 0.4	Inexperienced
Stenotype	3.3 - 5	Chord typewriter
Touch-tone telephone	1.2 - 1.5	
Thumb-wheel	1.8 digits/second	Sequence of 10 digits
Rotary dialing	1.5 digits/second	Sequence of 10 digits

Table 3-7. Representative human information assimilation rates

VISUAL
30 to 40 characters/second for test assimilation. Several million bits/second for pictorial data.
AURAL
2 to 4 words/second with tens to hundreds of tonal pitches distinguishable.
MANUAL
Several digital bits/second. Parallel sensing of pressure, temperature, motion, texture.

It will be helpful to distinguish between unidirectional and interactive human-machine communication, with the understanding that in general an interactive exchange is a sequence of unidirectional ones.

In unidirectional communication, the information recipient plays a passive role. Nothing the recipient does or says affects the communicator, the communication process, or the message content. Off-line software generation, or the design and coding of computer programs before they are run on the machine, is offered as an example of unidirectional communication from human to machine.

Interactive communication is two-way. Each party provides feedback to the other, usually indicating whether or not the last message of the other was understood and supplying results or progress indications for any action requested. Speed of response is an important element in such an interaction. Responses by the machine to the human must be made promptly enough that everything related to the dialog remains fresh in mind. The machine responses must also be given in such a form and at such a rate that a human can assimilate them. Interactive communication is necessary for the execution or use of many computer programs, and in the development of computer programs using interpretive compilers.

Communication between humans and computers can be characterized by such factors as the size of the vocabulary used, the syntax of the language and the semantic variations allowed, modes of transmittal, and the actions available to the receptor.

Presently, most computer programming involves highly restricted vocabularies with simple syntax and virtually no semantic content. The principal modes of human-computer communication are via manual, visual, and audio channels. The manual channel includes all mechanically operated input devices. The visual channel consists of printouts, displays, and signals for visual sensing by man and electro-optical sensing by computers. The audio channels are the computer equipment and systems for recognizing spoken utterances as well as the equipment for producing spoken output. Table 3-8 (Ref. 3-74) summarizes this spectrum of communication modes and briefly assesses their availability. From this table it is apparent that, at present, the dominant mode of human-to-machine transmittal is mechanical while from machines to humans it is visual. Presently, most machines are highly restricted in the types of action or response available to them.

The choice of human-machine communication mode and the level of sophistication provided in the implementation depend on numerous operational, human, and economic factors as well as on the availability of the technology. Among these factors are the ease of use of the channel in the context of the human computer task, the nature of the transmittal language, the ability to maintain desired information transmission rates — in particular with regard to constraints inherent in the receiver of the information — and the effects of the operational environment. The processing and storage requirements of the communication channel and its cost-benefit advantages, or disadvantages, with respect to those of competing channels, are important factors. An ideal configuration for human-machine communication is easy and natural for the human to use; that is, it matches his intellectual and sensory abilities to acquire and assimilate knowledge, is compatible with the total system, provides operational advantages, and is cost-effective. Many of the research systems that provide larger vocabularies or sophisticated language facilities are not yet suitable for widespread use because they do not meet criteria of convenience, general compatibility, and cost.

b. Unidirectional Human-Machine Communication. Within this category the production of computer programs is considered. Programming implies the need for an expert who stands as an intermediary between the ultimate user and the computer, someone who is familiar with the way the computer works and with the special languages needed to address it. The amount of effort (or time) that a programmer must spend to instruct a machine to perform a given task affects the rate of information flow across the human-machine interface as well as its cost.

From the time of the first stored program machine, the cost of producing computer software has spiraled. The increasing expenditures can be largely attributed to the growing use of automatic data processing, which imposes ever-increasing demand for software generation, and to the increase in human labor costs. Given that information-system hardware costs have been plunging dramatically, it is easy to understand the projection that software expenditures may rise to 90 percent of automatic-data-system development costs by 1985 (Ref. 3-75). Increases in programmer productivity are thus essential to a reduction in software costs.

For the purposes of forecasting, it would be desirable to find a parameter that reflects the amount of machine work that is produced as a result of human efforts to program it. As technology advances soften the interface between humans and machines, this parameter should increase.

Unfortunately, forecasting human-machine technology is somewhat different from predicting hardware technology. While many appropriate measures exist for gauging hardware performance — cost per bit, add time, transfer rate, byte capacity, etc. — we do not have similarly agreed upon comprehensive and meaningful metrics for human-machine technology. Attributes of human-machine communication have not, in general, been quantitatively expressed.

In principle, one could equate machine work to the resulting displacement of human labor. To determine this quantity, however, would be difficult. Without historical data, it is virtually impossible to state how much work, expressed, say, in man-years, the use of a given program made unnecessary. Furthermore, there are many tasks that would not be attempted at all without the use of a computer.

The results to be presented here are based largely upon those of an Air Force forecast

Table 3-8. Interactive communications modes: human to machine (Ref. 3-74)

Input Mode	Availability
Keyboard	Numerous variations, insufficient standardization.
Pointing	Lightpen, data tablet, trackball, mouse and hardware cursor all readily available.
Hand editing	Requires moderate resolution tablet, easily programmed.
Handwriting	High resolution tablet; good software is currently beyond state-of-the-art; should probably use software approach of speech-understanding research.
Limited voice	About 50-100 isolated words or phrases are state-of-the-art; commercially available with about 95% accuracy.
Continuous speech	Under development in ARPA-sponsored projects; expected to be available in limited task domains in about 3 years.
Physiological signals	Eye motion, muscle contraction, alpha waves, pulse, etc. at research stage.
Pictorial data	Presently requires line scanning devices; picture interpretation still quite limited except for very narrow task domains.
Optical character recognition	Several commercially-available high-speed devices, with limited type fonts and handprinted characters.
Low-density text	Numerous commercially-available hard- and soft-copy terminals; 25 lines typical. Ann Arbor displays 40 lines of 80 characters; typical full-graphics terminal displays 50-55 lines of 70-80 characters.
High-density text	Tektronix 4014 can display 64 lines of 133 characters - equivalent to one computer printout page.
Multi-font text	Full-graphic terminals allow programmable character generator; TV-based terminals convenient for bold-faced type.
Low-resolution graphics	Low-resolution (256 x 256 to 512 x 512) TV-based terminals; plasma panel.
High-resolution graphics	Requires high resolution (1024 x 1024) TV or refreshed or storage directed-beam CRT; many available.
High-speed graphics	IMLAC and GT40, IDIIOM, Vector General, Evans-Sutherland.
Color graphics	Data disc; RAMTEK.
TV images	Data disc; RAMTEK; other TV-based systems.
Immediate hardcopy	Tektronix in 18 sec; plasma panel hardcopy being developed; graphics printer + software in about 1 minute.
Overnight hardcopy	Commercially-available devices produce publication quality.
Voice	Several commercially-available devices.
Physiological	Research underway in biofeedback and "vision" devices for the blind.
Half-tone graphics	Evans-Sutherland "Watkins box" for surface shading; GE/NASA system.
Feel	"Feelie box" investigated by A.M. Noll (Ph.D. thesis); also under development by Kent Wilson at U.C. San Diego.

(Refs. 3-75, 3-76). It is assumed that machine work can be measured by the number of machine instructions in a job. While this assumption is surely not strictly true, it may have some validity on the average. The following definition is adopted:

$$P = \frac{NI}{MN}$$

where

P = programmer productivity,

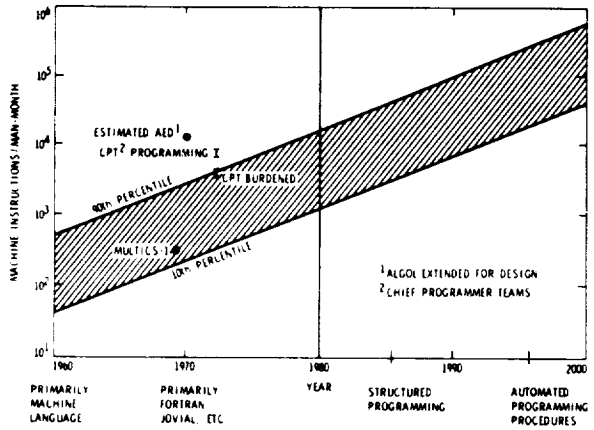
NI = the number of checked-out, delivered machine instructions,

MN = the total number of man-months of effort required to produce the software.

Software production is taken to include system and program design, program coding, debugging, testing, integration, and the preparation of all the associated documentation that the user needs to execute the programs, support his decision-making, and solve problems. Maintenance is not included here, although it is a major element in the cost of software during its useful life.

c. Forecast. The advantage of the parameter defined above is that it is one measure for which historical data can be found. Forecast 3-67 is a plot of programmer productivity as a function of time to the end of the century. The band reflects a factor of 10 spread between the tenth and the ninetieth percentiles of software productivity. Significant technological tools that have influenced or are expected to influence the software trend are shown along the abscissa to coordinate them chronologically with the curve.

FC 3-67. Programmer Productivity



DISCUSSION

The large variance exhibited in FC 3-67 above is a reflection of a number of factors:

(1) Project Size: Small projects generally yield higher programmer productivity than large ones.

(2) The Nature of the Programming Task: Some programs are by their nature easier to develop than others.

(3) Programmer Proficiency: Even for the same task, differences among individual programmers can be large.

(4) Hardware Constraints: Requirements for minimal run time and memory restrictions usually reflect themselves in decreased productivity.

(5) Software Constraints: Requirements for reliability, adaptability, and transferability usually reflect themselves in decreased productivity.

The productivity of programmers using assembly language has not increased over the years. On the other hand, higher order languages (HOL), procedure-oriented languages (POL), macro-assembly languages, more sophisticated supervisor facilities, and subroutine libraries have allowed most programmers to produce programs more easily to perform a given task (Ref. 3-77). For a medium-sized project employing these tools, the current average productivity is estimated to be about 900 checked-out machine instructions per man-month.

Until recently, the emphasis in software production has been to write programs that had high core efficiency and minimum run time. The result, when considered in the context of a complex processing problem, has been cryptic systems of code, difficult and expensive to test, debug, maintain, and modify. It is these activities, however, that consume by far the most programmer time, and consequently account for the most expense as hardware costs go down and labor costs go up.

Today there is a changing emphasis in software design that is increasing programmer productivity. In the approach that has come to be known as "structured programming," the goal is to produce programs that, despite their large size, are so well organized that they can be easily understood, analyzed, and modified; the new emphasis, in other words, is on improving human-machine communication.

In the past, problem solutions have been resolved into an intermediate language by the software designer and then automatically compiled into machine language. Now, what is sought is better methods of representing solutions. In structured programming, "solution structures" are designed that consist of relatively independent modules, each designed to realize a single function or operation, and simple enough to be exhaustively tested. Modules are linked according to a set of explicit rules and constraints. They are organized functionally in a hierarchical fashion and developed and checked out from the top down. In this manner, interfaces are defined before they are used. High-level modules are exercised from the start, and programming proceeds by the stepwise addition of new modules to an already checked-out system. Sets of rules to enhance program readability reduce stylistic variations among programs produced by different individuals and improve the ability of other programmers to understand and change the code.

Structured programming practice is spreading rapidly, and numerous tools have been developed for adapting present languages to it. Many difficult problems remain, such as the proper organization of data, the building of well-ordered and efficient program hierarchies, the design of powerful specification languages, and proof of the correctness of large hierarchical systems. Also accompanying the introduction of structured programming methods is an increased emphasis on software management practices that will increase efficiency and decrease the cost of large programming efforts. Notable among these is the "chief-programmer team" concept applied at IBM.

FC 3-67 Continued

Software production is a complex activity consisting of many individual and interlinked steps. Its cost is directly related to the amount of human effort required to carry them out. No single breakthrough is foreseen over the next ten to fifteen years that will suddenly decrease the cost of the entire process; rather, it is expected that there will be a series of gradual improvements.

Structured programming has yet to have its maximum impact. It is expected that this technique and others related to it will not become standard practice for another ten years.

As structured design procedures mature, they will be accompanied by the introduction of distributed computer architectures based upon the availability of low-cost microprocessors. Large-scale computer systems will be standardized from manufacturer to manufacturer with a concomitant standardization of (and less demand for) operating systems and the more common procedure-oriented languages (FORTRAN, PL/1, APL, etc.). Dialects for these POL's will be developed to accommodate structured programming techniques and to help with testing and with event synchronization problems.

Automatic aids for software development are presently in their infancy. As they are developed, they will enable the machine to take over some of the functions presently performed by humans. We expect continued progress in the development of macrocompilers, automatic checkout, debugging, and maintenance procedures. The steady maturization of such aids will continue to force programmer productivity up after the full impact of structured programming has been felt.

It is believed that the application of the results of artificial intelligence research will not begin to have a truly significant effect on software production until well after the decade of the 1980s (see subsections 8, Natural-Language Understanding, and 9, Problem-Solving Systems). The automation – and psychological understanding – of human use of language, problem-solving, decision-making, value judgments, and a variety of intellectual functions are faced with problems of great depth, difficulty, and complexity, and it is believed unlikely that such processes will be understood in any general way before the end of this century.

All things taken together, it is believed that there will be a reduction in software costs, measured into today's terms, by approximately one order of magnitude between now and 1990, perhaps another order of magnitude by the end of the century. It can be expected, however, that the use of computers will grow correspondingly, so that the total software expenditure will continue to increase.

d. Interactive Human-Machine Communication. Much human-to-human communication involves people working together to solve a common problem or to reach a common goal, each person providing something that the others cannot, and all dependent on each other for a successful conclusion of the effort. As machine technology improves in time, it can be imagined that human-machine communication will take on more of the characteristics of the human-to-human example. An objective toward which much present research is directed is the design and construction of conversational computer systems — ones that can interact with people in such similiar and human-like ways that they exhibit no or few machine-peculiar characteristics that inhibit their use. This prospect invokes the ultimate possibility of humans communicating problems to machines in their natural language and the computers devising solutions and communicating them in modes matched to human capabilities. The importance of this development can be highlighted by pointing to a trend in human-machine communication that is likely to continue to the end of this century. The development of distributed computation, of intelligent terminals, and of networks that tie these facilities together will present human beings with access to a wide variety of different computer facilities whose languages and conventions will be unknown to them. The only practical way in which the use of these facilities can be made widespread is to adapt machines to the conventions of natural human languages.

The limitations of present languages used in human-machine interactions are described in subsection 8. In time, the size of the vocabulary used by machines will grow, and the syntax and semantic content will become sufficiently complex that the computers will no longer perform mundane branching and indexing operations to select a course of action, but rather will rely on operations that simulate human cognition and perception. The human-machine problem will then fall into the domain of artificial intelligence. Text recognition, speech recognition, and image analysis and interpretation are examples of human-to-machine communication modes that are presently limited by the state of artificial intelligence technology. This statement refers not only to ease of human communication with a machine (that is, speech vs. keyboard), but also the responses available to the machine (sophistication of analysis). Human-to-machine communication is limited by the cognitive and perceptive powers of machines; these will advance in time. The machine-to-human channel is limited in the reverse sense: machines are capable of providing data at a rate that exceeds the human assimilation rate, which is fixed in time. Data, however, are not necessarily information. Needless to say, eventual advances in artificial intelligence will allow machines to perform more perceptive data analysis and control. Thus, while machine-to-human data rates will not increase, the information content of the data will increase and the mode of transmittal will be better matched to the human powers of assimilation. In the same context, machines will gradually be given the capability to display analytical results in such a form that their significance can be more readily perceived by the user.

Characterization of the human-machine interface for interactive communication must take into account such factors as the nature of the tasks to be performed; the human roles, capabilities, and shortcomings in performing these tasks as well as those of the machines; the task-performance environment; and the capabilities of the interface equipment. To find a parameter that gauges the cognitive and sensory mismatches between humans and machines, and enables the softening of this interface with the passage of time to be forecast, does not seem possible at this time.

Exactly how problems of human-machine interactive communication will be alleviated is not clear. It is believed that one important avenue to a solution is through giving computers an ability to understand human inputs expressed in natural language — either written or spoken — and to use such language to communicate results. Another is to enable computers to derive relationships among items or categories of information in a data base that were not foreseen or provided for when the data base was constructed. The methods reviewed in subsection 9, Problem-Solving Systems, represent part of the capability that will be needed to operate on data, information, or knowledge stored in the computer. It is clear from the language and problem-solving forecasts that, while some progress can be expected toward the interactive capability described above by the end of the century, its full attainment will await a later time.

What is the likelihood that computers will be able to understand human speech? Isolated-word speech-recognition systems are already on the market. Typically they can be trained to recognize utterances employing small vocabularies and highly restrictive syntax. The pause between words must be greater than 0.2 second (Ref. 3-73).

The implementation of continuous-speech recognition systems is much more difficult. One of the problems is the absence of word-boundary indications in the acoustic signal representing a word on the predecessor and successor words. Table 3-9 (Ref. 3-73) shows the recognition accuracy that has been achieved by various experimental and prototype speech recognition systems to date. As stated in the forecast at the end of subsection 8, speech recognition systems should have recognition vocabularies of several thousand words spoken by a variety of human voices by the end of this century.

3. Data Compression (Forecast 3-68)

a. Introduction. This forecast treats the spaceborne information-system elements which collect, process, and encode measurement information for transmission to Earth. It is assumed that economics is the main factor which will shape their evolution. Many interesting and technically feasible missions and system designs will be foregone because they do not compare favorably with alternatives in a cost-benefit assessment. Thus, future information systems will be designed to maximize the value of the acquired information

Table 3-9. Speech interface performance (Ref. 3-73)

Researcher	Capability		
	Vocabulary	Speakers	Correct Recognition Percentage
Vicens (1969)	54 isolated	1	98-100
	54 isolated	10	79
	560 isolated	1	91
Yilmaz (1971)	16 isolated	10	99
Hill (1969)	16 isolated	12 unknown	78
Medress (1972)	100 isolated	5	94
Glenn (1971)	10 isolated digits	Many	>99
Doddington (1973)	10 continuous digits	Many	>99
Tappert & Dixon (1971)	250 continuous	Several	75

within severe mission-cost constraints. It is also assumed that image data in various spectral bands (including those used for radar imaging) will place the greatest demands on the information system. Consequently, multispectral image data (similar to that collected by ERTS) are emphasized in the following material. However, the concepts discussed would also be useful for other types of information sources.

The two preceding forecasts in this section relate to the hardware characteristics of spaceborne computers and the human-machine interface. The forecast of subsection 7 deals with the history and expected growth of methods for automating picture processing and interpretation. This subsection, therefore, concentrates on the expected impact of such methods on space measurement-data handling and their incorporation in space-related information systems.

b. Present Status. The approach to in-space collection and encoding of data has not changed substantially over the past decade. Data have been collected according to a prescribed instruction sequence, and then transmitted as a structured sequence of digital words representing samples taken from one or more information-bearing signals.

Often the instrument-sequencing and data-formatting operations have been controlled by fixed-wired special-purpose logic. Such systems have not had the flexibility to adapt to new requirements; consequently, new missions have usually required extensive hardware design changes in the spaceborne data-system elements. Recent designs employ programmable sequence control and therefore exhibit greater flexibility.

The encoding of data has continued to be quite primitive over the past decade. Efficient source-encoding (data-compression) methods have seldom been used. In general, the trend has been to increase the transmission-channel capacity rather than to increase the efficiency of channel utilization. The main reason for this approach was that there were straightforward and economical ways to increase the channel capacity whereas the existing data compression systems did not exhibit good enough performance to justify their cost during that period.

During the past decade, transmitted data rates have increased by approximately a factor of 100. (For example, see FC 3-1). Because of this, the cost of data records and data interpretation has become a major item in space project budgets.

The usual approach to on-Earth data management has been to store all received data in some form of archive and to distribute appropriate subsets of these data to each of the numerous investigators. Data interpretation has usually been performed in non-real-time with major reliance on human judgment and participation, although computer processing of received data has often been used to facilitate interpretation.

More recently, there has been interest in using digital computer processing (on Earth) partially to automate the data interpretation process. As part of the ERTS program, computers have been used to implement pattern recognition (classification) algorithms to derive thematic maps from multispectral image data. These maps efficiently present desired information regarding the size and distribution of agricultural crop acreage, regional water supplies, etc. It appears that an extension of this approach will facilitate the timely and economical compilation of results during future missions.

Current research activities are leading to the development of improved data compression and feature extraction algorithms for application in-space. Concurrent advances in channel coding technology have overcome the need to sacrifice data transmission rate to meet the more stringent accuracy requirements of compressed data. Also, there are parallel research activities leading to the development of high-performance, low-cost computers for spaceborne systems (subsection 1, Hardware Characteristics). One of the keys to this activity is the emergence of large-scale-integrated-circuits (and microcomputers) as a viable technology. These developments have stimulated research on architectures for spaceborne data systems which employ a large array of interconnected microcomputers. Also, new forms of data processing hardware are being developed which have the potential to revolutionize in-space data processing. For example, a parallel optical data processor is being developed at GSFC (Ref. 3-66), and a unique imaging radar signal processor using charged-coupled devices is being developed at JPL (Ref. 3-78). Thus, the stage appears to be set for a great increase in the amount of on-board processing of measurement data.

c. Forecast. The character of future Earth-orbit and deep-space missions will undergo marked changes for a variety of reasons. There will be increased emphasis on practical space applications as opposed to experimental and

exploration projects. More attention will be given to cost-benefit considerations in system-design. There will be an enormous increase in the amount of information to be collected, processed, and disseminated by space projects.

The main challenge to designers of future space information systems will be to provide timely and economical production and dissemination of space investigation results as the amount of acquired data undergoes explosive growth. To do these things will require a dramatic increase in the degree of automation of the processes of data acquisition and data interpretation.

Initially, the major part of the data acquisition and processing automation will be implemented on Earth. Ultimately, however, compelling technical and economic considerations will result in substantial on-board automation. The cost of spaceborne data-processing hardware will decrease markedly in future years. On-board processing will enable a high degree of data compression to be accomplished, and also will facilitate quick reaction to discovery of targets of opportunity.

The first missions to employ highly automated data acquisition and data interpretation are likely to be Earth-observation missions for which the data interpretation process can be well defined and will remain stable over a long series of observations. Automation of processes associated with more dynamic missions will be much more difficult. These missions will require more extensive human participation in the data collection and interpretation process until further technology advances occur.

By 1980, image data compression will become economically attractive for many space missions. The degree of data compression which is attained in a specific application is a function of many factors including the following:

(1) The fidelity criteria which apply to the delivered data.

(2) The degree of predictability of the source data.

(3) The constraints placed upon the design including those pertaining to physical characteristics, schedule, risk, etc.

An explicit set of illustrative applications is hereafter defined to enable a technology forecast to be presented in quantitative terms. The ERTS type of multispectral data (a total of 24 bits per pixel, 6 bits for each of four spectral bands) is assumed as the data source in all of these illustrative applications. The following fidelity criteria distinguish four different classes of applications:

(a) Those requiring nearly exact reconstruction of the original source data.

(b) Those requiring an approximate reconstruction of the original source data, such that there is very little perceptible difference between a photograph produced from the compressed data and one produced from the original data.

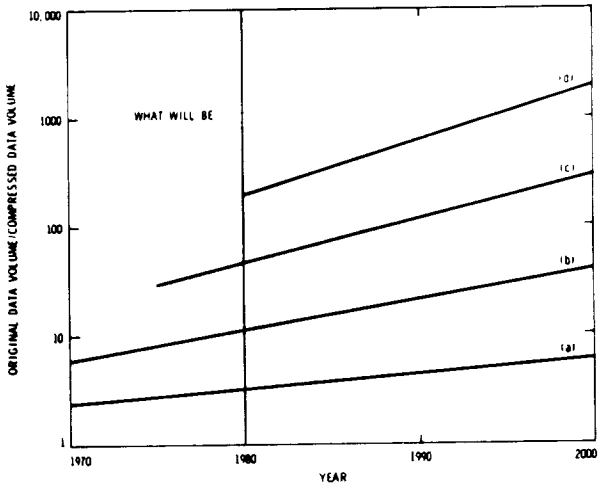
(c) Those requiring production of a high resolution thematic map which describes the spatial distribution of a small number of source "classes" which are recognizable from the spectral properties of original data samples.

(d) Those requiring determination of the location and key parameters of prescribed features which occur infrequently within a survey area.

Forecast 3-68 presents estimates of expected growth rates in the degree of data compression for each of the four previously defined classes. Caution should be exercised in using this forecast not only because it is subject to the inherent uncertainties of the future, but also because of the sensitivity of the compression ratio to the exact details of an application.

The same type of on-board pattern recognition capability which yields high degrees of data compression can also be used to accomplish important advances in automatic adaptive control of the data acquisition process. For example, Earth-based supervisors can specify criteria which govern adaptive behavior of the space system. If the space system should then discover an important feature (target of opportunity) during a routine global survey, it could automatically preempt the survey activity to conduct an intensive examination of the important feature. Simple forms of such behavior are now possible. During future years the adaptive control processes will become increasingly sophisticated. By the end of this century, the sophistication will be sufficient to regard the spaceborne data system as possessing artificial intelligence.

FC 3-68. Data Compression Ratio



DISCUSSION

The curves relate to four different classes of applications distinguished by the following fidelity criteria:

(a) Those requiring nearly exact reconstruction of the original source data.

(b) Those requiring an approximate reconstruction of the original source data, such that there is very little perceptible difference between a photograph produced from the compressed data and one produced from the original data.

(c) Those requiring production of a high-resolution thematic map which describes the spatial distribution of a small number of source "classes" which are recognizable from the spectral properties of original data samples.

(d) Those requiring determination of the location and key parameters of prescribed features which occur infrequently within a survey area.

All four curves represent "what will be." No "what is possible" projection is made.

Refer to the text for further discussion.

d. System Implications. The cost of timely data interpretation is emerging as the most important factor limiting the amount of valuable information which can be obtained from future space missions. It appears that this factor will force development of technology to automate much of the data acquisition and data interpretation process. There are substantial reasons to believe that much of this automation will be implemented in the spaceborne system.

The required automation of the data acquisition and interpretation process will require substantial advances in information science and artificial intelligence. It implies revolutionary changes in the spaceborne and Earth-based data system elements. It also has enormous implications regarding the design of future telecommunication systems. If the capabilities forecast in this section are realized, on-board data compression will provide an economically attractive alternative to transmission of unprocessed data at extremely high rates.

4. Teleoperators (Forecasts 3-69 to 3-72)

a. Introduction and Background. A large class of projected space missions will require physical interaction with objects and environments far removed from the sphere of normal human activities. The work to be done can be as varied as controlling the manipulator of the Space Shuttle from the cockpit, removing a bolt to replace an instrument on an Earth-orbiting satellite, assembling a large space antenna, or picking up a rock sample on the surface of Mars or a Jovian satellite and performing an experiment with it.

Modern technology has made possible two ways of conducting such missions: it can provide transportation to carry people to the work site and give them the necessary life support while they carry out the tasks directly; or it can provide machines to be operated remotely by people from less hazardous surroundings. Both of these methods have been employed in past space exploration and both have their proper roles in future programs. This group of forecasts deals with machines of the latter type — called "teleoperators" or "remotely manned systems (RMS)" — that enable human capabilities to be exercised across physical barriers.

Teleoperators can be defined (Refs. 3-79 to 3-83) as dexterous, cybernetic, human-machine systems that enable the manipulative, sensory, locomotive, and cognitive capabilities of people to be exercised safely and effectively in remote environments. The machines do not replace human faculties, but rather allow them to be enhanced and extended. The human being possesses the ultimate control authority; he decides what must be done and how the necessary functions are to be performed. Automation at the remote site is provided to facilitate human control decisions; hence the alternative name for teleoperators — "remotely manned systems."

Teleoperators are integrated systems containing a variety of major functional components: mechanical devices such as manipulators (or "arms"); end effectors (or "hands"); mobility units; sensors that measure position, rate, touch, force, or proximity; television units; control terminals with various display and command input capabilities; data-processing units at both the remote site and at the control station; communication channels between the remote equipment and the control terminals; and power units. There is no specific technical discipline which deals with teleoperators. Their development is a task involving many disciplines, including human factors engineering, but some of the central problems of teleoperator design can be formulated within the context of information and control theory.

Teleoperators represent a relatively new systems technology. Historically, they arose 20 to 25 years ago out of a need to manipulate radioactive materials from a safe remote location. More recently, undersea, industrial, biomedical, and space applications have provided additional stimulus for their development. Most existing teleoperators have been built on an "ad hoc" experimental basis. Because of the limited experience with such systems, there is no organized body of knowledge on teleoperator technology. The last few years, however, have witnessed the start of a more systematic development effort in which NASA has played a leading role largely because of the increasing volume of prospective space applications.

The primary reasons for the development and use of teleoperators are to reduce the hazards or the inconveniences faced by human beings in the performance of certain tasks, to make otherwise difficult operations feasible, or to lower their cost. Some external differences between teleoperators derive from the characteristics of the application environments and of the tasks to be performed. Irrespective of such differences, however, the design of a teleoperator must address the same two basic technical challenges, both related to information and control problems in the operation of remote dexterous machines: (1) to generate, process, and use the sensory information necessary to give the remote equipment some "awareness" of the task environment and to aid the operator in overcoming a "sense of remoteness" at the control station and (2) to provide an overall control system with appropriate command and feedback capabilities, operational procedures, and performance criteria so that control decisions can be conveniently, safely, and effectively allocated between the operator and the remote equipment.

An important factor in space applications of teleoperators is the communication time delay between the control station and the remote machine, which can vary from a fraction of a second (e.g., for the repair of Earth-orbiting satellites using ground-based control) to several thousand seconds (e.g., for surface exploration of Mars or a Jovian satellite with a mobile laboratory controlled from Earth). The anticipation of missions with long time delays strongly motivates the development and use of advanced techniques of automation of sensory and motor functions to render the space application of teleoperators more efficient (see subsection 5, Robots). While the details of implementation may vary depending upon whether the expected time delay is short or long, teleoperators for space or for Earth applications present similar technical problems to

their designers, and most advances in either arena are transferrable to the other (see, for example, Ref. 3-84).

b. Approach and Measures. Teleoperators represent a special category of information-management systems. All information functions — acquiring, transferring, processing, and storing — must be properly combined and coordinated to perform the remote task efficiently and economically. To forecast the performance of such systems, it would be desirable to find some figure of merit or quality factor, a "coordinated information and control capacity," that could be assigned to past and existing systems and projected into the future. Such a measure should reflect such considerations as the following:

(1) The task complexity, as measured, for example, by the number of discrete actions required or the number of decision points encountered.

(2) Continuity in action toward task completion, as measured by the number of interruptions for situation assessments or for changes in control decisions.

(3) The time to complete a task.

(4) The level of human involvement in the information/control loops in task performance.

Ideally, as system performance increases, human involvement in the information/control loops will be more on the level of a "supervisory" action (see Ref. 3-85), monitoring performance progress and making comprehensive control decisions. Of course, such supervisory control requires increased automation of teleoperator functions.

Unfortunately, a unified, quantitative measure for teleoperators does not exist, and it has not been found possible in this study to construct one. Because each teleoperator is a system designed to meet a given set of requirements with unique constraints, it will be a difficult task to assign general performance parameters to them that realistically reflect all the subtleties and complexities of such complex actions as manipulation or locomotion. Comprehensive measures for system performance usually are found only after a large volume of experience has been accumulated with many different systems of the same kind. The number of teleoperators and the experience that has been gained with them are presently very limited. The experimental foundation seems insufficient to define a unified system measure that would be useful or meaningful here. Consequently, in this forecast, the approach has been to find indicators of growth in applications for, and experience with, teleoperator systems, on the assumption that their capabilities at this early stage will be directly correlated with amount of effort spent on their development and use.

Four general growth variables are considered: plans, experience, components, and total systems. Each is defined below. No exactness is claimed for the definitions and quantitative figures. In interpreting the forecasts, more weight should be given the "trends" and "rates" than the exact numbers; nevertheless, the numbers themselves are based on a great variety of data contained in the references and in other works cited therein. Growth during the last ten years (1965-1975) has been studied and used in making the projections.

c. Forecasts. In general, analysis of the available data from the last 10 years, averaged over 3 to 4 year intervals, reveals a very nearly exponential growth in teleoperator technology. The forecast diagrams (FC 3-69 through FC 3-72) for the coming 25 years are extrapolations of the exponential growth experience during the last ten. It seems natural to assume that such growth rates will persist for some time to come for a newly-born technology which is favored by so many aspects of our technological civilization. As in space, there is a need on Earth for machines that can expand human activities beyond physical barriers and contribute to the growth of industrial productivity by humanizing the machines rather than mechanizing the humans. Of course, exponential growth cannot last forever; saturation will eventually occur, but it would be very hard to specify now why teleoperator technology should reach a saturated state during the coming 25 years instead of continuing with a nearly exponential growth.

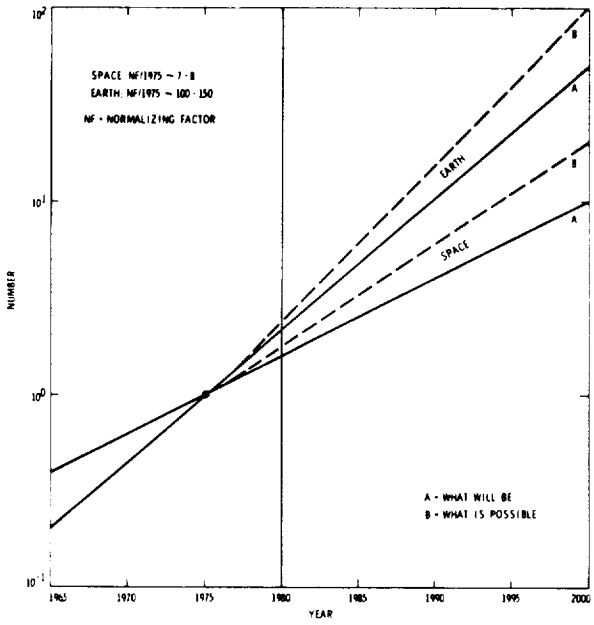
(1) Plans. This variable represents the indicated and well-established need for teleoperators, normalized to the status in different application areas in 1975, as determined from the number of program plans, requests for proposals, and development or study contracts. Numerical data on the present status can be found in the state-of-the-art survey literature (see e.g, Refs. 3-86 to 3-90).

(2) Experience. This variable estimates the experience gained in the development, use, and performance evaluation of teleoperators, measured in man-years and normalized to the status as of 1975. Again, numerical data on the present status can be found, e.g., in Refs. 3-86 to 3-90.

(3) Components. This is the most comprehensive variable and the most difficult to project. It includes such diversified items as special sensors (displacement, orientation, range, touch, force, proximity, rate, navigation, etc.); displays (visual, audio, etc.); TV cameras or other imaging sensors; mechanisms (joints, linkages, wheels, tracks, actuators, etc.); data-handling/processing units (minicomputers, multiplexors, microprocessors, I/O devices, etc.); communication links, power units; and control input devices. Of course, many of these components also have other applications, but here we consider only units specifically oriented toward teleoperators, normalized to the state-of-the-art as of 1975 (Refs. 3-86 to 3-96).

(4) Total Systems. This variable measures the number of total teleoperator systems actually built and/or in operation at a given time. The systems can be breadboards or prototypes, operational or educational; the important point is that this variable deals with integrated systems and not components. The design and integration of a complete working system is a most demanding task. Again, the volume of total systems is normalized to the status as of 1975, numerical data for which can be found in Refs. 3-86 to 3-90.

FC 3-69. Number of Teleoperator Program and Development Plans



DISCUSSION

Space-application plans for teleoperators, as indicated by the number of established study or development programs and proposals, have nearly been tripled during the last 8 to 10 years. In the period 1965-1970, only two or three plans (related to Lunar and Martian rovers) were considered sufficiently serious to warrant the financing of advanced studies. Today, in addition to the roving surface explorer plans, there are five or six new plans and funded advanced studies related to dexterous operations in Earth orbit (cfr., studies at JPL, MSFC, JSC, ARC, Martin-Marietta, Rockwell International, and Spar Aerospace Product Ltd., etc., relating to the Space-Shuttle manipulator and the free-flyer manipulator).

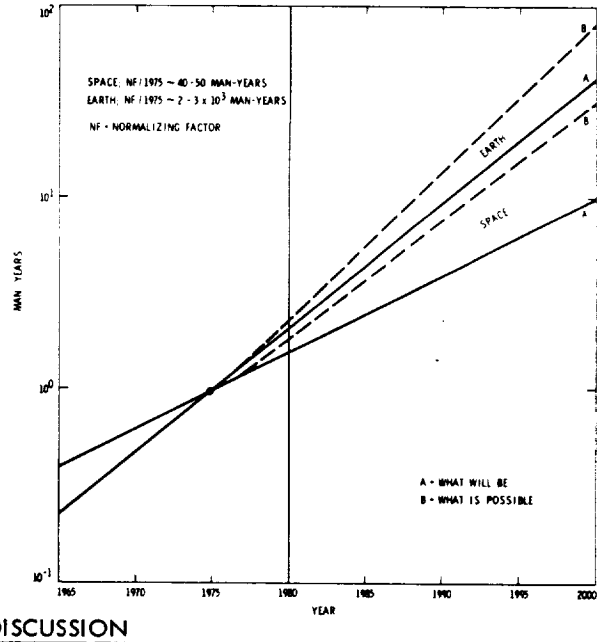
The space-applications forecast envisions a steadily increasing demand for dexterous operations in Earth orbit after the Shuttle becomes available. After 1990, growing demand for teleoperators for further exploration of remote bodies of the solar system and the moon is envisioned.

The difference between A and B in the figure is due to the uncertainties in future budgets. Since there will not be space projects involving teleoperators before 1980, the number of "likely" (A) and "possible" (B) plans will not differ significantly; however, by 1990 there may be as many as 45-50 plans "possible," while the more realistic "likely" count is about 30. The projection is essentially that, by 2000, it is realistic to expect that there will be ten times more space-application plans for teleoperators than in 1975.

The Earth-application forecast includes all areas: industrial processes, undersea operations, bioengineering applications, operations with or near dangerous material, etc. It is noted that Earth-application tasks are much more diversified than those for space. In California, for example, there are presently grapepicker machines, each capable of the output of 40 handpickers per day. Further, an American blueberry-picking machine can shake off berries with hydraulically controlled fingers. A British black-currant-picking machine can produce the output of several hundred handpickers and save $30 ton. As an indicator for the number of requirements in Earth applications, it is worth noting that there are well over 100 manufacturers of general-purpose industrial robots in the world today.

It is predicted that Earth-application plans for teleoperators will grow at a faster rate than those for space. This expectation rests on three reasons: (1) already, today, the application of industrial robots/teleoperators is economical in many areas; (2) the number of tasks unsuitable for direct human performance will grow (maintenance of nuclear reactors, undersea operations, etc.); and (3) as a result of growing educational opportunities, society will demand more interesting and satisfying involvement in industrial production.

FC 3-70. Experience with Teleoperators in Man-Years

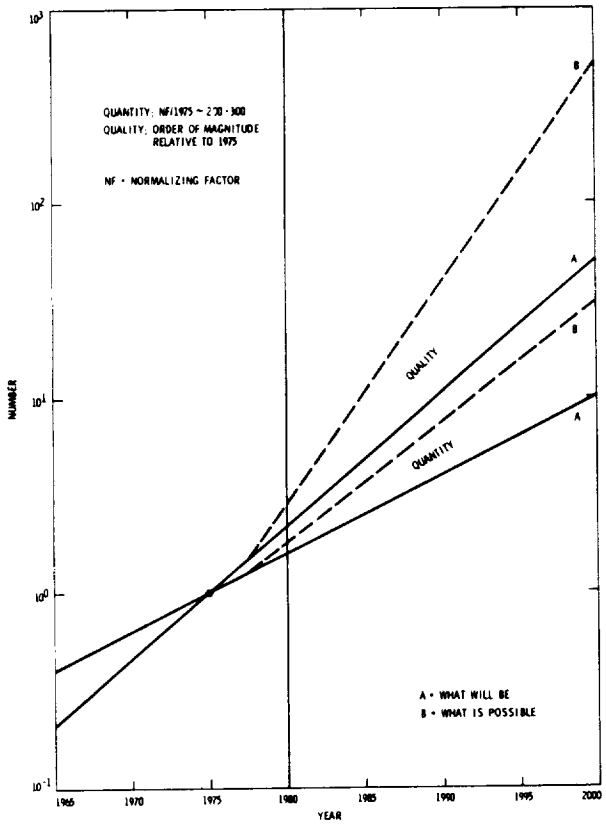


DISCUSSION

The projected growth in man-years of experience with teleoperator systems includes effort invested in experimental studies, breadboards, prototypes, actual operating systems, education, symposia, and publishing. It is worth mentioning a few data: one industrial robot system, the Unimate, has a record of nearly half-a-million hours' cumulative operational experience as of 1974; in 1969, there were several hundred engineers and scientists actively using remotely controlled manipulators in the nuclear industry; since 1970, the number of symposia and publications related to teleoperators or robotics has more than tripled. It is also noted that the Japanese government will spend nearly 100 million dollars for robotics research and development over the next few years.

It is seen that the cumulative experience in Earth-application teleoperator systems over the past ten years is nearly two orders of magnitude more than the cumulative experience in space-application teleoperator systems during the same time period. The 40-50 man-years' effort quoted in the figure as a normalizing factor for 1975 for space corresponds very closely to the total research and advanced development effort in space-application teleoperators funded at or through NASA centers.

FC 3-71. Growth in Number and Quality of Teleoperator Component Types



DISCUSSION

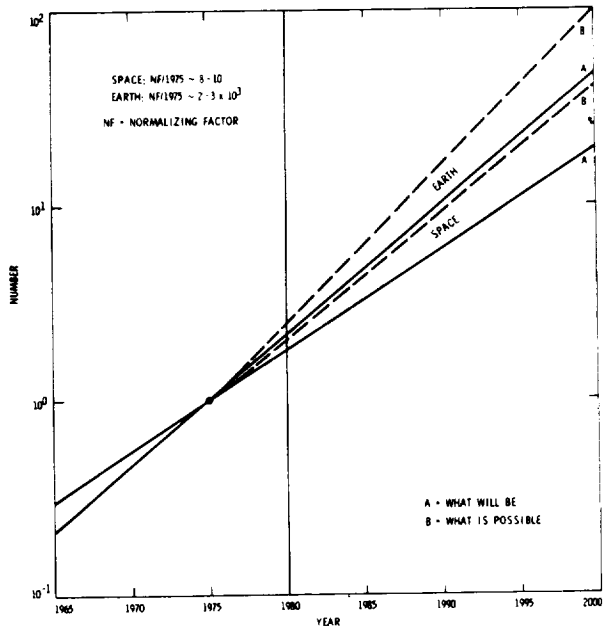
This forecast should be interpreted both quantitatively and qualitatively; that is, not only quantity but, more importantly, the quality and diversity of components will grow.

The number of components shown in the figure refers to the types of components rather than the actual number of manufactured or breadboarded items. As an example, for the normalizing factor for the number of component types for 1975, a recent survey (Ref. 3-90) found more than 50 different types of robot hands in application. As for the component quality factor shown in the figure, it should be interpreted in terms of the characteristic performance measure of the different types of components. For example, the spatial resolution of touch sensors commonly used today is about 0.5-1 cm with a sensitivity factor of about 10 to 15. The figure predicts that in about 6-8 years there will be touch sensors with a spatial resolution of 2-5 mm and with a sensitivity factor of about 25 to 30.

It is noted that the slope of the quality factor curve in the figure represents an average value for several different component types, and should be interpreted accordingly. Some components may considerably exceed the one-order-of-magnitude improvement in resolution, etc., predicted for the coming 15 years, while other components may not reach that predicted improvement level. Past experience shows, however, that the quality factor of components tends to follow an exponential growth rate.

The explanation for the difference between curves A and B is the same as discussed under FC 3-69.

FC 3-72. Number of Integrated Teleoperator Systems



DISCUSSION

The 1975 normalizing factor for integrated teleoperator systems for space application is simply the count of known bench model or breadboard systems existing mainly at NASA centers (MSFC, JSC, JPL, etc.). The integrated Earth-systems forecast includes all Earth-application areas. As for the 1975 normalizing factor for integrated teleoperator systems for Earth-application, it is noted that there were more than 40 undersea research vehicles in operation already in 1970. It is predicted by several analysts (e.g., Refs. 3-86, 3-87, 3-90, 3-91, and 3-92) that the teleoperator/robot production industry will be a multi-billion-dollar enterprise by the end of this century. The total world sales of industrial robots reached about $35 million as of 1974, and it is predicted by industrial analysts that it will reach about $200 million by 1980. The projected growth rate for industrial robots alone is more than 30% per year (Refs. 3-91 and 3-97). The growth rate shown in this figure for all integrated Earth-application teleoperator systems is about half the predicted growth rate of the sales value of industrial robots. The lower rate is due to the effect of averaging over the growth rates of several different Earth-application systems, of which industrial robots represent only one class.

5. Robots

a. Introduction. The purpose of this forecast is to discuss the present status and potential uses in space of semiautonomous or autonomous machines, and to indicate the pace at which they are likely to become operational. Robots are complex information and control systems. For the reasons given in the preceding subsection devoted to teleoperators, there are as yet no accepted parameters that can be used to characterize their performance; consequently, the presentation here is descriptive. Robots combine many independent functions related to sensing, control, and advanced information processing. Forecasts in related fields of artificial intelligence that have some bearing on these functions will be found in subsections 7, Picture Processing and Scene Analysis, 8, Natural Language Understanding, and 9, Problem-Solving Systems. A broader forecast of artificial intelligence and robotics and references to the pertinent literature will be found in the article by Coles et al. (Ref. 3-59).

The robot is here viewed as a machine that, without step-by-step human control, can safely complete certain complex procedures or tasks that require coordination of sensing and control functions in a changing environment. "Safe" execution means that the robot does not place itself or its mission in jeopardy. A complex task is to be regarded as one involving many individual steps or decision points. The changing environment can result from the robot's own activities. The focus is primarily on machines that can move about and interact with objects in the world, but the definition is intended to include systems that may respond to and modify information sources other than physical features.

The preceding group of forecasts is concerned with teleoperators -- machines that enable human beings to interact with a remote environment through a communication link. The teleoperator concept covers a broad spectrum of control methods and machine capabilities. At one end is direct control, in which the human operator initiates each primitive action of the machine and monitors its successful completion before proceeding to the next. Since the operator must make all plans and decisions necessary for execution of the task, including those involved in error recovery, he must be provided with adequate knowledge of those aspects of the environment that affect them. Farther along toward the other end of the spectrum is "supervisory control," as described by Ferrell and Sheridan (Ref. 3-85). In this mode, upon receipt of a command from a human supervisor the machine carries out a sequence of primitive actions, making use of information gained from its own sensors to control and correct them during execution. The plans may be transmitted by the supervisors or developed by the machine. The human interacts with the machine at a relatively high command level, initiating task sequences and stepping in only when it is necessary to correct or override machine actions, to make a decision, or to introduce a new plan. As the remote tasks and environments become more complex, the strings of primitive actions larger, and the degree of human involvement in the details of task performance smaller, the machine takes on more and more of the characteristics of autonomy generally associated with robots.

From the above discussion, it is clear that robots and teleoperators share some common features and that it is possible to regard a robot as an advanced teleoperator with sufficient automation to permit the use of supervisory control. Much of the research and development concerned with robots and teleoperators for space applications is directed toward the same ultimate objectives and many of the comments made in the preceding subsection about problems of design and use of teleoperators apply to robots as well. A close look at some of the details of this work and the context in which it is done, however, reveals that there are also some important differences in immediate objectives and in emphasis that it is worth enumerating here.

(1) Application. Most of the space teleoperator systems currently being developed are destined for use in Earth orbit, for example, in Space Shuttle and Tug operations such as payload deployment and retrieval and satellite servicing. The purpose of present teleoperator work is to provide human beings with the manipulative and sensory aids that they will need to carry out, by direct control, those tasks that it would be difficult, hazardous, or expensive for astronauts to do first-hand by extravehicular activities (EVA). Many of these tasks are highly unstructured and nonrepetitive, and require human judgment, adaptability, and intelligence to a high degree.

Results of the present robotics work sponsored by NASA are likely to find their first application in planetary or satellite surface exploration, at a time perhaps 10 years after near-Earth teleoperators have been placed in service. The first tasks required of robots will be capable of being structured to some extent, will be repeated many times in a given mission, and would not ordinarily require the continued exercise of human judgment during execution.

(2) Time Delay and Autonomy. The communication path for the near-Earth teleoperator systems will be relatively short, and the time delays for round-trip signal transmission will typically be well below 1 second. It is therefore practical and expedient to put the human being directly in the control loops for sensory interpretation, decision making, planning, and motor control. Very little autonomy need be given the remote system. For planetary surface exploration at the distance of Mars or beyond, the round-trip communication time delay will be on the order of 6 minutes or longer. Reliance on direct human control to accomplish complex tasks would make the execution slow. Furthermore, because of the time delay, the Earth-based operator would not be able to take corrective actions in time to meet an emergency. A planetary robot therefore needs considerably more autonomy than a near-Earth teleoperator.

(3) Automation. Experience has shown that direct control of a remote machine can be difficult, slow, and tiring for the human operator. The purpose of much of the automation planned for teleoperators is to relieve the human being of some of the physical and mental burden of overseeing all details of the remote action, and thereby to decrease his discomfort and fatigue. In the space-related robotics work automation is

introduced to overcome the control problems associated with long time delays.

(4) Vision. A difficult problem in teleoperator design is how to give the human operator or supervisor a clear enough view of the work space that he can see what is being done and assess the probable effect of various actions on the surroundings. The goal of vision work done for teleoperators is primarily to give the operator a greater "sense of presence" in the remote environment. In robotics, a central long-range objective is to automate as much of the function of perception as is possible. If the sensorimotor control loop can be closed locally, through the machine rather than through the human operator, the amount of sensory data (largely pictures) that must be transmitted back to the human supervisor can be greatly reduced, and the downlink communication channel used more effectively for other control and scientific purposes.

(5) Decision-Making and Planning. These are functions that human beings perform rather effortlessly and well. Very little is known about how to automate them, even though much current research in artificial intelligence is concerned with it. An implicit assumption in most current teleoperator work is that human beings will make the decisions and plans that affect what the remote system does and how it does it. This assumption will at first also be valid for robots for all but a few sensor and motor functions, but there is motivation eventually to delegate some additional decision-making and planning responsibilities to the remote machine to make it more independent of Earth-based surveillance. If such a degree of autonomy could be achieved, it would benefit some Earth and near-Earth applications as well.

The preceding discussion implies that even a primitive robot must have certain capabilities that are not necessary for simple teleoperators. The fact that a robot can complete a task, or some portion of the task, automatically implies that it have some internal representation of a goal, perhaps expressed as a state of the machine and of its environment, and that it possess some built-in criteria for deciding that the goal has been reached. Then, given an initial state and the desired final state, the robot must be able to make a plan -- that is, a sequence of actions of the sensors and effectors that will achieve the final state. A useful future measure of robot performance may be the complexity of the plans developed autonomously.

The machine must be able to obtain data from its surroundings and extract from it all the information that it needs for following its plan. A very important requirement is that it be able to represent the data and information in such form that it can be used by the motor subsystems. This representation or "world model" must incorporate salient characteristics of environmental features, critical parameters of the robot's own physical characteristics and internal electronic states, and means of predicting the consequences of actions taken in the world that can serve as constraints on the robot's plans. This latter ability enables the robot to recognize and react appropriately to hazardous conditions that could not be dealt with from Earth. There must be an overall integrating faculty that ties together the various perceptual, motor, and cognitive functions and gives machine actions purpose and coherence. Finally, because of the fact that the robot will possess more information about its immediate environment than will the distant human supervisor, it is necessary that the communication between the robot and its home base be at a high (macrocommand) level.

b. Background and Present Status. Robot toys — automatons — have been made for generations (Ref. 3-98). Only with the development of control theory and the computer were their principles introduced in industry. Most present industrial machines called robots perform some motor function in a well-controlled environment. Until recently, most of them have not incorporated sensors, feedback, or error recovery. The range of operation of most present systems is fixed, and each task consists of a preprogrammed sequence of repetitive operations (mostly stored in the hardware). When a digital computer is introduced, however, as is now being done in industry, there is the potential for storage of a variety of task sequences and therefore much more versatility. A good example of a first-generation robot is the "Unimate" (Ref. 3-99), which is now employed in hundreds of industrial applications.

The period 1955 to 1965 saw the beginning of studies in artificial intelligence and the growth of interest in machine cognition (Refs. 3-100 to 3-103). Work in robotics began with the initial emphasis on computer-controlled manipulation (Ref. 3-104) and automation of vision (Ref. 3-105), the functions that underlie the most likely NASA applications of robots during the next 25 years.

The level of activity in artificial intelligence and robotics grew rapidly during the period 1965 to 1975, largely as the result of funding provided by ARPA in the United States. Much work was done to understand and simulate the various cognitive functions that will be needed for an intelligent robotic system: representation of knowledge, machine vision, problem-solving, planning, machine-recognition of speech, and understanding of natural language. Some of these developments are reviewed in subdivisions 7, 8, and 9 of this section. Reference 3-106 is a useful guide to the literature.

Of special relevance to this forecast are advances in machine manipulation, perception, planning, and the integration of these functions.

An important advance in computer-controlled manipulation was reflected in the design of the Scheinman manipulator (Ref. 3-107) and its programming (Ref. 3-108). During the same period of time, progress in computer vision (Refs. 3-109 to 3-112) was reflected in advances in integrated "hand-eye" systems (Refs. 3-113 to 3-115). The incorporation of functions such as locomotion and planning is evident in the work at SRI (Refs. 3-116 to 3-118), at Edinburgh (Ref. 3-119) and in Japan (Refs. 3-120, 3-121). All of these investigations represent important experiments in the integration of basic and necessary functions. Although none of it has yet led to practical machines, it provides definition

to robotics as a new discipline with a search for methods and applications.

Some capabilities achieved at three of the pioneering artificial intelligence and research laboratories — those at MIT, Stanford Research Institute, and Stanford University — will be described. Their initial approaches have involved simplifying the environment. At MIT, much effort has gone into analyzing a "blocks world," emphasizing the relationship of objects to one another and the context of knowledge in which actions performed upon them are to be planned and interpreted. The results have been major advances in the ability to "perceive" arbitrary polyhedra with plane surfaces in scenes of great complexity. The polygons can be parts of structures, can cast shadows, and can occlude each other; the computer can still quickly and accurately model such a world (Ref. 3-122).

At Stanford Research Institute, a complete robot system, "Shakey," was developed that integrated locomotion with problem-solving and planning. The environment consisted of large cubes, wedges, walls, and doors. Baseboards of the walls were painted to contrast with the background so that wall and floor could be distinguished from one another. Analysis of scenes obtained from TV pictures was automated. The major motor functions were locomotion and the pushing of cubes. The principal goals were to develop a complete integrated system that including sensing, locomotion, and autonomous decision-making, and to provide sophisticated problem-solving abilities based upon formal theorem provers (Ref. 3-123). Prior to the conclusion of this project in 1973, Shakey had demonstrated an ability to reason to this extent: given a ramp in one location and a block on a raised platform in another, it would push the ramp to the raised platform, go up it to gain access to the block, and push it off — in effect, solving the "monkey and bananas" problem. SRI's present research in robotics is focussed on industrial automation, specifically the use of manipulators and vision systems in realistic and economical industrial contexts.

At Stanford University, the initial emphasis was on the development of an exceptionally dexterous, fully coordinated manipulator under computer control (Ref. 3-124). As this work matured, the attention shifted to the analysis of more natural environments with TV cameras, and containing complex objects other than polygons. The Stanford University system has assembled a Ford Model A water pump, starting with the parts of the pump and the gaskets in arbitrary positions in a work space, placing these in jigs, and proceeding to assemble them using bolts and tools in known places. In addition, a two-arm system has assembled hinges.

In addition to the pioneering work done at the above-mentioned institutions and in other United States and English universities, recognition should be given to the efforts in Japan and in the Soviet Union. In Japan, a major effort has been mounted in the construction of a number of working manipulator-eye systems for industrial environments. An important theme of the Russian work is undersea exploration and display systems for human supervision.

Within NASA, in research sponsored by OAST, the long-range goal is to combine sensing, locomotion, and manipulation functions in an integrated system that could guide the designs of automated roving vehicles to be used for surface exploration of planets or planetary satellites. The emphasis is on the analysis of natural environments using TV cameras and range and proximity sensors. An initial, integrated "hand-eye" laboratory system demonstrated in FY'75 has the dexterity of the Stanford system but works with objects such as rocks. Computer-assisted graphics displays will give the operator or "supervisor" the information necessary to control the robot when control-loop time delays are long and the bandwidths for the transmission of sensory information are narrow. Reliance is placed on the human operator for higher-level problem-solving, although strings of commands to accomplish specific tasks whose structures are known in advance can be stored as plans. A reflex action is to be provided that will permit stopping execution of all tasks if errors or unplanned difficulties are detected.

In summary, most of the present work in robotics is directed to creating machines sophisticated enough to cope with a highly variable, more-or-less natural environment, and to interact with humans at a relatively high level. One of the most difficult problems faced in all of this work is that concerned with the representation of knowledge. Various solutions so far tried have included formal, logical languages, such as first-order predicate calculus, and a variety of special computer languages. Some of the more promising developments for the future appear to be representations resulting from research into the meaning of natural language utterances (statements in English). (See Subsection 8, Natural-Language Understanding.)

c. Forecast. In general, robot evolution for space applications will proceed in a succession of small but significant steps. Initial systems will be highly interactive. Automated task sequences will be short and each string will require human initiation. Human beings will thus make most of the plans and decisions necessary for remote-task execution and will also provide some of the sensory interpretation. Gradually more functions will be automated and the machines will become capable of coping with more complex settings and tasks. Delay in the introduction of robots will result from engineering development necessary to simplify the implementation of perceptual and motor functions, and to provide systems reliable enough to be committed to a mission. The emphasis in technology development will continue to be on the acquisition and interpretation of sensory data in complex settings, efficient motor control, development of strategies for using a variety of sensors and effectors to reduce software complexity and the number of failures in task execution, and the construction and management of the large data bases that will be required for the robots to carry out such functions as locomotion. Since the human being will always remain in control of remote operations, an important aspect of robotics is to improve methods of interaction and display so that the operator will have a sense of participation in the remote operations and be able to make judgments about them. Much emphasis, too, will be given to reducing the cost

of implementing robots so that their use can compete favorably with direct-control methods.

(1) 1975 - 1980. Within NASA and at a variety of other laboratories in the world, test-bed systems capable of manipulation and locomotion in relatively realistic and complex environments will be developed and used in experiments. By 1980, NASA capabilities will include 1-2 km traverses in terrain that roughly approximates Martian conditions, sample collection, instrument deployment, data collection, and system operation in the presence of signal delays from 5 to 10 minutes. Outside of NASA, similar work will be done to develop underwater free-swimming vehicles for a variety of deep-sea applications — mapping the ocean floor, obtaining core samples, and prospecting for oil and other minerals. Undersea exploration with untethered craft presents problems similar to those of a planetary rover because of the limited bandwidth of the sonar communication channel and the time delay. Underwater applications will require automated scene analysis using sonar data.

(2) 1980 - 1990. During this period of time, teleoperators will come into use in the near-Earth environment and robots will reach the stage of prototype development. Practical problems not considered in earlier test-bed research will be addressed. Algorithms will be simplified, and reliable spaceworthy computer systems able to meet the information-processing requirements of robots will be developed. Tasks to be faced during this time will include managing the supply of power to a system with complex and competing demands for it, and developing reliable and effective electromechanical systems that can withstand repeated use, harsh treatment, and environmental conditions such as temperature extremes and sandstorms.

During the 1980s the architecture of information systems will be revolutionized, and these changes will be reflected in the organization of robots. Individual sensory and motor functions will be performed by independent processors or processor arrays; the function of the robot executive will be to coordinate the activities of the parallel networks of information subsystems. Sensors will be developed that will enable image-data preprocessing to be done within the vicinity of the light-sensitive element in much the same way that visual data is processed in the retinas of higher animals. The front ends of such vision systems will then consist of a very large number of parallel computing structures that will be able to process scene data in times less than a millisecond, so that scenes can be analysed while the rover or its manipulator is in motion.

Scientific instruments such as those required for geological studies will become more automated through the use of microprocessors and improved electromechanical hardware. Telemetry systems will be developed that can vary the content of the downlink data stream on the basis of what is important. These systems, when combined with those needed for robot control, will make the automated rovers effective agents for Earth-based scientists to use in remote surface explorations.

Advances in automated vision for robots and in data compression and image extraction for Earth satellites will lead to highly sophisticated Earth-satellite systems that can perform some automatic on-board searches of incoming data in real time, guided by fidelity criteria provided by humans. Some of the automated capabilities developed for robots will be incorporated in teleoperators, and the present boundaries between robots and teleoperators mentioned in the introduction will fade.

Continued drop in the price of microcomputers and increases in labor costs will have a significant impact during this period of time on industrial automation. Robots with sensory feedback will come into wide use in a variety of industrial applications early in the decade, and the development of inexpensive components for these systems will reduce the cost of robots for space applications.

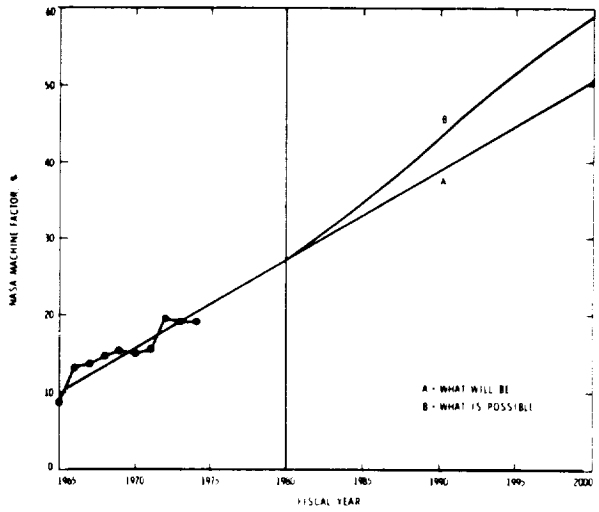
The end of this decade may see the first use of robots in space. The first applications may be Lunar rather than planetary exploration; established teleoperator systems can be combined with the newer robotics technology to provide effective supervisory control for surface exploration of the near or far side of the moon.

(3) 1990 - 2000. During the last decade of this century the technological and economic developments of the preceding 15 years in information science and in computer hardware, combined with advances in problem-solving, learning, decision-making, sensory analysis, and other fields of artificial intelligence, will permit the introduction of simple robots to society at large. These systems will be special-purpose machines able to perform a variety of repetitive tasks requiring low judgment in a somewhat structured environment. Better and more expensive machines will be available for use in hazardous environments -- radioactive laboratories, the ocean floor, fires, mines. Early in the decade, technology will be ready for landing a semi-autonomous rover on Mars or on a satellite of Jupiter or Saturn.

6. Automation of Space-Related Information Processing (Forecast 3-73)

Rapid growth in information requirements and decreasing hardware and utilization costs promote the automation of NASA information management activities. The purpose of this forecast is to indicate the level of computer-related human efforts in the performance of NASA work. Administrative functions are included as well as those related directly to the scientific and engineering aspects of missions (or projects) and programs.

FC 3-73. NASA Machine Factor



DISCUSSION

Computer involvement in NASA work is measured by a NASA Machine Factor, defined as

$$\text{NMF} = \frac{\text{Total man-years of effort devoted to computing in support of all NASA projects}}{\text{Total man-years of effort in support of all NASA projects}}$$

The NMF numerator includes man-years for personnel with at least 50 percent of their work time computer-related. Data are obtained from the NASA annual ADP plans for each center and for JPL. Data for the denominator are obtained from the NASA Historical Pocket Statistics, January 1974. Forecast 3-73 shows the NMF plotted for the years 1965 through 1974 and projected to the year 2000. Over this period of time we expect the NMF to increase linearly if there is no significant breakthrough in human-machine communication technology - that is, if progress continues in the future as in the past. However, significant advances in human-machine communication technology will result in increased machine utilization, as reflected in the curve labeled "what is possible." At what point the curves will level out cannot be predicted now. For either projection, the prospects are that, before the turn of the century, more than half of all NASA employees will be devoting more than half of their working hours to tasks involving computers.

Although present administrative applications primarily concern budget and manpower management, in the future, computers can be expected to be used for somewhat more sophisticated managerial tasks – for scheduling, design and quality control, and other functions that require the use of machines in an interactive mode for quick and repeated investigation of alternatives, and modeling of the outcomes of prospective managerial decisions and strategies.

7. Picture Processing and Scene Analysis

a. Introduction. This forecast deals with computer processing of pictorial information. The topics covered include picture compression, image enhancement and reconstruction, picture matching, picture parsing, pictorial pattern recognition, picture properties and descriptions, and automated interpretation. Digital methods are emphasized and optical methods mentioned, but photographic and analog electronic methods are not discussed. Theory, capabilities, and applications are emphasized instead of implementations and devices. For imaging sensor forecasts, see Part Three, Section II, Acquiring Information. Applications of interest to NASA are featured.

b. Background and Present Status.

(1) 1955-1965. The late 1950s mark the onset of serious work in computer processing and analysis of images. For example, two basic papers (Refs. 3-125, 3-126) that appeared in 1955 introduced a number of the fundamental techniques in image deblurring, edge detection, and noise cleaning. Compression and encoding of images had begun a few years earlier, and recognition of various types of pictorial patterns — alphanumeric characters, in particular — was beginning to be of research and commercial interest. During this period, little if any practical image processing was accomplished, and NASA, of course, was not significantly involved.

By the early 1960s, research interest in the field had grown around several specializations. The theories of multidimensional sampling and optimum quantization were formulated during this period, and Fourier methods of image evaluation became popular. Within NASA, the first digital spacecraft television camera was flown, and the performance of both analog and digital space camera systems was analyzed using computer methods (Ref. 3-127). Image enhancement techniques were widely studied in research (Ref. 3-128) and basic image restoration and enhancement processes were applied to deep space photography (Ref. 3-127).

Character recognition was an area of considerable interest and effort (Ref. 3-129). A variety of pictorial pattern-recognition applications were actively studied. Many basic pattern-analysis techniques were developed during this period; in particular, much work was done on the definition of invariant pattern properties. Interest in optical information processing mushroomed with the advent of practical methods of holography and coherent optical spatial filtering (Ref. 3-130). Parallel image-processing computers, first proposed in the late 1950s, began to be constructed. Image segmentation techniques, particularly based on tracking methods, were extensively explored. By 1965, the first work on three-dimensional scene analysis had appeared (Ref. 3-131).

(2) 1965-1975. In the late 1960s the theoretical community saw the beginning of a long series of meetings, special journal issues, and books on image processing and pattern recognition (Refs. 3-132 to 3-138). In image compression, attention began to shift from predictive coding to transform coding schemes. Image-restoration techniques, based on inverse Fourier-domain filtering and on least-squares linear filtering, became subjects of active interest. In the pattern-recognition area, specialized meetings were devoted to applications in high-energy physics, biology and medicine, and military reconnaissance (later expanded into remote sensing of the environment). The theory of "computational geometry" was inaugurated with an analysis of the computational complexity of certain basic classes of picture properties (Ref. 3-139). Interest grew in global image-segmentation techniques such as connectivity and concavity analysis, thinning and skeletonization. Languages for picture and scene description became an important research topic, and many different types of formal "grammar" models for such languages were developed. Activity in scene analysis continued, and the subject has been well represented at the International Joint Conferences on Artificial Intelligence, the first of which was held in 1969. A specialized journal in the area of pattern recognition began publication (Ref. 3-140).

During the early 1970s, the level of activity in the field continued to rise. It is estimated that at least 1000 papers per year now appear in the English-language literature on image processing, recognition, and analysis. Many specialized meetings have been held, and the number of books is growing rapidly. This growth makes it increasingly difficult to identify important developments in processing techniques. In the area of image coding, attempts are being made to formulate fidelity criteria in terms of human visual models. Such models are also being used as a basis of advanced enhancement techniques, e.g., homomorphic filtering. Image modeling by two-dimensional random fields is an active area of interest and is being applied to the development of estimation techniques for restoring noisy images. In image filtering, extensive use is being made of Hadamard transform techniques and of recursive filtering methods. Much new work has been done on basic-image-segmentation techniques such as edge detection and texture analysis. Many of the classical methods are being reexamined and refined.

During this same period, practical applications of image processing by NASA followed the theoretical work quite closely, often pacing the theory. Applications to remote sensing of the planets and the Earth expanded beyond camera system characterization and restoration to include interpretive aids. Among these were included innumerable different approaches to enhancement (visual emphasis of pictorial features) and quantitative image analysis (numerical feature measurement). Many thousands of image frames were processed with these methods for non-expert users. Significant emphasis and progress were focused in the area of multispectral image interpretation (Ref. 3-141). Rudimentary image data compression systems were flown in conjunction with sophisticated coding schemes. Successful flight experiments aimed at autonomous optical navigation systems were also conducted. On Earth, simple optical process control and inspection operations were automated as were several space-derived applications to medicine, biology, forensics, astronomy, and governmental land management, among others. During this period, digital image-processing applications far outnumbered optical ones, and new applications were heavily influenced and paced by

the substantial advances in computer system capabilities and cost performance.

c. Forecast. The following forecast of future developments in image processing and scene analysis is divided into three time periods: short-range (1975-1980), intermediate-range (1980-1990), and long-range (1990-2000).

(1) 1975-1980. Greater experience with basic image-analysis algorithms will be accumulated as standard techniques become more widely accepted. Interactive image-processing systems will come into wide use, and steps will be taken toward standardization of their image-input/output device specifications. These systems will become essential elements in more comprehensive image interpretation and process-control facilities, where they will assume important preprocessing, image-input/output and system-control roles. There will be a corresponding shift in emphasis toward productivity and cost performance. Computer vision applications to various industrial inspection tasks will become more widespread. Optical navigation and similar automation precursor experiments will continue. (The sparseness of flight projects will deter more rapid advances in this area.) Languages and structural schema for images and image processing will become more prominent in practical systems. Computers will automatically identify and measure major components of moderately complex scenes. Computing hardware limitations to practical image processing will virtually disappear. Several commercial parallel processing computers suitable for image processing will be available.

In the theoretical arena, image models based on random field concepts will be extended to take shape, texture, and structure into account. Since processing pertaining to sensor characteristics will be routine, research emphasis will shift heavily toward visual psychophysical topics. Visual models will be developed that go beyond simple spatio-temporal frequency-response characteristics. Work in image processing will receive greater attention from perception psychologists and physiologists, who will use it as a source of models for human image perception. Theoretical computer scientists will give increasing attention to establishing bounds on the computational complexity of basic image-processing analysis operations.

(2) 1980-1990. Image models will be applied to the development of optimal algorithms for basic image-processing and analysis operations, such as grayscale transformation, enhancement, thresholding, edge detection, texture analysis, and template matching. These algorithms will be optimal not only in the sense of signal-detection theory, but also in computational simplicity. Extensions in dimensionality (time, three-dimensioned space, multiple sensors) will be included. There will be closer cooperation between image-processing and scene-analysis researchers; the latter will use image models to develop "visual microsemantics" for general classes of images. Cooperation with psychologists will lead to greater understanding of the types of errors and distortions that can be tolerated by human users of images, so that more realistic criteria for image-coding and processing can be established.

Robot vision systems using scene-analysis techniques will proliferate for both inspection and assembly work in controlled industrial environments. Vision of dynamic processes will be common. Automated vision in space will become more common as additional flight opportunities emerge. These will be included in vehicle, sensor system, and mission and experiment sequence control mechanisms. Highly human-interactive exploration image-analysis facilities will be available, as will similar facilities for remote sensing monitoring applications. The latter will include some automated image analysis for alarm detection and, later, automatic corrective action.

(3) 1990-2000. Increased insight into human visual abilities will lead to modelling of how humans organize their perceptions of complex images and scenes. These models will make possible true human-machine dialog about scenes, since the computer will be able to determine what the human is able to see when he looks at the scene. Development of such models requires techniques for representation of fuzzy knowledge (which should be developed during the 1980-1990 time period), since the parts of a scene are fuzzily defined entities, and it is not appropriate to represent them using conventional discrete data structures. Advances in the theory of image structure will make it possible computationally to optimize the scene-analysis process.

Robot vision systems will begin to appear outside the factory environment, and will be used for various office and household tasks. Most routine visual tasks will have been automated. In the main, performance capabilities for these tasks will be limited by machine cognitive capabilities as compared to image-manipulation capabilities per se.

8. Natural-Language Understanding

a. Introduction. This forecast is concerned with the present status and future prospects of work directed to automating the understanding and use of natural language. Giving machines the ability to use languages more like those of normal human-to-human discourse may be essential in facilitating the use of computers and overcoming the problems created for nonprofessional users by the diversity of specialized formal computer languages and their "dialects." (See subsection 2, Human-Machine Communication.) Within the field of natural-language understanding by computer there are six main subfields:

(1) Sentence analysis (parsing).
(2) Generation (production of language).
(3) Memory and inference.
(4) Representation.
(5) Control structures.
(6) Speech recognition.

Although the boundaries delimiting them are generally acknowledged to be artificial, these six subfields provide a good framework for describing past and future research, and hence will be used in the brief description which follows:

b. Problem Characterization and Present State-of-the-Art.

(1) Analysis. Analysis, or parsing, is the process which transforms an input utterance (generally, a sentence typed at the console rather than spoken speech) in some natural language into a decided-upon representation. Existing parsers can be classified into two major schools: formal parsers (those which make no claim to model humans) and cognitive parsers (those based on processes presumed to be akin to those employed by humans). Additionally, most parsers can be characterized as inherently syntactic or inherently conceptual (semantic) according to the techniques used to implement them and the target representation (a description of the sentence's syntax vs. a description of the sentence's meaning, frequently quite unrelated to syntax). Representative of relatively successful and state-of-the-art formal systems are Woods' Augmented Finite State Transition Net (ATN) parser (Ref. 3-142) used in his LUNAR system (Ref. 3-143), and Winograd's SHRDLU (Ref. 3-144), designed to be conversant about a restricted "blocks world," and based in part on Halliday's systemic grammar (Ref. 3-145). The input to such systems is assumed to be syntactically well-formed (this is a general weakness of the formal syntactic approach); the output is either an explicit or an implicit parse tree which elucidates the syntactic relation of each word to the whole sentence. Woods' and Winograd's systems handle vocabularies on the order of several hundred words and do not, for the most part, cope with multiple word senses. The assumption underlying these and any formal syntactic model is that a syntactic parse will be valuable in determining a sentence's meaning.

Representative of parsers which attempt to extract meaning rather than structure are Riesbeck's conceptual analyzer (Ref. 3-146) and Marcus' "wait and see" analyzer (Ref. 3-147). Riesbeck's approach is based on the premise that language comprehension is a fitting-together of concepts rather than a fitting-together of words. His conceptual analyzer is driven by an expectancy/fulfillment paradigm based on conceptual case frameworks of primitive actions (combinations of which can represent, as an interlingua, verbs in any language). In this paradigm, some words, on the basis of their meaning rather than syntactic class, set up expectancies. The output of this system is a conceptual graph which elucidates meaning relationships, such as causality, enablement, and actor-action, among the concepts referenced by the words in the sentence. Important to Riesbeck's system is the notion that parsing interacts with general world knowledge as well as syntax and semantics.

Marcus' approach is more stratified in that analysis occurs at three distinct levels: syntactic, semantic, and conceptual. In his system, syntax packets fuel a semantic case-framework level (much akin to Fillmore's case system - Ref. 3-148) consisting of semantic packets, which, in turn, fuel a conceptual level. Each level interacts strongly with adjacent levels, and rules (packets) are encoded as a battery of programmed specialists such as "Participle Diagnostician," rather than as formal production rules.

Notably, in these two cognitive systems, "back-up" (in which a misparse resulting from selection of a bad alternative at some point must be undone) is designed to occur only on seriously ambiguous or anomalous sentences which also cause back-up to occur in people. This is an important feature; in most formal systems, back-up is designed into the formalism to get it to work.

Most of the current problems with parsing theories relate to context: How does syntactic and meaning context guide the selection of a word's sense from among several alternatives? Currently, no parser truly copes with more than one or two senses for each word, and it is fair to say that no one yet understands the context problem in any generality.

(2) Generation. Excluding the initial transformational grammar approach to syntactic sentence generation (e.g., see Friedman – Ref. 3-149), there has been relatively little research on the generation of sentences, the process of constructing a syntactic and/or meaningful sentence from some internal non-language-like representation. Simmons (Ref. 3-150) has applied Woods-like ATN grammars in reverse to transform syntax nets back into English. Although this model cares not whether what it produces is meaningful, it is a relatively successful model of syntactic sentence generation.

In 1974, Goldman (Ref. 3-151) demonstrated the feasibility of generating sentences that were meaningful as well as syntactically well-formed. His program (BABEL) starts from a conceptual dependence graph (Schank – Ref. 3-152), which provides a language-free (interlingual) representation of a thought and decides, by filtering the graph through discrimination nets (Ref. 3-153), what words to use to express the graph. (Selection of verbs represents the bulk of this task.) The output of Goldman's system is a syntactic net suitable for input to Simmons' program. Used in conjunction with Riesbeck's analyzer and Simmons' generator, a "smart" paraphrasing system has been assembled (Ref. 3-154) which can produce paraphrases that are meaning-based rather than just syntactic. Such a system also has potential for machine translation from one language to another, since it is based on a representation which captures sentence meaning.

Notably absent from generation research has been a successful theory of how to decide what is interesting or relevant to say in the first place. Since any such theory must relate to some sort of motivational structure of the speaker, advances in deciding what to say will come by building small domains in which the computer is motivated to speak. Such a project involving the game of Diplomacy (which requires a highly motivated bargaining model) is currently under way at the Stanford University Artificial Intelligence Laboratory (Ref. 3-155).

(3) Memory and Inference. If one believes in cognitive conceptual parsing rather than purely syntactic analysis - and most people today do - then one rapidly concludes that language analysis and world-knowledge are inseparable. Hence, there has been a wide body of research devoted to

constructing models of memory, inference, and belief which are imagined as being interposed between the processes of analysis and generation, interacting highly with both.

Representative of memory research via cognitive modeling are Quillian's Semantic Network Model (Ref. 3-156), Rumelhart, Lindsay, and Norman's Process Model for Long-Term Memory (Ref. 3-157), Abelson's Cold-Warrior Model (Ref. 3-158) and his related research concerning models of the belief systems of political idealogues (Ref. 3-159), Rieger's model of Conceptual Memory and Conceptual Inference (Ref. 3-160), Charniak's model of Children's Story Comprehension (Ref. 3-161), and Schmidt's computer-oriented psychological model of personal causation (Ref. 3-162). Common to all these models are such issues as these: What kinds of structures are necessary for storing the kinds of information communicated by natural language? What does it mean to comprehend an utterance, given some syntactic or conceptual parts of that utterance which have already been constructed by an analyzer? How does such comprehension occur? How do a person's beliefs affect the quantity and quality with which he comprehends? To what extent must a comprehender make meaning inferences in order to understand? How are references to real-world objects established? What are the sources of interaction between a knowledge base and the processes of analysis and generation?

Although there are many competing theories of memory, and by its nature it is the least-well-defined component of the natural-language comprehension task, there have been several attempts to assemble "vertically integrated" comprehension systems. Representative of these are Winograd's Blocks World (Ref. 3-144) (which is not fully a cognitive model), and Schank, Goldman, Rieger, and Riesback's MARGIE system (Ref. 3-163), which is an integrated model of sentence comprehension. Additionally, although it was never scaled to a large implemented system, Charniak's Story Comprehender also holds considerable potential as a vertically integrated system. It is important to note, however, that no model yet exists which can analyze multiple-sentence or multiple-paragraph passages; it is fair to say that the state-of-the-art is still at the single-sentence, neutral-context level.

(4) Representation. Language understanding presupposes some sort of descriptive representation which serves both to store knowledge about process (inferential knowledge) and as the target representation for a conceptual analyzer (and hence which prescribes the format in which knowledge is represented in the memory and as input to a generator). Representation seems to be at the core of every language-related problem, and no one yet has any lasting insights into what is an adequate representation. However, there are several competing schools of thought:

(1) Semantic networks (e.g., Quillian - Ref. 3-156).
(2) First-order predicate calculus (e.g., Sandewall - Ref. 3-164, Coles - Ref. 3-165).
(3) Conceptual dependency (Schank - Ref. 3-152).
(4) General frameworks (Minsky - Ref. 3-166).
(5) Procedurally encoded knowledge (e.g., Hewitt - Ref. 3-167, Winograd - Ref. 3-144, and Sussman - Ref. 3-168).
(6) Production rules (e.g., Newell - Ref. 3-169).

(5) Control Structures. It has gradually become apparent that the way in which language models are implemented is as important as the essence of the model itself. Consequently, there is emerging a concomitant development of new programming languages, specifically, new control structures which allow heretofore too-complex processes to be implemented. Representative of the revolution in control structures are the recent developments in the following languages: SAIL (Ref. 3-170), MICRO-PLANNER (Ref. 3-168), CONNIVER (Ref. 3-171), INTERLISP (Ref. 3-172), POPLAR (Ref. 3-173), Reddy's "Blackboard System" (Ref. 3-174), Charniak's "Demon System" (Ref. 3-161), and Hewitt's Actor Paradigm (Ref. 3-175). Taken together, these languages have provided insights into some novel control structures which emphasize issues of parallelism and context. In addition, research into a fairly exotic, general-purpose control structure called a "frames interpreter" (Bobrow and Winograd - Ref. 3-176), and a context-related control mechanism for interpreting actions in context (Rieger - Ref. 3-177) are underway. Even with these new developments, and with better theoretical models, language processing is confronted with combinatorial search problems so acute that no system with more than a few hundred inference rules and pieces of factual knowledge and a vocabulary of more than a few hundred words has been constructed. Even for the extant models, limits of contemporary computers are being pushed: Winograd's Blocks World model and the MARGIE system can require on the order of several minutes and 100,000 words of computer memory to react to one sentence input.

(6) Speech Recognition. Speech recognition refers to the process which accepts an acoustic waveform, preprocesses it by filtering and sampling techniques, identifies phonetic groups, and segments them into words. There is an excellent report on the state-of-the-art and projected research goals in speech recognition entitled "Final Report of a Study Group on Speech-Understanding Systems," by Newell et al. (Ref. 3-178). The reader is directed to this report for a summary and projection of speech-recognition efforts.

c. Core Problems. There are two core problems facing language-comprehension model builders today. First, the field is desperately in need of a theoretical breakthrough in the area of meaning context. That is, whereas researchers have good ideas already about how to represent meaning, analyze isolated sentences, understand special cases of simple stories (e.g., 4 and 5 sentences), and establish references to real-world objects described by language, no one yet really knows how to characterize context in a way general enough to explain how the decisions made during analysis, inference, and generation are guided by context. Hence, the first core problem is the context problem. The second is language-learning and development. Although there are a few people currently examining the problem relative to computers (e.g.,

McDermott - Ref. 3-179), no one yet has much of an idea how language is acquired. Some researchers feel that insights into language development must await some crucial breakthroughs in our understanding of nondevelopmental languages issues.

d. Applications. The current applications envisioned for natural language and hence the ones serving as a motivation for language-system research today are:

(1) Story comprehension.
(2) Machine translation of one language into another (see Wilks' "Preference Semantics" - Ref. 3-180).
(3) Paraphrasing and text abstraction.
(4) Question-answering.
(5) Automatic programming (generating programs from a natural language description of a problem; see also subsection 2, Human-Machine Communication, this section).
(6) General-purpose robots (see subsection 5, Robots, this section). These will probably remain as the general applications of natural language systems through the year 2000.

e. Forecast.

In the next 5 years

- Systems based on vocabularies of up to 2000 words (single senses) and inference components of up to several hundred inferences, which can comprehend the underlying causal connections in 5-10 line children's stories.

In the next 10 years

- Systems which can cope with multiple word senses by using context in the selection process.
- Systems which can function from spoken speech over a vocabulary of up to 1000 words (speech recognition will be driven in part by meaning context).
- Systems which can comprehend the essence of, say, a Sunday "Peanuts" comic strip.
- Systems which can translate, with relatively low error rate, an average newspaper article in one language into another language.

In the next 25 years

- Systems which can abstract text, capturing a passage's relevance along a specified dimension (e.g., political impact, economic impact).
- Systems which, given a natural-language description of some task, can synthesize small programs to accomplish that task (e.g., "how to assemble an engine," "how to bake a cake").
- Small-scale personal secretaries which can transcribe spoken natural language; such systems will incorporate a model of the speaker and of the domain of discourse.

Although strides will be made in language-learning and development, there is no evidence that suggests that any major results will be achieved in this area by the year 2000.

9. Problem-Solving Systems

a. Introduction. Problem-solving by machines consists in formulating a problem in a suitable representation, planning its solution, and solving it using information about its domain of application. A problem-solver is a general mechanism which works on a wide class of problems. Representative fields to which such techniques have been applied are game-playing (chess, checkers, go, etc.), propositional calculus, mathematics (symbolic integration, abstract algebra, geometry, etc.), robotics, question-answering, language-understanding, automatic programming. (See subsections 2, Human-Machine Communication; 5, Robots; and 8, Natural-Language Understanding.)

b. Background and Present Status

(1) 1955-1965. Research in problem-solving by machines was initiated in the late 1950s by Newell et al. (Ref. 3-181) with the development of the Logic Theorist (LT), a program designed to prove theorems in the sentential calculus. The LT successfully proved 38 of the 52 theorems of Chapter 2 of Whitehead and Russell's Principia Mathematica. Twelve of the 14 unsolved problems were not completed because of the physical limitations of the computer then available. The others were beyond the capacity of the algorithm for logical reasons. A modified LT operating on a larger computer later solved all 52 theorems (Ref. 3-182). The significance of the work lies in how the proofs were produced, not in the proofs themselves. In addition to the proof method, a new programming tool - list processing - was developed. List-processing techniques have found wide application throughout computer science (Ref 3-183).

A second major early development was the General Problem Solver (GPS) program of Newell et al. (Ref. 3-184). This effort was able to show that general problem-solving skills, divorced from specific content, did exist and could be implemented on a digital computer. To use GPS one had to define the structure of states specific to the program and operators capable of mapping a state into sets of states. Problems solved by GPS involve elementary logic, chess, high-school algebra, word problems, and question-answering for small data bases. The solutions of ten different small problems in fields ranging from symbolic interpretation to the "missionaries and cannibal problem" are described by Ernst and Newell (Ref. 3-185). GPS uses the heuristic technique of means-ends analysis, in which an initial problem state is transformed to a target state by applying operations which, step by step, reduce the differences between the states.

A number of different programs were developed using the basic ideas proposed by Newell et al. and a wide range of heuristics for specific problem domains. Typical problems dealt with involved symbolic integration (Ref. 3-186), geometry (Ref. 3-187), question-answering for trivial data bases (Ref. 3-188), and chess playing by machine (Ref. 3-189), to note but a few examples. The concept of a semantic net was developed by Quillian (Ref. 3-190), who recognized the need to guide searches

by using semantic knowledge about a problem domain. His approach was to build knowledge into a system based on a semantic network of objects and relations. The approach, although useful and interesting, was restricted to small semantic nets and was cumbersome to use.

The problems solved by a general problem-solver all shared the characteristic of smallness; nevertheless, the work in the first ten years, approximately 1955-1965, was a promising start.

(2) 1965-1975. Work during this period was in the following areas:

- Development of problem-solvers based on theorem proving.
- Formalization of problem-solving processes.
- Development of theoretical results on heuristic search.
- Development of problem-solving languages.

In 1965, problem-solving based upon work in mathematical logic was shown to be mechanically feasible by Robinson (Ref. 3-191), who developed what has become known as the Robinson Principle. Several problem-solvers were developed that used concepts originated by Robinson. The QA 3.5 system of Green and Raphael (Ref. 3-192) was used for question-answering and was also a part of STRIPS, a problem-solver developed by Fikes and Nilsson (Ref. 3-193) for work in robotics. STRIPS also combined the concept of means-ends analysis. A second problem-solver based on theorem proving was MRPPS, developed by Minker et al. (Ref. 3-194), which used numerous refinements of the resolution principle and heuristic techniques to guide the search. A number of experiments on different classes of problems (Refs. 3-195 to 3-197) indicate that only small, not very complex problems are capable of being solved by theorem provers based on what is now known, and other techniques are required.

Amarel (Ref. 3-198) and Banerji (Ref. 3-199) have attempted to formalize the problem-solving process. The concepts of state-space and problem-reduction representation are two formalizations associated with problem-solving (Ref. 3-200). To these representations one may add a third - theorem-proving. Problem-solving is intimately bound up with problem representation because, in a good representation, the solution of a problem might be obvious, while in a poor representation it might not be achievable within reasonable time or resource limits. Problem-solvers based on state-space representations provide bottom-up search, those based on problem-reduction provide top-down search, while those based on theorem-proving provide either top-down or bottom-up search depending on the inference system used (Ref. 3-201).

During this period the subject of heuristics came under theoretical attack and, as a result, several theorems were developed. A heuristic is any rule of thumb, strategy, or trick that may be useful in guiding a search. It may be based upon syntactic or semantic conditions. For the class of heuristics $f(n) = g(n) + h(n)$, where $g(n)$ represents distance from the starting problem and $h(n)$ is a heuristic measure of the distance from the current problem to a goal state, it has been shown that, if $h(n)$ is less than or equal to the "true" distance to the goal node, then the least-cost solution will always be found if one exists. These results have been found by Hart, Nilsson, and Raphael (Ref. 3-202) for state-space representations, Chang and Slagle (Ref. 3-203) for problem-reduction representations, and Kowalski (Ref. 3-204) for theorem-proving representations.

The approaches to problem-solving that have been described above are based primarily upon syntactic considerations. It was recognized that, to make greater strides, problem-dependent knowledge must be built into a system. One way to do this was to build in special procedures that would be called by the user when appropriate. To facilitate doing so, procedural programming languages were developed (MICRO-PLANNER by Hewitt - Ref. 3-205; CONNIVER by McDermott and Sussman - Ref. 3-206; QA-4 by Ruliffson et al. - Ref. 3-207; SAIL by Feldman et al. - Ref. 3-208). The language facilities of automatic backtracking and contextually supplied information are important tools for building interesting problem-solvers.

Problem-solvers were still characterized as capable of handling only small problems. Smallness is still the rule and will be so until and unless it can be established that the methods applicable to small systems can be extended to large ones.

c. Forecast. The forecast of developments for problem-solving systems is subdivided into three time periods: short-range (1975-1980), intermediate-range (1980-1990), and long-range (1990-2000).

(1) 1975-1980.

- Syntactic heuristics will be realized to have been developed as far as possible, and continued efforts in this area will not be significant (1975).
- Procedural languages will become more widely used for developing problem-solvers. The features in current systems will be exercised, and additional features will be incorporated. By the end of this period, the specifications for a procedural programming language for the next generation of problem-solvers should be in hand (1980).
- Inference systems, useful for problem solvers based on theorem proving, will be understood better. There is currently a large number of refinements of resolution in existence, while little understanding exists as to which may be useful under what circumstances. Some slight insights will be developed on the basis of experimental work during this period, while theoretical answers will have to await a later date (1980).
- Problem-solvers that employ parallel search methods will start to appear and be more widely used. A modest improvement in problem-solving capabilities will result for some problem types (question-answering), while for others there will be no major advances. Such capabilities are

being incorporated into a general problem-solver at the University of Maryland (Ref. 3-209) and into the CONNIVER programming language (Ref. 3-206) (1976).

- New control structures (generators, demons, message systems, etc.) will become generally available for problem-solvers. These will permit greater control over the growth of the goal graph and permit actions to be taken at nodes of the graph (1980).
- Fuzzy problem-solvers with the ability to handle data and general rules whose validity has some "fuzziness" will be available. The output of such systems will provide a solution to a problem and a measure of belief in the outcome. The best possible solution should be attainable (1980).

(2) 1980-1990.

- Knowledge-based problem-solvers will be developed for small problems. These will incorporate user-provided semantic information about the problem domain that can be handled in a general manner. The general problem of a good representation of semantic information will not yet be solved (1985).
- Interactive problem-solvers which permit user-control of the search process will be developed. Insights could be developed into the types of machine output to be presented to the user to permit him to exercise control over the system. Again these will exist only for small problem types (1985).
- Syntactic and knowledge-based information will be experimented with and a fuller understanding of when syntactic information will be useful relative to knowledge-based information will be achieved. Such trade-off studies will yield more intelligent problem-solvers (1990).
- Specialized tailored problem-solvers should exist. These will employ particularized methods that enable special knowledge of the problem possessed by the user to be transmitted to the problem-solver. Such systems will be able to handle only the specialized types of problems for which they have been designed (1985).
- Large system problems will start to be tackled so that problem-solvers may be used to solve significant problems. The problems capable of being solved now are relatively small and, with some exceptions, not significant. We are as yet unaware of the problems that may exist for problem-solvers in such an environment. This area will require special attention. Little thought has been invested in it, and yet if problem-solvers are to be useful they must work on real problems and not toy ones. By the mid-1980s some directions for the next major push could become apparent (1985).
- Inference systems in predicate-calculus-based systems will be characterized in relation to how well they might operate on different classes of problems (1985).

(3) 1990-2000.

- Representation of problems will be a major area of research whose outcome will affect how well problem-solvers work (2000).
- Effective representations of semantic knowledge to be used in guiding problem-solver searches will be developed. These will provide a framework around which problem-solvers will work (1995).
- Problem-solvers for large data bases using parallel search, syntactic clues, and semantic knowledge in an interactive dialog with a user should be available for experimentation and use (1995).
- Higher order logic-based systems will be available for use with problem-solvers. These will extend the types of problems that can be handled (1995).
- Inductive inference methods should be sufficiently understood to permit their incorporation in problem-solvers (1995).
- Large-scale question-answering systems that perform complex deductive searches should be available (1995).
- Automatic programming systems employing problem-solvers and able to handle loops will be successfully applied to problems larger in size than those that can be dealt with today (1995).
- By the year 2000 the following may become available:
  - Automatic selection of data representations for problems.
  - Automatic selection of representation for a problem.
  - Automatic debugging tools.
  - The ability to determine program correctness for programs of modest size (1000 lines).

D. SUMMARY

The forecasts in this section have been concerned with the hardware characteristics of Earth-based and spaceborne processor and storage systems, with the mechanics of their use and their programming, and with representative applications of importance to future space activities. Attention was focused on the prospects for giving computers more of the perceptive and cognitive faculties used by humans in processing information, and on two types of information systems that seem destined to become important human tools in the exploration and the utilization of space – teleoperators and robots. The purpose of this summary is to review the major trends and highlights of these forecasts.

The rapidly increasing gate density and decreasing cost of logic and memory will have a profound effect on processing and storing over the next quarter of a century, making it possible to experiment with and to use, in commercial systems, many architectural concepts formerly thought to be beyond feasibility. The impact of large-scale integration is already making itself felt in the consumer market, where small hand-held calculators with computational abilities exceeding those of most of the early computers are available for less than a hundred dollars. Largely as the result of the burgeoning demand for "personal" computers, total computing power is expected to expand at the rate of approximately three to four orders of magnitude per decade.

Over the next quarter-century, the performance (instructions per second, suitably averaged) of Earth-based systems is more likely to increase at a rate of approximately one order of magnitude per decade, roughly half that exhibited over the past 20 years. Improvement by a factor of ten overall can be expected from increases of logic speed; beyond that, what is achieved will depend strongly upon the nature of the application. For array and image processing and other procedures that lend themselves to a high degree of parallel computation, three to four orders of magnitude increase in processing speed may well be expected before 1990. For general applications, the rate of increase will be slower. The structuring of algorithms that will lend themselves to parallelism will present problems that are not expected to be easily solved. These will demand considerable theoretical attention during the remainder of this decade and throughout the 1980s. Overall, beyond the increase attributable to logic, another factor of one to two orders of magnitude in performance can be expected from the introduction of new architectures.

The capacity of Earth-based mass-storage systems has been increasing at the rate of approximately 10^4 per decade. If this growth continues, systems of 10^{21} bits will be available by 2000. In view of the present trend toward the combination of logic and memory in low-cost processor-storage elements, it seems likely that more "intelligent" schemes will be introduced to manage and use such enormous quantities of data. To keep problems of access and search within bounds, information may be organized and stored in relation both to its content and to the context provided by the information already in storage.

The increasing density and reliability and decreasing cost of logic and memory will make it possible to place far more computing power on board spacecraft. Each independent function will be controlled by a separate processor-storage element, acting independently or under central coordination with other such elements. Mass-storage systems for spacecraft holding 10^{14}-10^{15} bits are foreseen. These capacities are three orders of magnitude beyond those projected for current approaches. Thus, the development of practical electro-optical systems will be necessary. Reliability will continue to be of concern for spacecraft data systems, despite advances in the reliability of components. Not until the end of the century will computers be able to detect, diagnose, and repair their own malfunctions.

The presence of more on-board computing power will make it possible to employ a variety of source-encoding methods that can extract from raw data the information needed by the users, thereby reducing the total quantity of data that must be transmitted. Their use will be essential in coping with the explosive growth in data from spacecraft instruments and sensors. Depending upon the needs of the users and the characteristics of the data source, compression ratios of from one to three orders of magnitude will be achievable. The significance of this capability is that, overall, and for a given data-transfer capability, the useful data return from a remote spacecraft can be increased by a factor of approximately 100. Throughout most of the century, on-board compression systems will be highly interactive. Users on Earth will control the criteria used by the on-board system to select and encode data for transmission. Perhaps toward the end of the century, some spacecraft systems operating very far from Earth may be able to change such criteria adaptively, in accordance with stored instructions, to focus on interesting features of incoming data.

The requirements for automated on-board image-processing and analysis will both stimulate and be benefitted by advances in the automation of vision. Throughout the remainder of the century, interaction between psychologists and physiologists concerned with understanding vision, and computer scientists attempting to automate perception, will lead to steady advances in this difficult and challenging subject. From greater understanding of the types of errors and distortions that can be tolerated by human users of image data will come more realistic criteria for image-coding and processing for interactive information extraction systems. The results of this work will be incorporated in autonomous vision systems. During the decade of the 1990s, robot vision systems using scene-analysis techniques will perform inspection and assembly work in controlled industrial environments. Vision sensors will be developed that will combine light-sensitive elements and logic, as within the retinas of the eyes of higher animals. The front ends of these systems will consist of a very large number of parallel computing structures, able to process data in times of the order of milliseconds. Machines can thus be given the ability to perceive

objects in motion. These sensors will be included in robot vision systems and in mission and sequence control mechanisms, and as flight opportunities emerge, automated vision in space will become common. Toward the end of the century, engineers will design vision systems incorporating knowledge of what humans are able to see when they look at scenes; most routine vision tasks will have been automated.

Presently, the practical use of computers is limited by the problems of software production and by the specialized knowledge of computers and procedures that is required. No breakthroughs are foreseen in steps to increase programmer productivity and to decrease the cost of software generation - computer software is the complex product of human creativity, and its generation is not likely to be advanced by any single development. Nevertheless, steady progress will result through a number of individual advances, such as better program design and software management approaches and more powerful languages and machines. Between now and 2000, programmer productivity may increase one to two orders of magnitude, largely as the result of the spread of structured programming, which should be widely adopted by the first half of the 1980s. Automatic software generation is not expected to be realized before the end of this century, although problem-solving systems may be available for proving the correctness of programs of modest size (approximately 1000 lines) by 2000.

The variety and limitations of present computer languages inhibit the use of computer systems by people who are not specialists. By the end of the century, machines will have advanced greatly in their capacity to understand natural language. They will be able to cope with multiple-word senses by using context. They will be able to translate, with relatively little error, an average newspaper article from one language to another. Given natural-language descriptions of some simple tasks, they will be able to synthesize small programs to accomplish them. They will be able to abstract text, capturing what is relevant in the passage in relation to a prespecified context or topic. By the end of the century, speech-input systems will be able to recognize several thousand words of spoken language. Small-scale personal secretaries which can transcribe spoken natural language may be available. It is not expected that, by 2000, machines will be able to learn or develop language skills automatically, but taken together, the advances forecast could give machines an ability to understand and use natural language that will somewhat ease the human-machine interface problems presently experienced.

During the early years of the 1980s, teleoperators will be introduced in near-Earth applications. Their further use and development will contribute to, and in turn be stimulated by, the development of facilities for automated production on Earth. The teleoperator/robot industry supplying components and systems is expected to grow by one to two orders of magnitude in annual volume over the next quarter century.

Space-qualified robot systems with some advanced automation will be available toward the end of the 1980s. The first robots used will be interactive in that they will depend upon human beings for most critical decisions and for planning. Their automated sensory and motor capabilities, however, will enable them to perform a wide variety of tasks needed for the exploration of remote planetary or satellite surfaces safely and efficiently in the presence of a long communication time delay.

E. PARTICIPANTS[1]

The people listed below as contributors assisted in the planning, solicitation, or preparation of the forecasts of this section. Those designated thus (*) bore major responsibility for the numbered portions of subsection C, Forecasts. Also included are the names of people who provided ideas or supporting material for the introduction to Part III, Management of Information. The efforts of all these contributors, made always with limited time and in the midst of other activities, are gratefully acknowledged.

Listed as consultants are people within NASA to whom earlier drafts of Processing and Storing of Information were sent for review, as well as people in outside organizations who, in discussions at meetings or in writing, made suggestions pertinent to this section. Many helpful comments and suggestions were received from the RTAC Committee on Guidance, Control, and Information Systems, from members of NASA Headquarters' staff during a telephone conference and in other meetings, and from P.G. Ackerman on behalf of the AIAA Technical Committee on Space Systems. The time given to this undertaking by those listed as consultants and by those not named specifically, their recommendations, and the uniformly constructive spirit in which they were given, were much appreciated by the contributors and the Coordinator. If all the suggestions were not acted on in the final revision, it is largely because time and resources did not permit it, not because their value and validity were unrecognized.

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F. INDEX OF MICROFILMED FORECASTS

No additional forecasts are available for the processing and storing of information.

Section V. SUMMARY AND IMPLICATIONS

W. M. Whitney

The purpose of this concluding section is to summarize and put into perspective the highlights of the forecasts concerned with the acquiring, transferring, processing, and storing of information. The emphasis is on the space applications of new technology. More detail, and some additional comments about non-space applications, will be found in summaries following the forecast sections.

The primary agents for change in the evolution of space-related information systems will be the steep growth in the amounts of data returned from space, and the necessity for making acceptable the cost of dealing with it and deriving the benefits from it. By the year 2000, imaging experiments in Earth-applications satellites will be capable of returning 10^{13} - 10^{15} bits per day, in comparison to the present rates of 10^{10} - 10^{11} bits per day. The lower value of 10^{13} bits will encode approximately one million 300-page books; that much data per day corresponds to 30 Libraries of Congress per year. Comparable increases can be expected from other missions, reflecting great improvements in the sensitivity (by factors of 30 to 3000), range, and versatility of remote sensing instruments. Providing for efficient and economical handling of the influx of data from the many Earth satellites and deep-space probes will create large management and technology problems that can be expected to stimulate a search for effective solutions.

Greater emphasis in the future will be placed on designing entire information systems from end to end for a given application. In implementation, the focus will be on more comprehensive functional subsystems, in which a variety of technologies and disciplines not traditionally tied together will merge. Broad technical understanding will be required of the people responsible for bringing these systems together, and some organizations may have to be restructured along new lines.

Improved and more numerous spaceborne instruments, whose sensitivity promises to increase between now and the year 2000 by factors ranging from 30 to 3000, will be the source of what has been termed the "data deluge." Performance improvements by factors of 10 to 100 for X-ray and gamma-ray instruments promise significant opportunities for exploration in this important new astronomical window. Steadily increasing use of radio and radar sensors for Earth applications will be a major driving force for the development of transmitters with multikilowatt peak power levels and with nanosecond pulse durations at L, S, X, and K bands and above, multiband receivers with extremely low noise temperatures at all microwave frequency bands, antennas with unique beam shaping to provide required Earth or planet coverage, and large volume, complex and real-time signal processing. A comparatively modest upgrading in the capability of landed instruments is suggested, but considerable uncertainty in the programmatic resources that will be available to support such instrumentation makes the "what will be" forecasts indeterminate. Many of the instrument advances forecast depend critically upon the development of high-capability spaceborne cryogenic systems.

The increasing use of large-scale integrated circuits (LSI) will have a significant impact on remote sensing. The instruments themselves will become more independent of step-by-step ground control during stages of the measurement process. Microprocessors contained within the instrument systems will enable the outputs of the physical sensors to be better accommodated to the requirements of the overall information system in which they are imbedded. Data-compression and information extraction performed on board will reduce the amount of data transmitted to Earth.

To take full advantage of the capabilities of remote sensors in specific applications (for example, Earth resource surveys), it will be necessary to upgrade strongly the level and sophistication of efforts directed to theoretical modeling, on which both experiment design and interpretation of measurements yielded by remote instruments depend.

Data rates of communication links between Earth, Earth satellites, and planetary spacecraft will increase to accommodate higher data transfer requirements, and their cost will decrease. Almost all deep-space links and a majority of satellite and Earth links will continue to use microwave bands up to 30 GHz. Higher bands will be used for military application, primarily to avoid crowding the lower bands and to achieve secure communications. For some Earth-space links, on-board source encoding or data compression (see below) will reduce channel capacity requirements. Space systems with inexpensive data and acquisition systems will take advantage of the availability of large transfer rates at relatively low cost by transmitting all data at high rate to central processing stations.

Communication among satellites in synchronous and low-Earth orbit and Earth-based stations will reach gigabit rates over microwave and optical links during the next 25 years. Satellite optical links will communicate to a multitude of Earth receiving stations, widely separated geographically. Optical cables will link these stations to central processor sites.

Use of satellites will make Earth communication costs largely independent of distance. The rate at which satellite communications will grow, however, is dependent upon a large number of complex positive and negative factors such as capital investment of existing communication facilities and frequency allocation problems.

Satellites in geosynchronous Earth orbit will relay data received from deep-space probes to a central station. In time, the Earth-based receiving stations located at longitudes approximately 120 degrees apart for continuous coverage of deep-space transmissions may be replaced by orbiting antennas.

Deep-space communication links will exploit communication-satellite technology to achieve higher rates at the higher frequency bands. Satellite requirements in this respect have historically led and will continue to lead deep-space link requirements.

For spacecraft, large, lightweight, deployable antennas, small integrated solid-state transmitters and receivers, and ultra-stable time standards are projected as major developments.

Near-theoretical limits of receiver-noise temperature and channel coding efficiency will be achieved by the year 2000 to the point of diminishing return. The emphasis in coding development will shift toward reducing bandwidth requirements, avoiding interference, and providing security.

By the year 2000, large structure technology will allow the erection in Earth orbit of antennas on the order of a km in diameter and on deep-space probes, antennas as large as 10^2 meters in diameter. The large antennas would be needed if a commitment were made to detect electromagnetic signals emanating from other civilization in space. In addition, there would be requirements for wide-band and low-noise receivers and processors, capable of searching hundreds of megacycles of bandwidth and resolve the spectrum to within 1 Hz.

If a major attempt is made during the next 25 years to detect electromagnetic signals from other civilizations in interstellar space, antennas with diameters as large as 3 km will be required. These could be constructed from arrays of large Earth-based antennas, or erected in space. It will be a significant challenge to reduce the cost of such a project to the point that it would be considered attractive.

Large-scale integration will also affect information transfer. More and more, communications systems will consist of integrated transmitters, receivers, and antennas. Antennas with large effective apertures will be synthesized from arrays of small dipole elements, each connected to its individual receiver. Phasing of electronic elements will point and shape the beams and adjust their polarizations. Various transformations — for example, time correlations and fast-Fourier transfer forms of signals of large bandwidths requiring high spectral resolution — will be accomplished inexpensively with microprocessors.

The rapid development of large-scale integrated-circuit technology (LSI) and its diminishing cost will have an especially profound impact on the processing and storing of information. The single-chip processors being introduced today will expand the number of computers and the computing power available at an expected rate of three to four orders of magnitude per decade. This increase will reflect largely the growth of the market in the small dedicated "personal" computer. The performance capability of medium-to-large-scale systems is expected to grow by one order of magnitude per decade over the next 25 years, roughly half the rate exhibited over the past 20 years. The increase will be achieved primarily through advances in parallel processing and the use of more intelligent peripherals. Users with limited computing facilities will have access to large-scale computing systems with additional processing capabilities and data bases through federated computer-system networks, currently in the development stage.

The implementation of spaceborne data-processing and control functions will follow commercial trends. The concept of applying dedicated computers to individual functions will be realized on board space vehicles by 1985. Initially, these computers (microprocessors) will be independent, to simplify software and hardware complexity. Later, still more dense microcircuits and new software concepts will permit integration of computer elements at higher levels to provide load-sharing and fault-tolerant operation.

Advances in flight data-system hardware and software will promote the transfer of more responsibility to spacecraft and satellites. Source encoding (data compressions) on board will reduce requirements for channel capacity for space-to-Earth communication links and ease problems of rapid and economical dissemination of mission results. By the year 2000, the volume of transmitted data required to meet currently considered space-mission objectives will be reduced by a factor of approximately 100 by such encoding methods. Users will interact with spacecraft and satellite image-processing systems to select and control the criteria employed in on-board information extraction. In future years, perhaps beyond 2000, the spaceborne information system itself will optimize the filtering of the measurement data to sift out the information that corresponds to criteria and constraints.

The information-return from missions on the surfaces of planets or their satellites will be greatly enhanced through the use of advanced robot systems. These will carry out certain operations automatically — for example, the collection and manipulation of rock and soil samples and the control of scientific instruments. Human beings on Earth will plan such actions and initiate them, but will not guide their step-by-step execution. Such "supervisory control" methods will also be employed in teleoperator systems used near Earth for Shuttle operations, in the construction of large space structures, and eventually on the Moon.

For other than surface explorers, similar control methods and more capable and reliable on-board operating systems will provide all classes of spacecraft and satellites with increased autonomy. Deep-space probes, for example, will

be able to determine their positions and calculate corrections to their trajectories. Earth-based control and communication facilities can be used to support more missions at a given time than is now possible with more dependent space systems. Automation should also eliminate some of the more tedious aspects of mission control.

Presently, the generation of computer programs and the mechanics of using computers present serious bottlenecks to obtaining the full benefits of automated information handling. Difficulties in planning, estimating, producing, controlling, checking, and maintaining software make it costly. Lack of standardization in machines and in programming languages, rigidity in the format of discourse, and many other limitations make the interface between human beings and computers uncongenial and the exchange of useful or valuable information across it slow. The direct use of computers in accomplishing a wide variety of tasks, which could benefit many, thus remains the professional domain of relatively few.

Significant software advances are seen as essential to facilitate the communication between user and computer for program generation and use, and to take full benefit of the great projected increases in the availability of low-cost computer systems. Although no breakthroughs are foreseen in addressing the many complex problems involved, certain developments are considered likely. Present structured design procedures for the analysis of a processing task into program requirements will mature. Increase in programmer productivity by a factor of approximately 10 to 100 by 2000 is forecast. There will be some standardization of programming languages, compilers, and hardware. Higher-order languages with syntax closer to English will be developed, with concurrent deemphasis on efficient use of the computer. Computer-generated program listings that clearly communicate the function of the program to the human user will be developed. Progress in computer recognition of spoken English, measured in terms of the size of speaker vocabulary allowed and the variety of speakers accepted, will enable people to speak with a vocabulary of a few thousand words to a computer and have the words understood. Advances in natural-language understanding by the end of the century will enable the computer to understand also the content of simple instructions and to prepare programs to carry them out. The abilities of the computers to understand complex instructions will still be limited and the domain of problems that computers can solve and reduce to programs will be small, but the advances will be significant and promising steps toward a better accommodation between human beings and machines.

In the Introduction to this Part of the Forecast of Space Technology, four issues were singled out for discussion as characterizing important trends or problems in space-related information management activities: the increasing quantities of data that must be handled — the "data deluge;" problems associated with programming and using machines; reliability; and the need for a better understanding of information functions so that they can be automated. It is now apparent from the summary that work being done in the areas forecasted addresses these problems and promises some significant improvements during the next 25 years.

It is also apparent, however, that reliability has not received attention in the individual forecasts in proportion to its importance. In future forecasts of space technology, more emphasis needs to be given to this essential attribute of all space hardware and software.

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A FORECAST OF SPACE TECHNOLOGY

Part Four. MANAGEMENT OF ENERGY

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PART FOUR GLOSSARY

DOD	Department of Defense
EMI	Electromagnetic Interference
ERDA	Energy Research and Development Administration
F	Thrust
F-1	Saturn First Stage Engine
FBB	Fly-Back Booster
GLOW	Gross-Lift-Off Weight
HST	Hypersonic Transport
HTOHL	Horizontal Takeoff- Horizontal Landing
IOC	Initial Operational Capability
LO_2-LH_2	Liquid Oxygen/Liquid Hydrogen Propellants
MGD	Magnetogasdynamic
MHD	Magnetohydrodynamic
MMH	Monomethylhydrazine
MPD	Magnetoplasmadynamic
NEP	Nuclear Electric Propulsion
NSF	National Science Foundation
N_2O_4	Nitrogen Tetroxide
OMSF	Office of Manned Space Flight - NASA
OSS	Office of Space Sciences - NASA
P/L	Payload
RJ-5, RP, HC	Hydrocarbon Rocket Fuels
RTG	Radioisotope Thermoelectric Generator
SEP	Solar Electric Propulsion
SRB	Solid Rocket Booster for Space Shuttle
SSME	Space Shuttle Main Engine
SST	Supersonic Transport
SSTO	Single Stage To Orbit
STO	Stage To Orbit
TUG	Chemical Stage for Use in Orbital Operations With Space Shuttle
T/W	Thrust-to-Initial Weight Ratio (lbf/lbm)
V_e	Effective Exhaust Velocity
VTO	Vertical Takeoff
VTOHL	Vertical Takeoff - Horizontal Landing
VTOVL	Vertical Takeoff - Vertical Landing
λ	Propellant Mass/Total Stage Mass

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Section I. INTRODUCTION

D. F. Dipprey

A. SCOPE

The primary goal of this portion (Part Four) of "A Forecast of Space Technology" is to examine the technological advances and innovations in the management of energy that could be made available to support the national space activities in the 1980-2000 era. Toward this goal, forecasts of the possible status of energy technology during that period have been made. It is the intent of these forecasts to provide support to the task of estimating the technological and economical feasibility of space activities during that time frame.

As in the case of the other technological areas examined, the forecasts in energy predict the foreseeable technical advances. The primary emphasis is given to the question "what is possible?" without any limits being placed on the authority and funding required to bring into being any of the innovations and advances being conceptualized. The question of a definitive "what is needed?" is not within the scope of this portion of the Outlook for Space Study. Some consideration is given to the question "what will be" the capability? Efforts to answer this question, however, are usually impeded by lack of insight into the Space Program funding and emphasis in the time period of interest.

The forecasts should, thus, aid in determining if proposed missions are possible and if so what they might cost. The forecasts are not intended to provide the detail or accuracy needed to recommend which of competing options may prove to be most cost effective, and therefore which of the many competing technologies should be accented. More extensive studies will be needed for this purpose.

B. ORGANIZATION

Generally, the concept employed in structuring the assessment in the matter and information areas was regarded as being applicable to the management of energy. Energy can be acquired, processed, transferred, and stored, and within these functions a structure was conceived and used to establish a comprehensive catalog of devices which could be available to space technology in the time period under consideration. It was decided, however, that within the field of management of energy the final uses of the assessment would be better served if two major uses of energy were examined separately; viz, (1) Earth-to-orbit operations, which are concerned with propulsion equipment and operational strategies for launch from the Earth's surface through the atmosphere to near-Earth-orbit and return, and (2) space power and propulsion, which are concerned with the functional devices for the acquiring, processing, transferring and storing of energy, for both power and propulsive applications, for all space operations outside of the Earth's atmosphere. Further details on the forecast structure will be given in the individual sections which follow.

Section II. ENERGY FOR EARTH-TO-ORBIT OPERATIONS

H. P. Davis and D. F. Dipprey

A. SCOPE

The forecasts which follow offer cost projections for launch services and are intended to aid in formulating programs. Neither the costs of employing the existing launch vehicle fleet nor the "tariff structure" of the Space Shuttle during its early operational phase will be addressed. These data may be readily obtained through the responsible OSS and OMSF staffs. What will be addressed are the relationships which are predicted by the forecasters to exist between the initial investment in major product improvement to present launch vehicles, including the Space Shuttle, or in new launch systems and the resultant costs of employing the increased capability and/or lower-cost launch systems.

The objective of the Earth-to-orbit forecasting activity is to develop information on the possible costs of placing material into low Earth-orbit during the 1980-2000 time period. The investment which can be justified in improving existing launch vehicles or in the development of new systems has become a familiar topic to NASA during the recent deliberations on the Space Shuttle Program.

B. BACKGROUND

The atmosphere which prevailed during the 1961 study of large launch vehicles (Ref. 4-1)* called upon the study group to define and assess the alternative ways of serving a generally well-defined set of needs - the Apollo Program and the large military space projects. Dominant factors in these 1961-62 evaluations were program risk, vehicle reliability, and the ability to maintain the schedule required by President Kennedy's statement of the Apollo goal - to complete the manned lunar mission within the decade.

The environment for the 1971-73 Shuttle deliberations required the decision-makers to provide careful consideration of total program costs, and annual funding limits for the several attractive system alternatives. A major difference in the 1961 and 1971 decision-making was the availability in 1971 of the much improved technology base established by the Apollo and contemporary space and missile programs of the preceding 10 years. Once again, a reasonably well-defined "traffic model" for the 1980-1991 time period was available and was employed extensively in the Space Shuttle Program decision-making process (Ref. 4-2).

*References may be found at the end of Part Four (see Page 4-48).

C. ORGANIZATION AND APPROACH

In the present launch vehicle forecasting endeavor, the Space Shuttle Program and the national capability it represents are well understood and are considered to be the points of departure for the forecasting process. The programs and projects which will generate the requirements for future launch vehicle capability are not yet completely defined. Consequently, when the requests for launch vehicle forecasts were formulated, four levels of space activity were postulated that covered a broad range of potential requirements of the annual total payload to and from orbit and of the payload capability of each launch.

Each forecaster was asked to provide forecasts in five parts: the first four to predict ("what is possible") non-recurring, annual capability maintenance and direct launch costs for four specified, increasingly ambitious, levels of activity; the fifth part was reserved for expression of the forecaster's personal view of "what will be" the time history of investments in, and costs of employing launch vehicles through, the year 2000.

The four levels of space activity were defined for the forecasters so that they could provide cost projections on a common basis, corresponding to "what is possible". For each level of activity they were asked to forecast the direct charge for space launch ($/unit mass delivered to low Earth-orbit), the one-time investment required to develop and acquire the launch vehicle fleet, and the annual investment required to maintain and preserve this fleet at zero launch rate. Forecasters were requested to express costs in terms of 1975 dollars. The levels of activity specified are as follows:

Level	Payload/Yr, 10^6 lbm/Yr (kg/Yr)		Payload/Launch, 10^3 lbm (kg)
	Up	Down	
I	0.5 (0.23)	0	30 (13.5)
II	4 (1.8)	1 (0.45)	60 (27)
III	20 (9)	2 (0.9)	400 (180)
IV	100 (45)	2 (0.9)	2000 (900)

The forecasters were asked to provide additional information on the vehicle concepts they envisioned to serve each level of activity so that their three monetary forecasts at each activity level could be better understood. They were also asked to forecast when, within the 1980-2000 period, any new systems might first attain operational status.

No attempt has been made to operate upon the forecasters' data, either to examine critically the technical features of the concepts suggested or to assess the cost factors offered. Such assessment will be essential to a comparison or selection of concepts, but it is not considered crucial for estimating the potential cost factors at each of the four levels of activity.

The forecasters were asked to comment upon the use of critical resources, possible adverse effects on the Earth's environment, the materials technology required, and safety considerations concomitant to the execution of the four levels of launch and recovery activity.

D. FORECASTS

1. Background, Present Status, and Forecast of 1980 Improvements

The United States entered the space age on February 1, 1958, with the launching of Explorer 1, a 14-kg satellite, into low Earth-orbit with the Jupiter-C launch vehicle which was derived from the Redstone artillery missile. The Thor, Atlas, and Titan II missiles have since been modified and pressed into service as standard space launch vehicles. The Scout, Saturn I, Saturn IB, and Saturn V were designed from the outset to serve space launch requirements rather than to provide a strategic force capability. The Saturn series was provided explicitly to support the Apollo manned lunar mission needs and, in spite of a very large payload capability, has not been utilized other than to serve the needs of manned space programs. With the cancellation of the Apollo missions (beyond Apollo 17, which was launched on December 7, 1972) the Saturn V has been used for only one subsequent launch; the Skylab Orbital Workshop, which was launched on May 14, 1973. Two Saturn V vehicles (514 and 515) are available for use until August 1977 when launch complex 39 is scheduled to be reconfigured for the Space Shuttle. Further study would be necessary on the question of availability of a fully trained launch preparation crew for Saturn after the July 1975 launch of the Apollo/Soyuz mission on the Saturn IB.

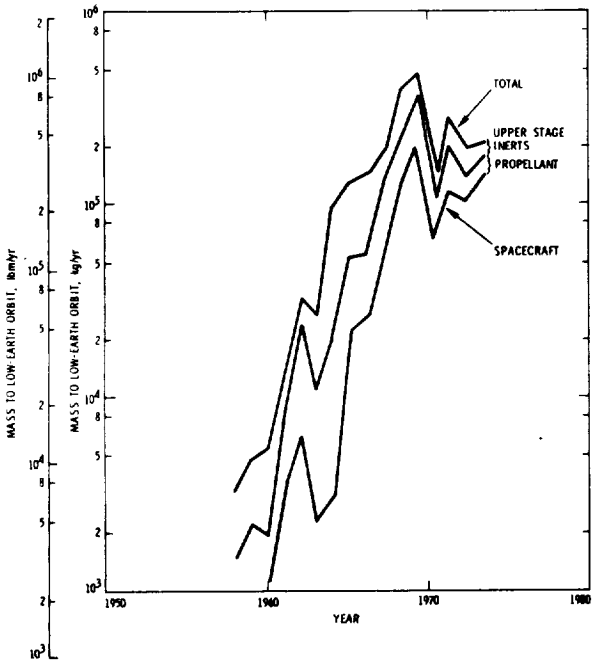


Figure 4-1. NASA launched mass to low Earth-orbit per year

Figure 4-1 illustrates the history of payload, propellant, and upper-stage mass placed into low Earth-orbit by NASA for the 16 years of U. S. space flight through 1973. An aggregate total of about 5×10^6 lbm (2.3×10^6 kg) has been placed into orbit during this interval. In the process of achieving this orbital placement, over 11×10^6 lbm (5×10^6 kg) of launch-vehicle inert mass has been expended (Ref. 4-3). Since 1970, about 25% of this traffic has been in support of commercially funded satellites.

Launch vehicles currently available include the small Scout multistage solid, the Delta family with several variations of strap-on solid motors, the Atlas-Centaur, and the Titan III vehicle family. Their characteristics and performance are available in Ref. 4-4. The primary distinction among the Titan vehicles is the choice of an upper stage - from none in the case of the Titan IIID, the Earth-storable propellant Transtage for the USAF Titan IIIC, and the Titan IIIE with the Centaur cryogenic O_2/H_2 stage. None of these vehicles is currently man-rated, though proposed effort and past usage of the Titan II for the Gemini Program could enable the Titan III vehicles to be candidates for upgrading to manned vehicle status. The only man-rated booster now operational is the Saturn IB, which will launch the Command/Service Module for the Apollo-Soyuz mission in the summer of 1975. Current planning is for NASA to phase out the Delta, Atlas-Centaur, and Titan IIIE vehicles for unmanned missions after the Space Shuttle becomes an operational vehicle.

By 1980, the launch vehicle capability of the United States will be dramatically improved by the attainment of operational status of the Space Shuttle. This vehicle will be capable of launching 30,000 kg payloads to low Earth-orbit within a protected payload compartment of 300 m^3 volume, of providing extensive orbital services to these payloads, including man-tending, for long durations and of returning, intact, payloads up to 14,500 kg from low orbit to Earth. Limited space maneuvering capability (several hundred m/s), high-accuracy placement, space positioning, and orbital assistance in deployment and initialization are all services that this system will provide to the orbital spacecraft after initial service as a launch vehicle.

The Space Shuttle will be a reusable vehicle; its external propellant tank is the only element expended during the conduct of a launch and orbital support mission. Consequently, the cost of launch to low Earth-orbit is expected to be reduced by a factor of three to five, compared to the present day expendable launch vehicles. Perhaps of equal importance, the payload compartment volume of the Shuttle will permit design

of low-density payloads, greatly facilitating their fabrication and functional testing prior to launch commitment. Furthermore, the intact return capability of the Shuttle will allow recovery from noncatastrophic spacecraft malfunctions on orbit, preserving the investment in the spacecraft, and will permit retrieval of satellites for updating or correction of flaws whenever retrieval and refurbishment is found to be less expensive than providing a new unit.

The development of the Shuttle is advancing the state of technology in several important areas of consequence to follow-on activities in space: high-chamber-pressure O_2/H_2 rocket engines, reusable surface insulations capable of repeated reentry through the Earth's atmosphere, large (3.7 m dia.) solid propellant rockets, the use of composite materials for major structural elements, and the generation of the advanced analytic techniques necessary to apply these technology improvements and to predict their behavior in the mission environment. In the aggregate, the technology advancement provided by the Shuttle Program will offer a new, higher-level plateau on which the Nation can build the space systems of the 1990s and beyond.

2. Forecasts for 1980 to 2000 (What is Possible)

a. General Observations. One of the more interesting observations of the forecasts was the absence of an expectation of "revolutionary" developments which would "drop the bottom out" of launch vehicle costs before the year 2000. A generally pessimistic view was taken by all of the launch vehicle forecasters concerning such breakthroughs, even though highly significant cost reductions are anticipated by evolutionary change.

Chemical rocket systems dominated the forecasts. Several approaches are considered for reducing the cost of use: technology extrapolation, greater application of reusable systems, and, for Levels III and IV, the benefits of larger scale. Another forecasting group suggested that atomic or metallic hydrogen or excited oxygen compounds in conjunction with hydrogen might find application to launch vehicles toward the end of the century, provided current research bears fruit.

Specific reference was made by several forecasters to their review of nuclear, beamed electromagnetic energy and other advanced concepts, with no satisfactory vehicle concepts resulting from their reviews. Airbreathing first stages were suggested, but these forecasts suffered from either sparse definition or extremely-high predicted development costs. This field was mentioned as having promise, with further definition needed to provide adequate forecasts. Air-breathing rocket composite systems could possibly find advantageous application late in the 1990s.

With a few exceptions, the forecasters saw the Space Shuttle accommodating the needs of Levels I and II, with product improvements folded in during the Space Shuttle's lifetime which yield benefits in rough correspondence to the investment. Levels I and II configurations are shown in Figs. 4-2 and 4-3. Note that some forecasters projected continued effective use of expendable vehicles at Levels I and II. Level I especially, calls for traffic sufficiently far below Space Shuttle capability that expendable vehicles may indeed provide a lower cost approach, assuming no expansion of space traffic beyond this level.

The Level-II forecasts revealed concern about both the high operational costs and possible environmental impact of the solid-rocket booster of the Space Shuttle. A general interest in proceeding with the early development of a reusable liquid booster of some form was noted. Forecasts of flyback booster systems generally anticipated a large investment, when compared to ballistic entry, parachute recovery of liquid booster systems. One forecaster suggested that the current Space Shuttle could be evolved later to utilize "mixed mode" propulsion and to eliminate continued use of solid-rocket boosters. He suggested incorporating an RJ-5 (high-density hydrocarbon fuel) propellant tank, an increased oxygen supply, and four O_2/RJ-5 engines into the Space Shuttle external tank, thus achieving single-stage-to-orbit with the current Space Shuttle Orbiter. This concept would utilize a portion of the Space Shuttle "down" payload capability to retrieve the O_2/RJ-5 engines.

While considering the higher capability Level III and IV systems, several forecasters made the point that such vehicles need not have payload retrieval capability, as the specified down-traffic could be accommodated adequately by the smaller Shuttle-derived systems of Level II, assumed to have continued existence after introduction of the new heavy-lift launch vehicle. Two forecasters, however, envisioned a need to return a much higher fraction of the deployed payload than specified for Levels III and IV and, consequently, they suggested far more expensive scale-up of either the Shuttle derivative vehicles or the airplane-like single-stage-to-orbit (SSTO) with an enclosed payload bay to serve that need. Level III and IV configurations are shown in Figs. 4-4 and 4-5.

The majority of forecasters did not offer a projection for Level IV (2×10^6 lbm/launch or 1×10^6 kg). The forecasters who did offer concepts envisioned vehicles based on ideas developed during the early 1960s' consideration of reusable vehicles of the NOVA class; giant modified conical shapes designed for single-stage-to-orbit, vertical launch and vertical landing. There were also suggestions of very large second- or third-generation SSTO and two-stage piggyback Shuttle-like vehicles.

A recurring theme for the launch vehicle technology was a need for a high-performance hydrocarbon/oxygen engine for use in the early part of the launch sequence. The benefits of high propellant-density in improving structural fractions of the vehicles led to conclusions that a new generation O_2/RP or O_2/RJ-5 engine would find broad application. Several of the SSTO suggestions included the dual-mode engine; i.e., an engine capable of burning a dense hydrocarbon as a fuel in the early phases of flight, shifting to hydrogen fuel in the same engine for the later phases. Other forecasters anticipated other means of achieving the same or greater benefits by staging tanks and/or engines after the early-boost phase or by employing a carrier aircraft for air-launch.

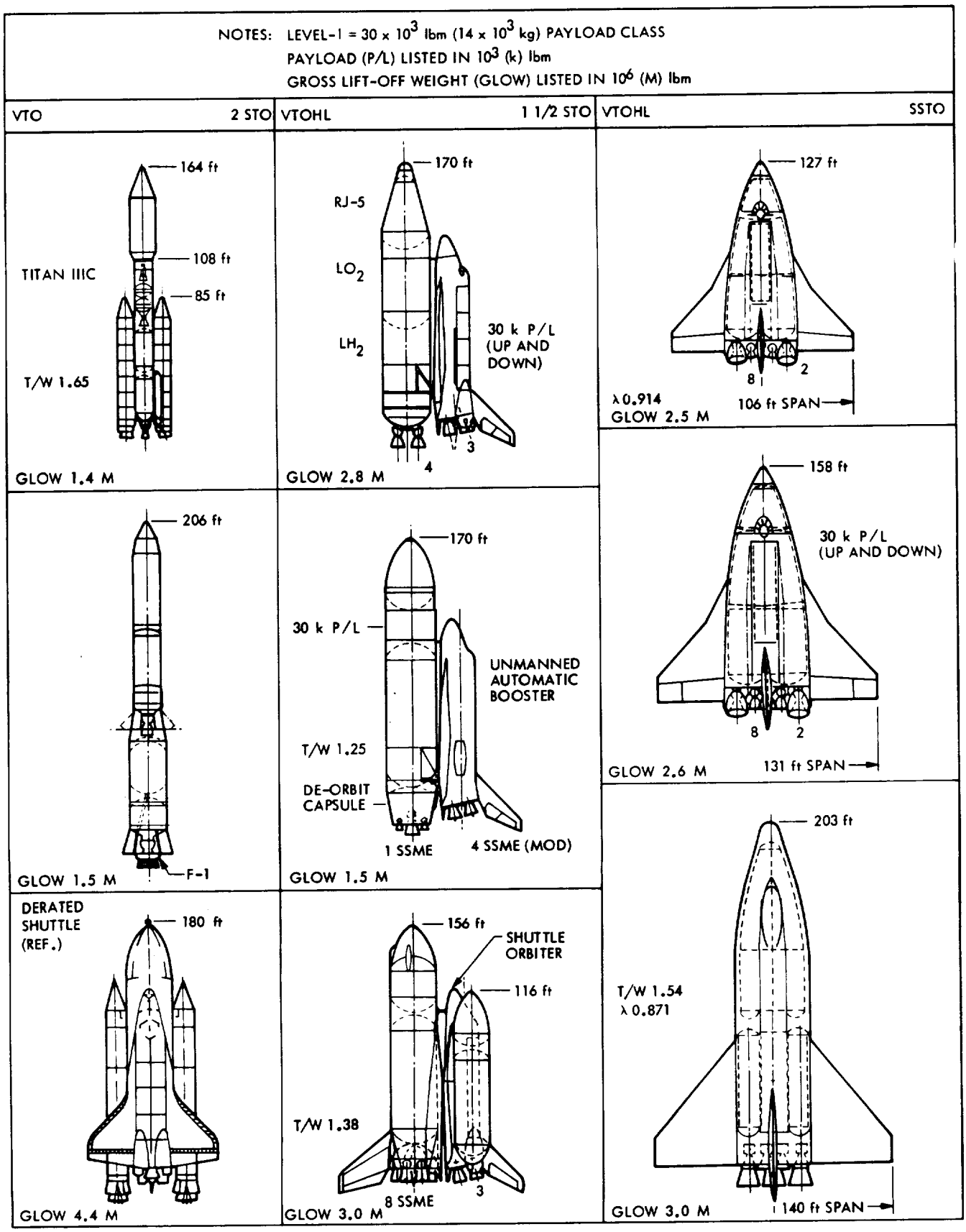


Figure 4-2. Level-I configurations

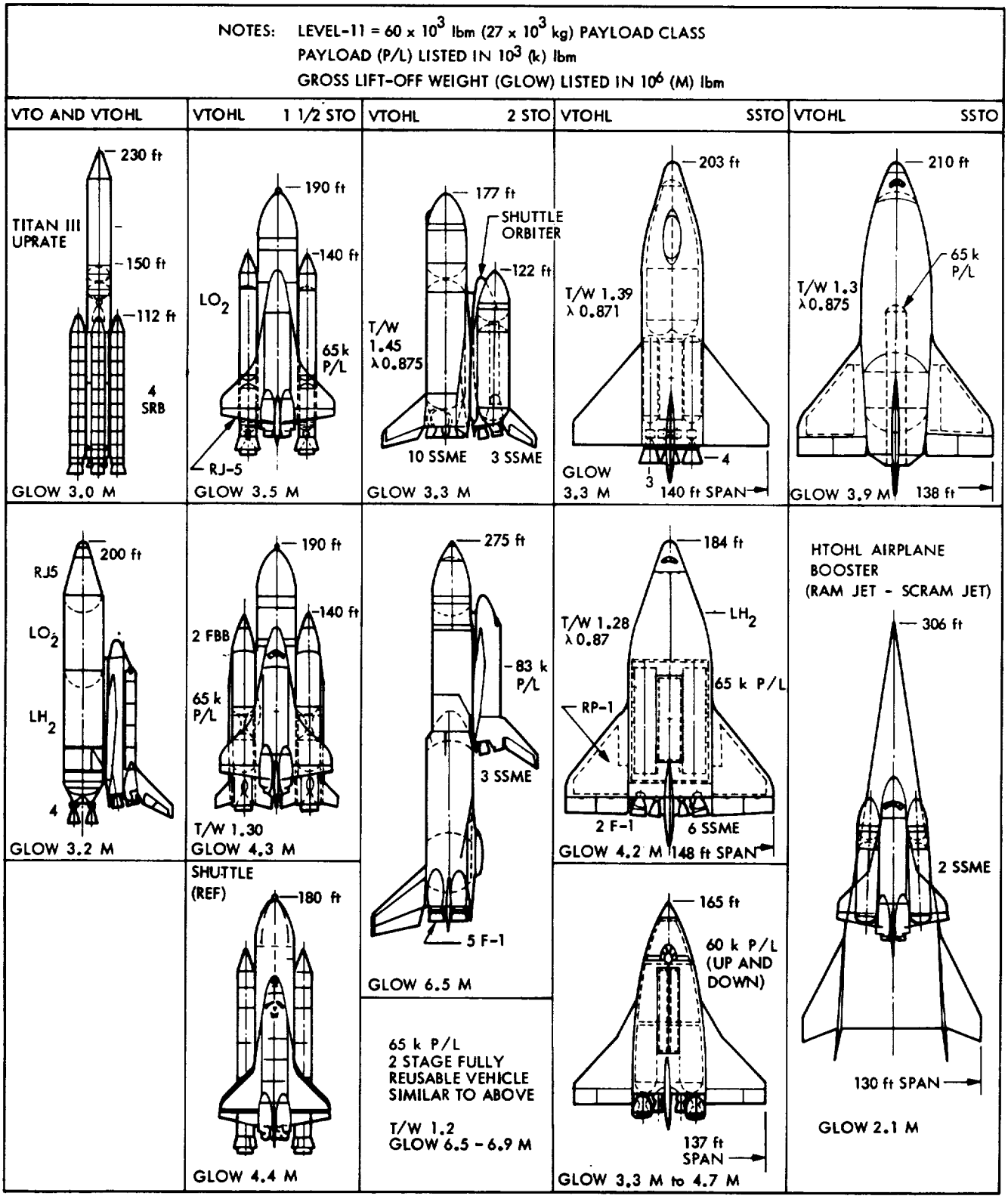


Figure 4-3. Level-II configurations

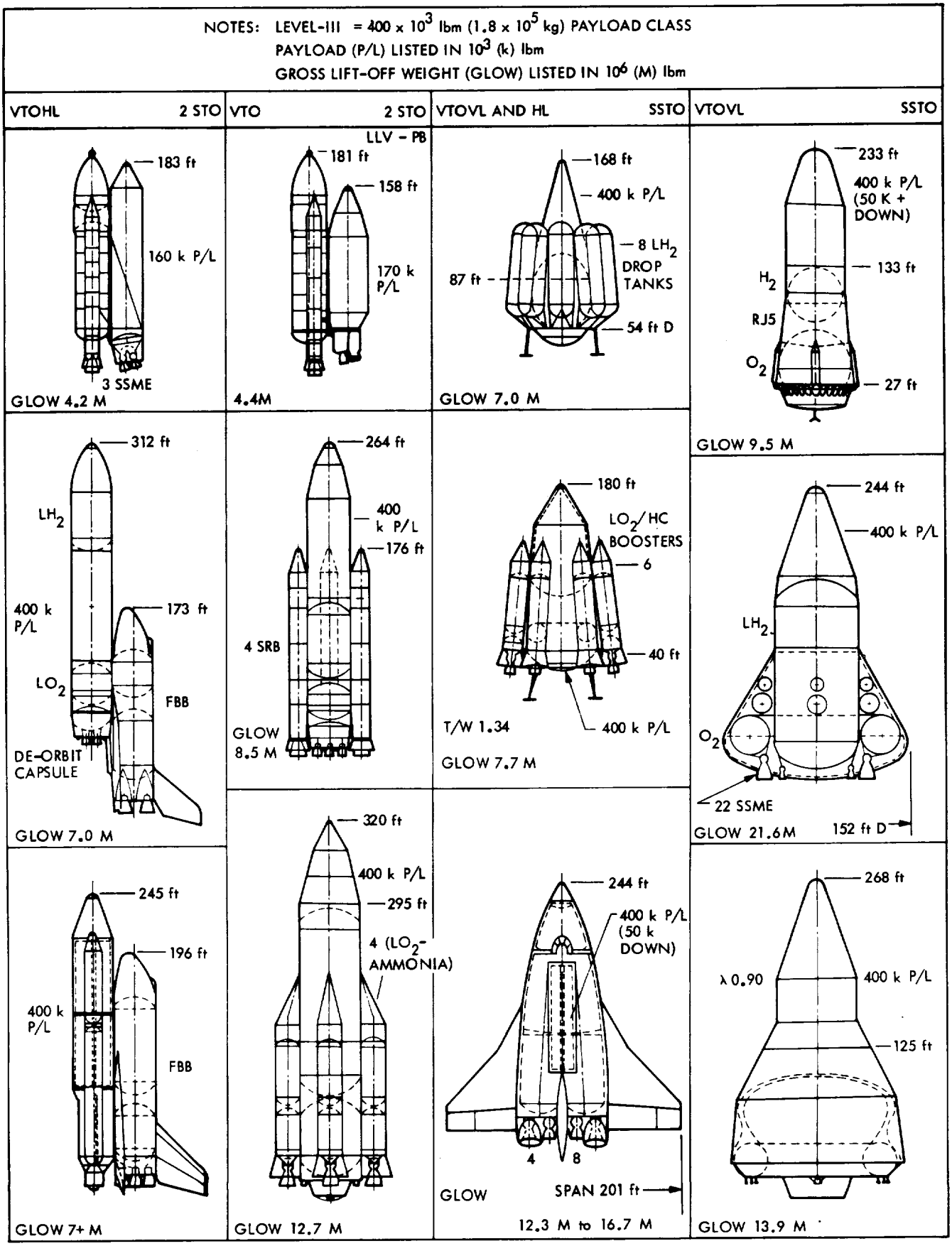


Figure 4-4. Level-III configurations

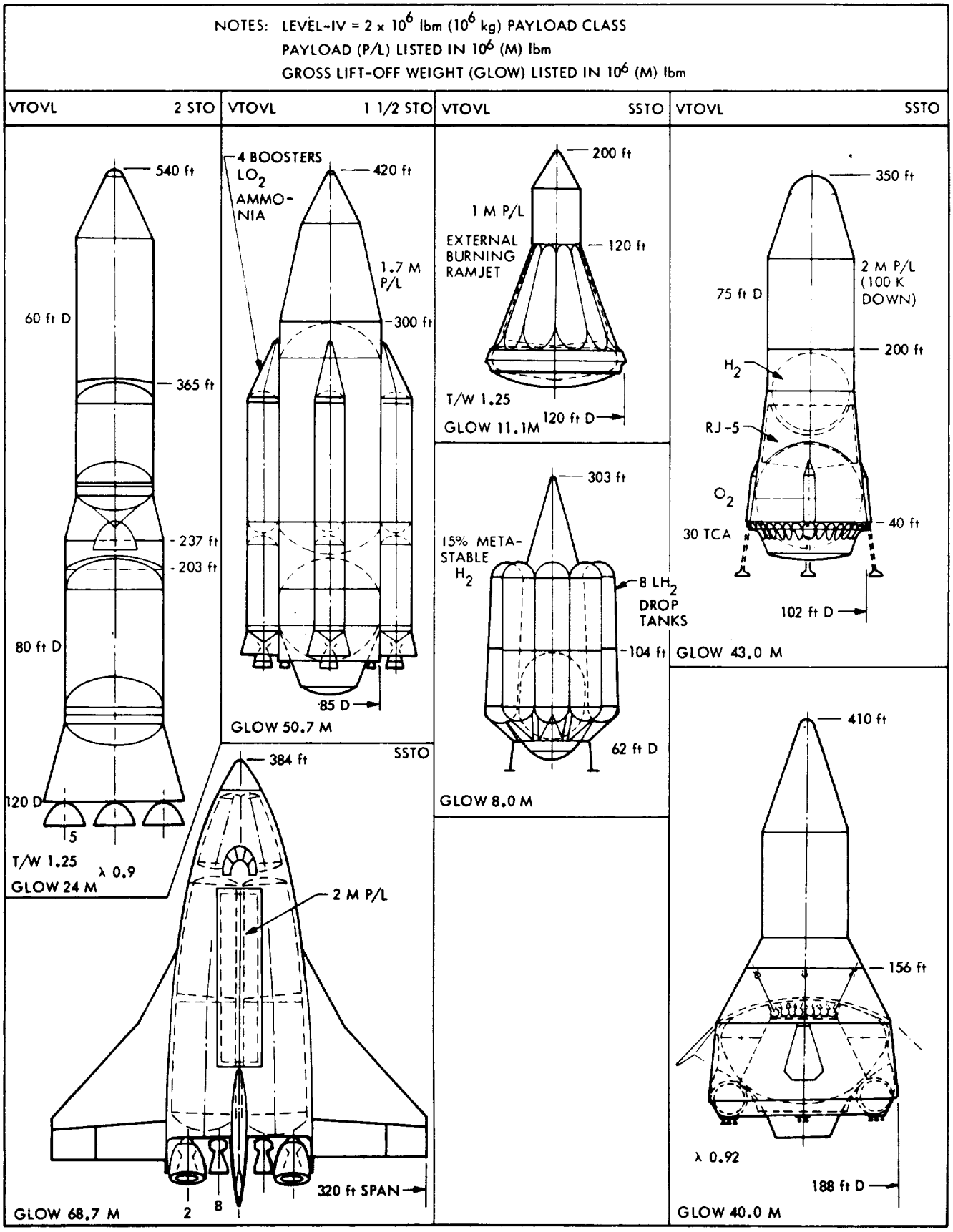


Figure 4-5. Level-IV configurations

Significant interest was evident for aerospike or plug nozzle concepts, to enable dual purpose use of the engine nozzle hot structure as a radiative heat shield for entry.

In response to the question posed to forecasters on the use of critical materials, considerable data were provided on the benefits of reusing the launch vehicle elements, but no real obstacles were projected in the availability of construction materials or propellants, even for the highest launch rate. Further discussions on hydrogen availability are presented in II-D-2-e below.

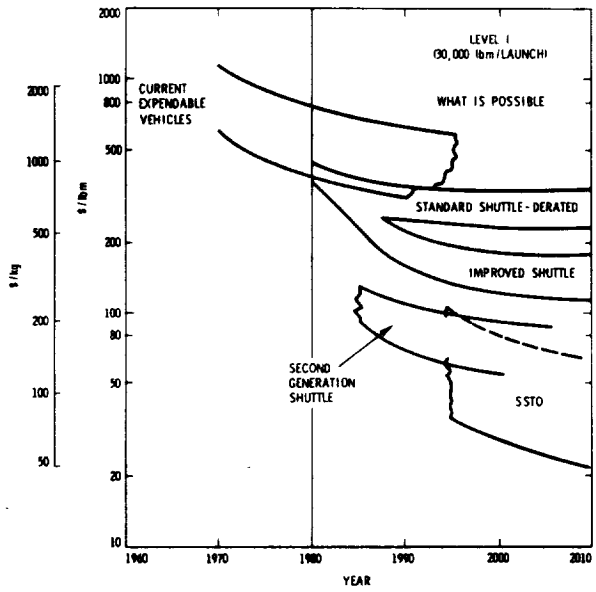
The question on materials technology was only lightly addressed. No forecaster applied revolutionary structural materials, yet several indicated the dependence of the SSTO feasibility upon signficant evolutionary improvements of the properties of both metals and composites.

One forecaster made the point that recurring launch costs may be reduced to $25/lbm ($55/kg) or less by the year 2000, but that if annual support costs and amortization of the investment are included, as they should be in his opinion, total launch costs below $100/lbm (220/kg) were not expected. This judgment was based upon a flight rate of about 60 per year. It may, however, be possible to approach the lower cost by a large increase in the number of annual flights - perhaps approaching 500 flights/year. This economic trend supports the view that the Level-IV requirement of 100×10^6 lbm/yr (45×10^6 kg/yr) may be better served by a vehicle of the 200,000 to 400,000 lbm (100,000 to 200,000 kg) per launch class, flown more frequently, than the guideline 2×10^6 lbm (1×10^6 kg) per launch vehicle.

b. Recurring Costs. Discussion of the recurring cost for placing payloads in orbit is shown with the Earth-to-Orbit Operations (FC 4-1, FC 4-2, FC 4-3, and FC 4-4 respectively for Levels I through IV).

Two basic classes of vehicles were provided by the forecasters for Level-III activities. The more expensive in terms of costs per pound in orbit were the two-stage vehicles with the first stage built from Shuttle components and recoverable. Second stages were unmanned, with recoverable engines and avionics, employing either orbital recovery of components or encapsulating the high-value components in an entry body. These vehicles yielded launch costs in the $75/lbm ($165/kg) range for the year 2000.

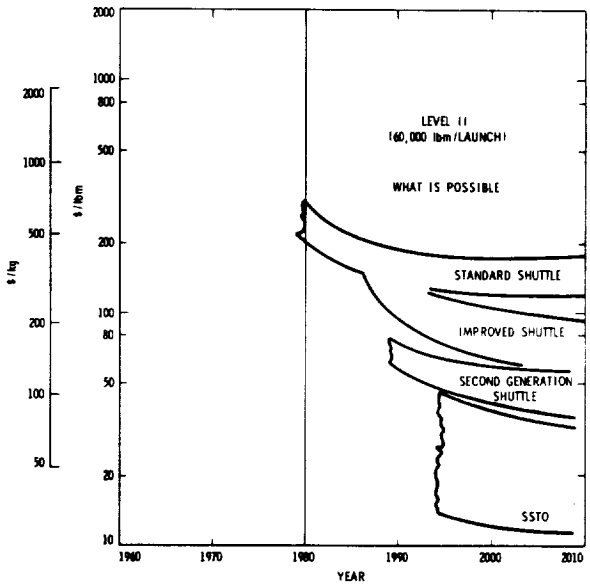
FC 4-1. Level-I Recurring Launch Costs



DISCUSSION

Costs per pound in orbit for Level I have been shifted upward by the forecasters for the Shuttle class of vehicles, because the small payload required underutilized the capability of the vehicle. A cost projection in the $150/lbm ($330/kg) range was suggested as attainable in the year 2000 with uprated Shuttle vehicles, and down to the $40 to $80/lbm ($90 to $180/kg) range for second-generation systems. Five classes of vehicles were suggested by the forecasters to serve the Level-I launch requirements. Actual and projected costs for current expendables, Scouts through Titan IIIs are shown first. These vehicles are followed in order of decreasing costs by projections for (1) the Shuttle as it evolves, (2) an uprated Shuttle with a liquid propellant flyback booster and an improved thermal protection system, (3) a second-generation two-stage Shuttle, and (4) a single-stage-to-orbit aerospace transport, the latter being a potential extension of first- or second-generation Shuttle technology.

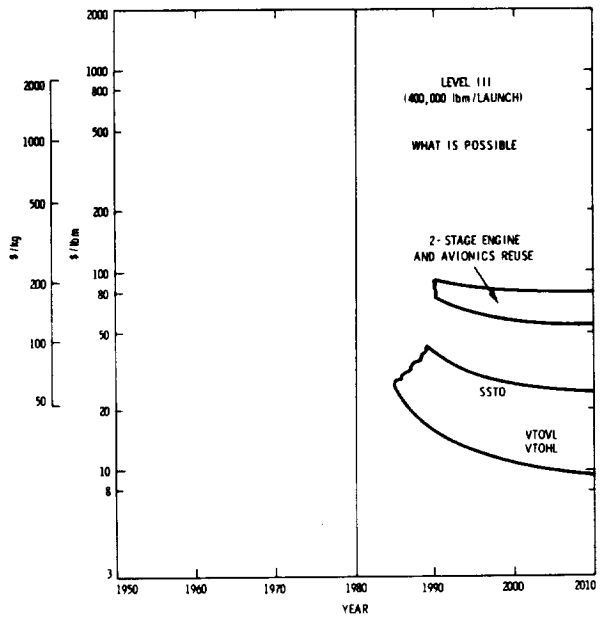
FC 4-2. Level-II Recurring Launch Costs



DISCUSSION

Evolutionary growth of the Shuttle system was projected to yield launch costs of the $80/lbm ($176/kg) range near the year 2000. Second-generation systems were considered capable of reducing these costs to the $50/lbm ($110/kg) range. The SSTO concepts were credited by those forecasters who suggested this approach as having the potential to reduce launch costs to the $15 to $30/lbm ($33 to $66/kg) range.

FC 4-3. Level-III Recurring Launch Costs

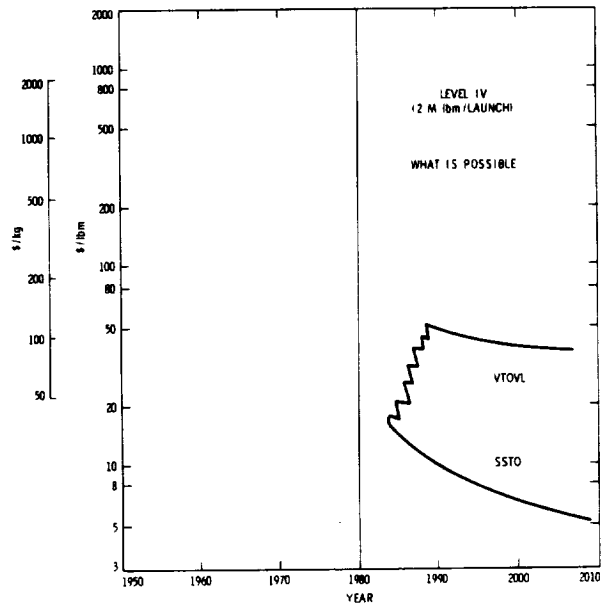


DISCUSSION

The second class of vehicles proposed were all variants of single-stage-to-orbit vehicles landing either horizontally like the Shuttle or vertically with heat shields, various aerodynamic devices, and a short engine firing for hovering vertical descent to Earth. In several of the forecasts, technology advancement to permit unaided SSTO operation was not predicted; in these cases, various means of assisting the vehicle to achieve velocity and altitude were suggested. Airborne launch, external propellant tanks and strap-on rocket propulsion units were all mentioned. Launch costs for these concepts were predicted to be in the $15 to $30/lbm ($33 to $66/kg) range.

Two basic classes of vehicles were provided by the forecasters for Level-III activities. The more expensive in terms of costs per pound in orbit were the two-stage vehicles with the first stage built from Shuttle components and recoverable. Second stages were unmanned, with recoverable engines and avionics, employing either orbital recovery of components or encapsulating the high-value components in an entry body. These vehicles yielded launch costs in the $75/lbm ($165/kg) range for the year 2000.

FC 4-4. Level-IV Recurring Launch Costs



DISCUSSION

The fact that neither rail nor other ground surface transportation networks have been sized to transport 2-million-pound payloads was noted by one forecaster, and based upon this history, he suggested orbital assembly of the Level-III size (400,000 lbm/180,000 kg) payloads into the larger aggregations which may be required.

With the exception of one SSTO forecast, the launch costs did not appear to benefit from scale-up to the Level-IV size. Launch cost projections for the year 2000 in the $20 to $40/lbm ($45 to $90/kg) range were most prevalent as shown on FC 4-4.

c. Annual Capability Maintenance Costs. The forecasts did not reveal significant trends in this cost category at any of the activity levels. There was a significant divergence of projections, ranging from the tens of millions to the hundreds of millions per year. This variance is considered to probably be more a consequence of different bookkeeping assumptions on the part of the forecasters than to either concept or level of activity differences. Two to four hundred million dollars per year appears to represent the most likely range of values for this parameter. Several forecasters indicated a sizable increase if the Level-II concepts were replaced by the larger Level-IV vehicles.

One observation to be made from the forecasts is that heavy lift derivatives of a basic system (either current or next generation Shuttles) could be maintained in the inventory for an incremental annual maintenance cost in the $50 to $100 million range.

Figure 4-6 illustrates the spread of annual capability maintenance costs for each of the four levels.

d. Nonrecurring Costs. Forecast 4-5 illustrates the forecasted nonrecurring costs for achieving the capability to accommodate Level-I launch vehicle traffic. The chart is arranged to group similar vehicle concepts together to illustrate the effects of concept selection upon predicted development and fleet acquisition costs. Those forecasters who suggested use of the existing expendable launch vehicles did not, in general, provide nonrecurring cost estimates because these costs have already occurred. Several estimates were provided, both for Levels I and II, for using the baseline Shuttle. These estimates are not included in this overview, because the Agency estimates of Shuttle nonrecurring costs available from OMSF and the records of the NASA budget hearings before Congress (Ref 4-2) are considered more appropriate for use than are other estimates.

Nonrecurring cost estimates provided for Level II are shown on FC 4-6. This size vehicle was studied extensively in many variations during the recent Space Shuttle Program study phase; hence most forecasters were equipped with a data base.

Level-III forecasts showed a wide variation in the projected nonrecurring costs. These costs are presented in relation to the recurring costs in FC 4-7. Level III elicited two types of responses. The first was a counterproposal to develop a "heavy lift" vehicle from the Shuttle at a significantly smaller 150,000-lbm (70,000 kg) payload size rather than the specified 400,000-lbm (180,000 kg) size. One cost estimate of 1.1×10^9 to 1.4×10^9 was offered. The second type of response was dominated by VTOVL configurations.

Two forecasters were of the opinion that a VTOVL SSTO could be built, while four others considered the use of drop-tanks or strap-on boosters necessary to achieve an acceptable payload fraction. The variation in cost estimates did not appear strongly influenced by the choice of SSTO or the assisted type of vehicle.

Vehicles suggested for Level IV are, as expected, significantly more costly than the Level-III size. Three forecasters suggested a "scale up" of either one- or two-stage winged Shuttles with enclosed payload bays - their nonrecurring cost estimates were a relatively very high level ($40 x 10^9 to $70 x 10^9).

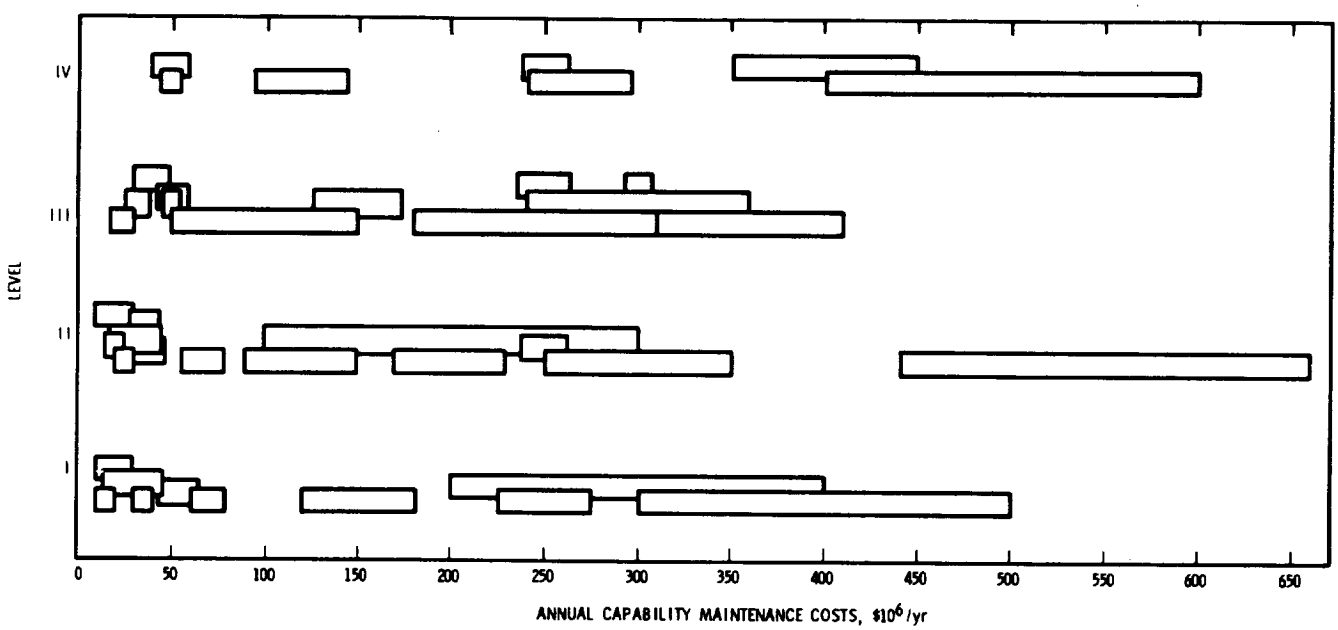
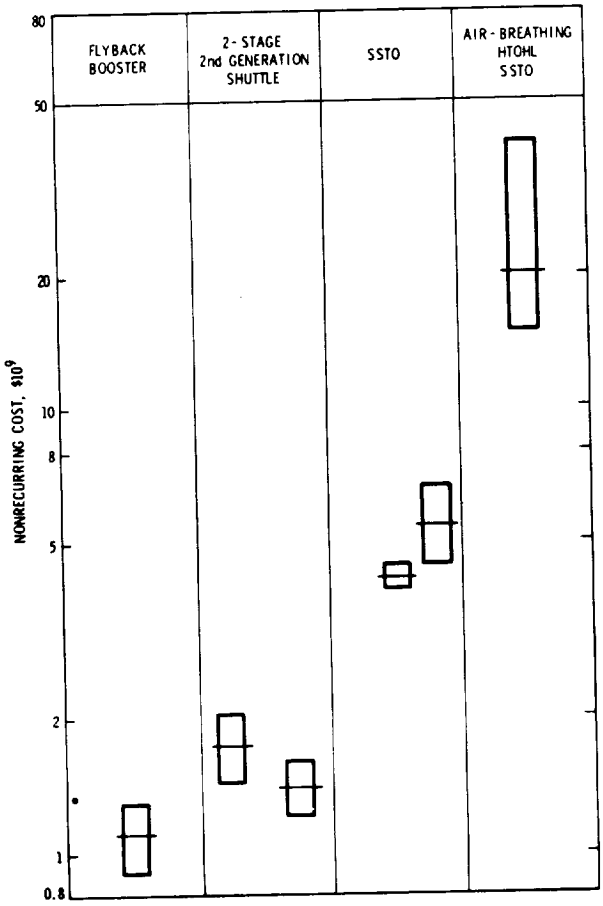


Figure 4-6. Annual capability maintenance costs (zero launch rate)

All other forecasts were of the VTOVL type, four SSTOs and two 2-stage vehicles. One of the SSTOs depended upon atomic hydrogen being developed as a propellant and several forecasters mentioned the need for a breakthrough in propulsion to make such a large vehicle practical. The average of the nonrecurring cost estimates for the 2×10^6-lbm (0.9×10^6 kg) payload VTOVL vehicles was about $\$15 \times 10^9$ -- the extremes were $\$6 \times 10^9$ to $\$30 \times 10^9$.

Unless a compelling need for 2×10^6-lbm (0.9×10^6 kg) monolithic payloads is identified, the forecasters indicate that more frequent flights of the Level-III vehicle may better serve the Class-IV flux rate.

FC 4-5. Level-I Nonrecurring Cost Estimates (What is Possible)



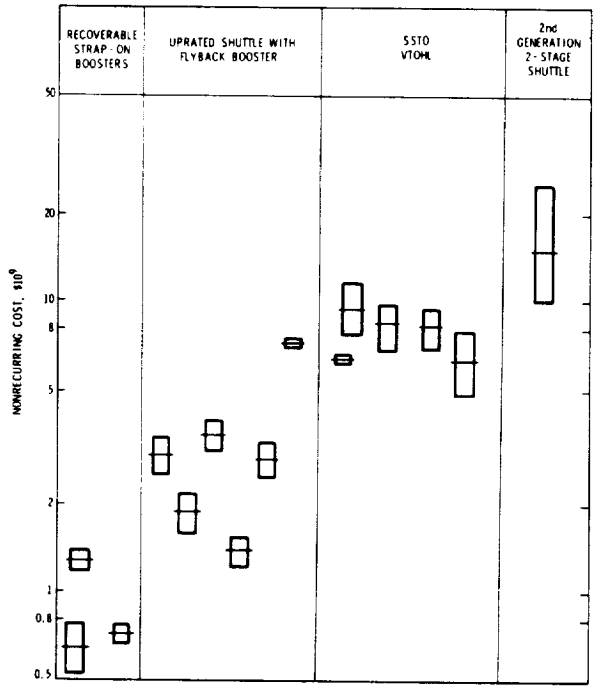
DISCUSSION

Two variations of the Shuttle were suggested to serve the Level-I needs. A glide-back O_2/H_2 winged-booster was suggested, sized to accelerate the baseline orbiter with smaller propellant tanks and a 30,000-lbm (13,500 kg) payload to the staging velocity. A nonrecurring cost estimate of $\$0.9 \times 10^9$ to $\$1.3 \times 10^9$ was offered. This estimate is atypically low for the winged boosters. Modification of a Shuttle Orbiter to serve as a flyback booster with a second stage powered by the Space Shuttle main engine was also suggested for the 30,000-lbm (13,500 kg) payload mission. This system was estimated to cost $\$1.2 \times 10^9$ to $\$1.6 \times 10^9$ for the additional development and fleet acquisition over and above the baseline Shuttle.

Two SSTO suggestions were offered for a later operational date. One was a mixed mode VTOHL system, estimated to cost $\$4 \times 10^9$ to $\$4.2 \times 10^9$. The second was a derated variation of a Level-II SSTO; modifications were estimated to cost $\$470 \times 10^6$ to $\$630 \times 10^6$, given the existence of the larger vehicle. The SSTO derivative of the baseline orbiter was estimated to require $\$6 \times 10^9$ to $\$7.5 \times 10^9$ nonrecurring investment above current plans.

A very interesting suggestion was made for an advanced airbreathing HTOHL SSTO, available for use shortly after the year 2000. Its purpose would be a personnel carrier and high-priority cargo vehicle to supplement a larger Level-II/III launch system. It was also intended for point-to-point transportation on Earth as a competitor to SST and HST aircraft and was expected to achieve a very high annual flight rate. The nonrecurring costs were high -- $\$15 \times 10^9$ to $\$40 \times 10^9$, but the payoff was reduction of recurring costs to \$20 to \$60/lbm (\$44 to \$132/kg).

FC 4-6. Level-II Nonrecurring Cost Estimates (What is Possible)



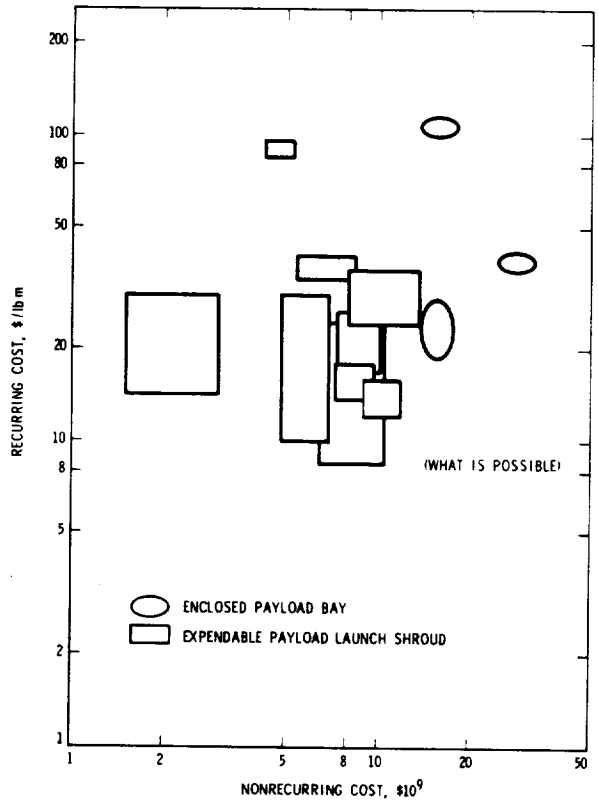
DISCUSSION

Glide-back or flyback boosters for the present Orbiter were suggested with costs ranging from $\$1.3 \times 10^9$ to $\$3.9 \times 10^9$. Ballistic recovered liquid boosters to replace the solid-rocket boosters (SRBs) were suggested by two forecasters. The nonrecurring estimate for this approach is of the order of $\$1.0 \times 10^9$.

One airbreathing booster was suggested with a nonrecurring cost estimate of $\$6.7 \times 10^9$ to 8.7×10^9. An advanced two-stage "piggyback" Shuttle of the 1971 Phase-B study type was estimated to cost from $\$10 \times 10^9$ to $\$25 \times 10^9$ at the 100,000-lbm (45,000 kg) payload size.

Five SSTO suggestions were made. The two "pure" SSTOs had nonrecurring cost estimates from $\$5.1 \times 10^9$ to $\$10.5 \times 10^9$, while the forecaster who considered subsonic air-drop launch necessary for SSTO operation estimated $\$6.9 \times 10^9$ to $\$9.9 \times 10^9$ for both the orbital element and the new carrier aircraft. The SSTO variant of the baseline Shuttle at Level II was only slightly more expensive than at Level-I.

FC 4-7. Level-III Nonrecurring Cost Estimates (What is Possible)



DISCUSSION

The forecasts which presumed a requirement for an enclosed payload bay and winged flight recovery were estimated to be more expensive than the VTOVL body-of-revolution vehicles. The average nominal nonrecurring cost for the vehicles with expendable shrouds class of vehicle was estimated to be about $\$8 \times 10^9$. One might expect to find another trend -- that a larger investment yields a lower operating cost -- but this is not apparent in these forecasts.

e. Operational Implications. Operational implications drawn from the forecasts fall into two categories: (1) implications of system design and (2) implications regarding total energy required. Regarding system design, one observes that the Shuttle Orbiter appears to be an investment which will be used in space missions for many years, possibly co-existing with a heavy-lift vehicle of some type in the 1990s, and serving all of the personnel transport and recovery needs. Concern about recurring cost and potential environmental impact of the solid rocket boosters leads to an interest in making a transition as early as possible to a liquid booster for the Shuttle and, if permitted by fiscal constraints, in achieving land rather than water recovery of that booster. Should the requirement arise to launch 100 million pounds per year or more, the consensus is that more frequent launches of vehicles in the 400,000-lbm payload class is likely rather than development of the larger Level-IV vehicle. This leads to the need for launch facilities capable of almost daily launches - 250 or more per year.

Energy required by the space transportation systems of 1980 to 2000 will, of course, be dictated by the activity level the systems are required to support. A range of activity levels was given to the forecasters; any attempt to specify the total energy required for these levels by considering facilities, flight equipment, ground-support equipment, payload manufacture, etc., would be a study in itself. However, the following example, which deals only with hydrogen propellant, is representative of the type of considerations which must be factored into an overall program plan.

Table 4-1 shows the yearly amounts of hydrogen required to support the four specified activity levels, assuming hydrogen-oxygen propelled vehicles are used exclusively.** These quantities were derived by averaging for each activity level, the hydrogen requirements for the vehicles specified by the forecasters and applying a buy-to-use ratio of 1.5. The currently planned Space Shuttle yearly quantity was obtained from presently available forecasts and is shown for comparison. The table also shows the quantities of natural gas, crude oil, coal, and electrical energy that would be required to synthesize the hydrogen from any of the fossil sources or from electrolysis. In addition, the table shows the electrical energy needed to liquefy the hydrogen.

The numbers in parentheses in Table 4-1 show the hydrogen requirements for the four levels of activity and the current Space Shuttle as a percentage of the 1974 national production capacity which is about 100 tons per day. The resources required to produce these quantities of hydrogen by the various methods are also shown as a percentage of their 1974 national consumption. Plans are currently underway to increase the national hydrogen production capacity to support the Shuttle. Increases in the hydrogen requirements dictated by activity level III would require further expansion, and significant expansion would be required to accommodate the needs of level IV. This in turn will cause an increased natural resource demand which, based on 1974 consumption, is quite small except at level IV. An assessment of the criticality of this situation must be related to projections of total space program activity levels

Table 4-1. Annual resources required to synthesize hydrogen from various sources

Activity Level	Hydrogen Required per Year, lbm	Potential Source				Energy Required for Liquefaction kWe-h
		Natural Gas, SCF	Crude Oil, BBL	Coal, Tons	Electrolysis of Water kWe-h	
Level I	10×10^6 (14)*	1.0×10^9 (0.10)	136×10^3 (0.0024)	44×10^3 (0.11)	300×10^6 (0.015)	65×10^6
Level II	40×10^6 (56)	4×10^9 (0.40)	545×10^3 (0.0093)	175×10^3 (0.44)	1.2×10^9 (0.06)	260×10^6
Level III	100×10^6 (139)	10×10^9 (1.0)	1.4×10^6 (0.0229)	435×10^3 (1.09)	3×10^9 (0.151)	650×10^6
Level IV	500×10^6 (694)	50×10^9 (5.0)	6.8×10^6 (0.1146)	2.2×10^6 (5.44)	15×10^9 (0.753)	3.3×10^9
Shuttle	20×10^6 (28)	2×10^9 (0.20)	271×10^3 0.0046	87×10^3 (0.22)	600×10^6 (0.030)	130×10^6

*Numbers in parentheses represent % of 1974 U.S. consumption.

**For this design approach, hydrogen is estimated to represent 40 to 50% of the total system energy requirement.

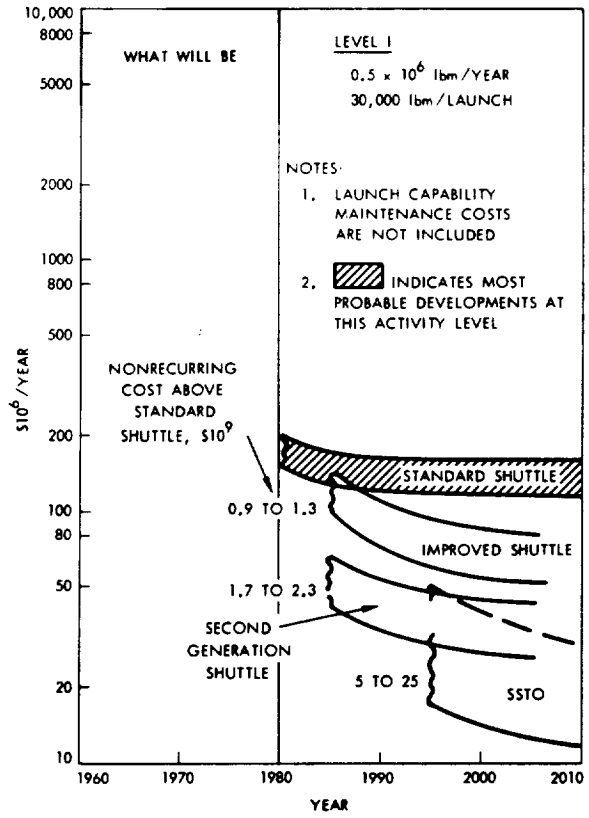
and total energy resource consumption in the 1980 to 2000 time period.

3. Effect of Transportation Demand on Future Developments (What Will Be)

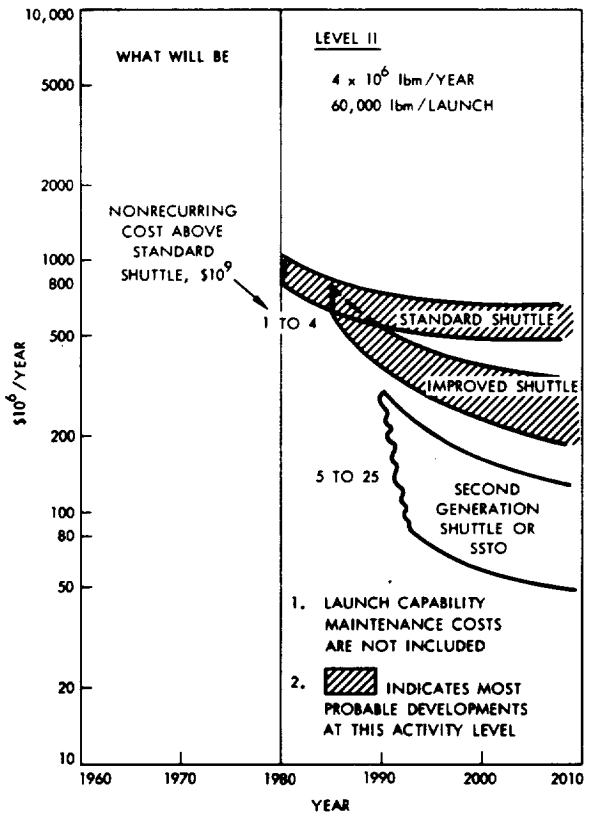
Analysis of the projected costs for the various systems proposed allows some insight into likely developments at each activity level. Forecasts 4-8 and 4-9 are plots of annual transportation costs to low-Earth-orbit for activity Levels I and II, respectively. These curves were obtained by multiplying the projected cost-per-unit-mass to low Earth-orbit by the mass rate per year. Also indicated are the nonrecurring costs estimated for the various design options. Launch capability maintenance costs were not included because of the wide disparity among estimates and because they would be primarily a function of activity level rather than design options at a given activity level.

The answer to the question "What will be the costs for space transportation?" is clearly a function of a second question "What will be the space activity level?". This answer is generally beyond the scope of these forecasts. Nevertheless, several forecasters ventured opinions as to what will come about by way of traffic demands and expected development trends and, through these, what the recurring transportation costs will be. Two of the projections which are representative of the spread in the "what will be" forecasts are included as FC 4-10 and FC 4-11.

FC 4-8. Possible Level-I Transportation Costs to Low-Earth-Orbit



FC 4-9. Possible Level-II Transportation Costs to Low-Earth-Orbit

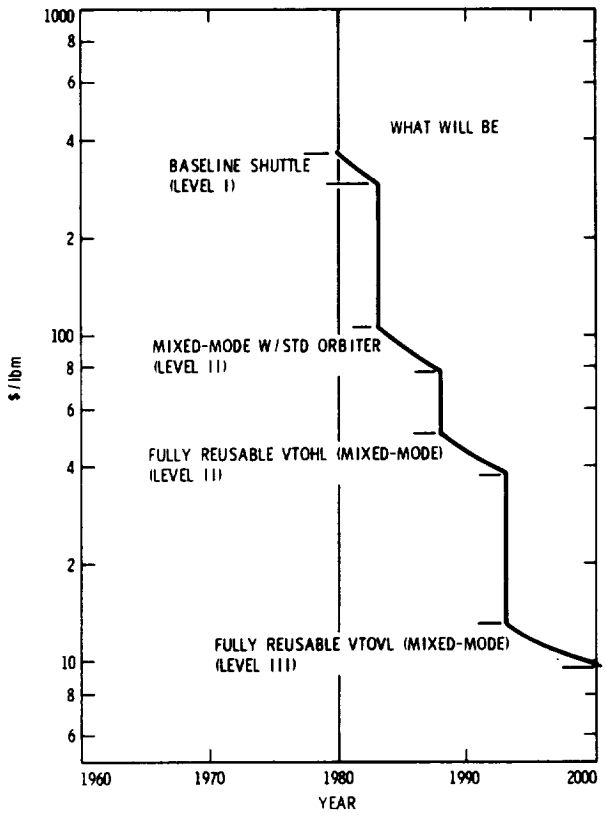


DISCUSSION

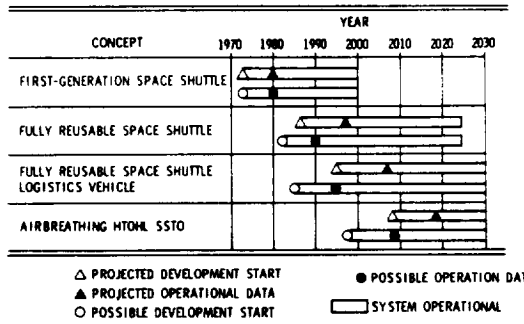
If one assumes that reduced transportation recurring costs are the payoff for improving a system at a given activity level, and that the investment should be returned within 10 to 15 years, then FC 4-8 indicates that major improvements to the standard Shuttle would be difficult to justify for Level I. On this basis, the improved Shuttle appears to provide a viable option at Level II. Although FC 4-9 shows this option to be possible starting in 1985, competition for funds with other systems (e.g., Space Tug) would probably delay initial operational capability (IOC) until around 1990.

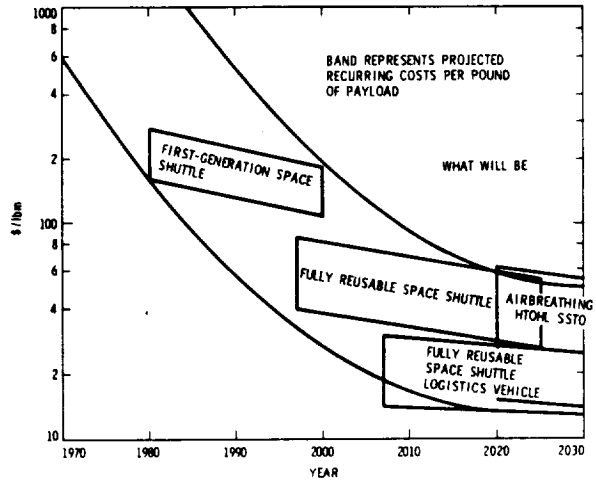
Second generation Shuttles or SSTO vehicles may provide economic benefits at Level II, but the relatively large nonrecurring costs required are likely to delay this class of vehicles until traffic demands of the order of Levels III or IV requires the so-called Heavy-Lift Launch Vehicle. This development, if undertaken as an evolutionary step following the improved Shuttle, would probably have an initial operation in the 2000 era. A driving mission requirement, however, could cause this development to come earlier if the improved Shuttle were bypassed.

FC 4-10. Example 1 of Projection of Vehicle Development and Recurring Cost per Unit Payload Mass-to-Orbit



FC 4-11. Example 2 of Projection of Vehicle Development and Recurring Cost per Unit Payload Mass-to-Orbit





E. SUMMARY

Forecasts were obtained for the nonrecurring, annual maintenance, and recurring cost elements of Earth-to-orbit operations at four increasingly ambitious levels. The present Space Shuttle system can accommodate traffic up to the second level: 4×10^6 lbm/yr (1.8×10^6 kg/yr) of payload in orbit, 1×10^6 lbm/yr (0.45×10^6 kg/yr) recovered at 65,000 lbm (30,000 kg) lifted per launch. The Level-III requirement of 400,000 lbm (180,000 kg) per launch can be filled by vehicles of the Rhombus/Nexus class studied as "Post-Nova" systems of the early 1960s.

The highest level of space activity for which forecasts were gathered called for the capability for 100×10^6 lbm/yr (45×10^6 kg/yr) to low Earth-orbit, with 2×10^6 lbm (0.9×10^6 kg) per launch. More frequent flights of the Level-III vehicle may be preferable to fill this need, as there does not appear to be further benefit of scale upon costs beyond the Level-III size. The more frequent flight rate would enable the total launch costs for Level-IV to be reduced signficantly when amortization of the nonrecurring and annual base cost is included in the total.

By the year 2000, the uprated Space Shuttle recurring flight costs should be about $80/lbm ($180/kg) at Level-II activity. A second-generation fully reusable Shuttle, generically related to the 1971 Phase-B study configuration, could reduce these costs to about $50/lbm ($110/kg). The winged SSTO could displace the Shuttle in the mid to late 1990s and reduce the recurring launch costs to perhaps as low as $20/lbm ($44/kg). This development, however, must have nonrecurring costs no greater than $\$5 \times 10^9$ to $\$10 \times 10^9$ to be economically competitive (see FC 4-9) and will require extensive technology developments in propulsion system specific impulse and in structure and heat shield mass.

The earliest heavy-lift vehicle which could be developed for a relatively small nonrecurring cost was projected to be derived from the Shuttle and to have a capability of about 150,000 lbm (68,000 kg) of payload per launch. This vehicle was estimated to have recurring costs in the vicinity of $75/lbm ($165/kg). An attractive alternative for this heavy-lift function at a high flight rate is the VTOVL vehicle derived from the Rhombus/Nexus studies of the sixties. This class of vehicle might be less expensive to develop than the horizontal landing winged vehicles in either the single-stage-to-orbit version or the drop-tank or strap-on booster versions, and could yield launch costs of less than $20/lbm ($44/kg) for an investment of $\$8 \times 10^9$ to $\$10 \times 10^9$.

At the component level, no propulsion schemes were found to displace the O_2/H_2 high-chamber-pressure engines. For early boost phases, O_2/hydrocarbon pump-fed and O_2/NH_3 pressure-fed engines appear to be viable options to reduce launch costs below those attainable with only O_2/H_2 first stages. Airbreathing systems offer promise, but no forecaster was able to project a specific configuration for use before the late 1990s. Further study of engine and airframe development and air-drop approaches was suggested.

In general, there appear to be more than ample approaches to reducing Earth-to-orbit recurring mission costs to the $20 to $30/lbm ($44 to $66/kg) range by the year 2000. These options will be developed, however, only if program requirements generate the need to launch many large payloads.

F. PARTICIPANTS

The Coordinators express their appreciation to those who so willingly and enthusiastically shared their experience by contributing to this study. Their inputs are maintained in a microfilmed version (see G below). The Contributors are members of the Energy Management Coordinating Committee who assisted in the formulation and writing of this report. Appreciation is also extended to those others who are not listed below whose many conversations helped focus the activity to the important areas treated in this report.

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G. INDEX OF MICROFILMED FORECASTS

The following forecasts, concerning Earth-to-orbit operations, are available on microfilm at the Jet Propulsion Laboratory. To retrieve copies of individual forecasts call Mr. George Mitchell at (213) 354-5090 and give the document number (1060-42) and the volume number (Vol. IV, Part I of 2 Parts) followed by the correct page numbers as listed below. These particular forecasts are categorized by Forecasters and are identified by the following letters and numbers.

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Q.	R. Salkeld's Forecast	
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R.	A. O. Tischler's Forecast	
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Section III. ENERGY FOR SPACE POWER AND PROPULSION

D. F. Dipprey and L. D. Runkle

A. SCOPE

Technology forecasts for spacepower and propulsion span four fields of the Working Group V work breakdown structure: acquiring (energy collection)*, processing (energy conversion), transferring (energy transmission), and storing (energy storage). The term "energy transmission" is taken to cover technology for transmitting photon (electromagnetic) beams, probably further restricted to laser light and microwaves. Carrying energy which is stored in matter from one place to another is covered in the "energy storage" field (see D-1-c below). Moving energy within the confines of a spacecraft or surface station is covered in two other fields: (1) Thermal control by means of thermal energy conduction, convection (including heat pipes), or radiation is covered in the "matter storing" field (see Part Five, Section VI). (2) Mechanical, electrical, or radiative means for distributing energy for onboard work is covered as part of the technology forecasts for the devices which carry out onboard functions; e.g., instruments, guidance devices, etc. (see Parts Three and Five).

Energy collection is taken to include collection of photons (electromagnetic waves), magnetic flux (particularly in the vicinity of bodies with large magnetic fields) and indigenous materials (from planetary atmospheres or surfaces).

Energy storage is taken to cover storage in magnetic and electric fields and in the states of matter. Energy storage in matter can be roughly categorized by a hierarchy of successively more intimate states of matter: mechanical energy involves kinetic and potential energy of bulk assemblages of molecules (e.g., flywheels); thermal energy involves the kinetic and potential energy of individual, complete molecules, ions, or electrons; electronic (including chemical) energy involves the energy states of the electrons of the molecules; and nuclear energy involves the energy states of the nucleus of the atom. Antimatter is included as a special category wherein stored energy can be released by conversion, to energy, of a major portion of the matter involved, in matter-antimatter reactions.

Finally, energy conversion is taken to cover either conversion to processed electrical energy for use in space operations or conversion to kinetic energy of exhausted mass (mechanical energy) for propulsion. Technology forecasts for the use of processed electrical energy for devices on board a space vehicle are covered in either the information or matter fields (see Parts Three and Five).

B. BACKGROUND

The use of forecast parameters in predicting mission capability and costs is generally straightforward; for energy transmission, collection, storage, and conversion to electrical energy, a single performance-parameter and a single cost-parameter are generally sufficient. For example, in energy storage, the mass associated exclusively with the storage of energy is orders of magnitude larger than that associated with the conversion to electrical; thus, storage parameters are of primary concern.

In the case of devices used to convert energy into mechanical energy for propulsion, more than one parameter is usually required to express performance, and costs can be estimated only after the performance parameters have been used to analyze payload fractions in terms of desired specific mission requirements. Generally, computer-generated iterative solutions to payload equations are needed to derive optimum trajectories (in the case of very low thrust-to-mass ratio systems), to determine optimum staging, and to determine optimum exhaust velocity in some cases. Once near-optimum conditions have been established, payload equations and parameter formulations can again be used in determining the implied size, mass, power, etc. of the various devices used in the propulsion systems. From these results and the cost-per-unit-mass forecasts, a rough estimate of recurring cost for hardware and propellants can be derived.

The complexity of the process outlined above limited the amount of mission-peculiar forecasting accomplished in this report. System concepts and costs were forecast for Earth-to-orbit operations because the requirements are easily defined and that step is common to all space missions. It was decided, however, to limit the remainder of the forecasts to subsystem capability parameters until a set of typical missions are defined by the appropriate groups of the Outlook for Space Study. Once missions are defined, the information used herein will be available to assess technology feasibility and cost. Even that assessment, however, will not point the way to a particular technology which is optimum for the future NASA program. That can only come after detailed system studies for the particular mission or set of missions of interest. Previous studies

*The terms in parentheses have been added to aid interpretation of the meaning of the fields as they relate to energy management.

of nuclear versus chemical upper stages for space missions are representative of the process.

C. ORGANIZATION AND APPROACH

The discrete technology forecasts for the areas of energy for space power and propulsion have been organized by using a matrix relating each of the four energy fields with the eight energy forms shown in Fig. 4-7. Some redundancy is used in this list of energy forms for practical reasons. Each intercept of the energy form with an energy field yields a potentially interesting functional concept. In the case of energy conversion the intercept is taken to mean conversion to the form indicated. The concept may involve several conversion steps internal to the overall function.

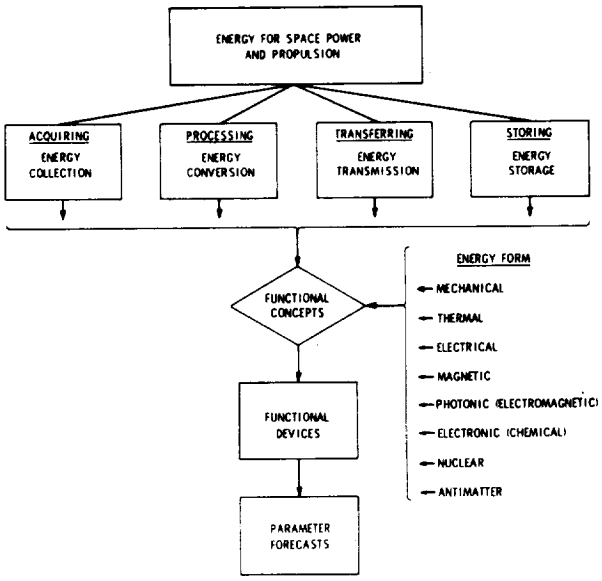


Figure 4-7. Forecast process

Interesting functional concepts have then been related to specific devices which might be used to implement the function. Functional devices were defined to be a mechanization for performing one or more functions and identified at the point of indivisibility; i.e., at the point where performance and mass optimizations can be established within the device concept. Thus, for each "functional device" one can identify mass, energy, power, efficiency, cost, or other material characteristics. Only those devices which are likely to significantly impact either space mission capability or the design of higher-level functional systems have been selected for technology forecasting.

Devices or classes of devices selected for forecasting are identified by a code number in Table 4-2. Those entries without code numbers are either deemed uninteresting in the sense just mentioned, or are included as part of a more complete device concept identified elsewhere in the field. Thus, many of the energy transmission, collection and storage devices are covered by forecasts for energy conversion devices.

The technology forecasts for space power and propulsion functional devices have been cast in terms of what the device is, its present technology status, when it could be made available, projected performance, and projected costs. A limited set of parameters, such as specific mass and efficiency, describe the performance of any of the functional devices identified in the space power and propulsion fields. These parameters are defined in Table 4-3. Recurring cost, another important parameter, is expressed as cost per unit-mass of the device or device elements. In addition nonrecurring costs — one-time costs required to establish technology readiness and to bring the device through first application — are estimated.

In general, one forecaster, with knowledge and interest in the appropriate advanced technology fields, was selected to treat each functional device and was asked to prepare a forecast for that device using a specified format and the prescribed parameters. In some cases two forecasters were solicited. The forecaster was to draw the forecast from personal knowledge, consultation, and the literature. Due to the limited time available, the forecasters were encouraged to use uncertainty limits with which they would be comfortable, given the status of the device and of the readily available information concerning its prospects.

D. FORECASTS

1. Background, Present Status, and Forecast of 1980 Improvement

a. Transmission. Laser energy beaming in the infrared spectrum has already been attempted for short distances. The unclassified literature shows no reference to the 10 to 100 MWe scale of lasers needed for effective uses in propulsion. Development of such large systems for space use is not likely by 1980. The use of large laser-beam sources operating in space will be paced by development of large solar or nuclear energy sources. These developments will not come along before 1980. Transmission efficiency for laser beaming is likely to be limited to less than 30% in 1980.

Microwave beaming for energy transmission has already been accomplished over short distances (the order of one mile). Overall short-distance efficiency of transmission measured from dc input to the transmitter to dc output from the receiver, is projected to be greater than 70% by 1980. Achievable transmitting distance is proportional to antenna apertures.

b. Collection. For space applications, collection and concentration of solar photons for thermal conversion has been used less extensively than has direct conversion via photovoltaic devices. Current activities in collection for thermal conversion are primarily related to terrestrial heating devices.

Table 4-2. Functional devices for space power and propulsion

Energy Form	FUNCTION									
	Energy Collection (Acquiring)		Energy Conversion (Processing)				Energy Transmission (Transferring)		Energy Storage (Storing)	
			To Mechanical From:		To Electrical From:					
	Device Code No.		Device Code No.		Device Code No.		Device Code No.		Device Code No.	
Mechanical		Momentum plate				Turbine generator		Linkages and devices	3.1	Flywheels (includes electric motors and generators)
		Turbine				Magneto fluid dynamics		Fluid flow		
						Electro gas dynamics				Springs
Thermal				Flow acceleration through nozzle				Radiators		Phase change materials
				Thermodynamic cycles				Heat pipes		Compressed gases
Electrical		Ionosphere grids		Electric motor	5.1.1	Science/housekeeping power conditioning equipment		Electron beam generator		Capacitors
		Lightning rods		Arc and resistance heated thrusters				Wire conductors		
			4.1.1	Electron bombardment electrostatic thruster	5.1.2	Electric propulsion power conditioning equipment		Superconductors		
			4.1.2	Colloid electrostatic thruster						
			4.1.3	Electromagnetic accelerator						
Magnetic		Magnetic antenna		Within motor	5.2.1	Energy tapping of ambient fields			3.2	Superconductors
				Within MHD accelerator						Permanent magnets
Photonic (Electromagnetic)	2.1	Solar concentrator	4.2.1	Beam energy driven thermal rocket engine	5.3.1	Photovoltaic cells	1.1	Laser generator		
		Laser collector				Thermoelectric	1.2	Microwave generator		
		Microwave antenna	4.2.2	Solar sails	5.3.2	Thermionic				
			4.2.3	Solar electric propulsion	5.3.3	Dynamic cycles				
					5.3.4	Dielectric converter				
Electronic (Chemical)		Chemical manufacture on Earth	4.3.1	Liquid propellant rocket engines	5.4.1	Fuel cells			3.3	Primary batteries
	2.2	Extraterrestrial surface materials collection and processing to obtain chemical reactants	4.3.2	Solid propellant rockets	5.4.2	Dynamic cycles			3.4	Secondary batteries
			4.3.3	Detonation rockets	5.4.3	Magneto gas-dynamic cycles			3.5	Stable chemicals as reactants
	2.3	Extraterrestrial atmospheric component collection and processing as chemical reactants	4.3.4	Metastable chemical rocket engines					3.6	Metastable chemicals
				Atmosphere-breathing thermal engines						
Nuclear		Manufacturing processes		Fission:		Radioisotope:				Radioisotopes
			4.4.1	Solid core rocket engine	5.5.1	Thermoelectric				Fission reactors: Solid core, Fluid core, Gas core
			4.4.2	Dust-bed rocket	5.5.2	Thermionic				
			4.4.3	Light bulb/gas core rocket	5.5.3	Dynamic cycles				Fusion reactors
			4.4.4	Nuclear electric	5.6.1	Thermoelectric				
				Atmosphere-breathing thermal engines	5.6.2	Thermionic				
				Fusion:	5.6.3	Liquid metal MHD				
			4.5.1	Direct heat rocket engine	5.6.4	Magnetogas dynamics				
			4.5.2	Micro explosions	5.6.5	Dynamic cycles				
					5.6.6	Gas/fluid core reactor/converter				
						Fusion:				
					5.7.1	Fusion energy conversion				
Antimatter	2.4	Manufacture of anti-particles		Matter-antimatter reactor		Matter-antimatter energy conversion devices				Antimatter storage via high-gauss magnetic field

Table 4-3. Space power and propulsion performance and cost parameters

Parameter Definitions	Parameters to be Forecast
Functional Device Mass $= M_p + M_{sp} + M_{ae} + M_{se} + M_{ce}$ $= (1 + \alpha_{sp})\,\alpha_q\,E_{sp} + \alpha_a\,P_a + \alpha_s\,E_{se} + \alpha_c\,P$ Functional Device Cost $= C_p + C_{sp} + C_{ae} + C_{se} + C_{ce}$ $= c_p\,M_p + c_{sp}\,M_{sp} + c_a\,M_{ae} + c_s\,M_{se} + c_c\,M_{ce}$ Energy $= E_{sp} + E_a + E_{se}$ where: M_p, C_p = mass, cost for propellant M_{sp}, C_{sp} = mass, cost for storage of propellant M_{ae}, C_{ae} = mass, cost for acquiring (collecting) energy M_{se}, C_{se} = mass, cost for storage of energy (separate from propellant) M_{ce}, C_{ce} = mass, cost for conversion of energy E_{sp} = energy stored in propellant mass E_a = energy acquired from outside source E_{se} = energy stored in separate energy mass P_a = power acquired (rate of energy acquisition) P = power (rate of energy conversion) V_e = effective exhaust velocity of expelled propellant η_c = energy conversion efficiency	$\alpha_q \equiv \frac{M_p}{E_{sp}}$ $\left[\frac{kg}{J}\right]$ * $\alpha_{sp} \equiv \frac{M_{sp}}{M_p}$ $\left[\frac{kg}{kg}\right]$ $\alpha_a \equiv \frac{M_{ae}}{P_a}$ $\left[\frac{kg}{W}\right]$ $\alpha_s \equiv \frac{M_{se}}{E_{se}}$ $\left[\frac{kg}{J}\right]$ $\alpha_c \equiv \frac{M_{ce}}{P}$ $\left[\frac{kg}{W}\right]$ η_c V_e $\left[\frac{m}{s}\right]$ $c_p \equiv \frac{C_p}{M_p}$ $\left[\frac{\$}{kg}\right]$ $c_{sp} \equiv \frac{C_{sp}}{M_{sp}}$ $\left[\frac{\$}{kg}\right]$ $c_a \equiv \frac{C_{ae}}{M_{ae}}$ $\left[\frac{\$}{kg}\right]$ $c_s \equiv \frac{C_{se}}{M_{se}}$ $\left[\frac{\$}{kg}\right]$ $c_c \equiv \frac{C_{ce}}{M_{ce}}$ $\left[\frac{\$}{kg}\right]$

*Note: For the special case of propulsion systems with all energy stored in propellants (e.g., chemical propulsion), the effective exhaust velocity can be expressed as

$$V_e = (2\,\eta_c/\alpha_q)^{1/2}$$

Continued interest in high-power beamed-energy might stimulate development of concentrators for space application, but this is unlikely before 1980.

Energy collection by way of using materials from extraterrestrial surfaces or atmospheric sources has not been accomplished, and missions are not planned before 1980 which will make use of these technologies.

c. Storage. Energy storage is required to provide both electrical energy and propulsive energy for space missions. Present-day spacecraft store energy for propulsion by compressed gas and chemicals. Electrical energy is derived from electrochemical storage and radioisotopes. As shown in Table 4-2, devices which utilize nuclear energy to produce either kinetic energy or electrical energy have been described and forecast under the general classification of energy conversion devices. Only those items that have code numbers under energy storage are discussed in this section.

Between now and 1980 no change is foreseen in the roster of elements or devices used for energy storage on spacecraft. Flywheels and superconductors as primary elements of energy storage are not on the scene now. By 1980 development of these storage devices could progress to the point where they begin to compete with batteries.

Primary batteries in current use produce 5×10^5 J/kg (140 We-h/kg) and secondary batteries described on a comparable basis can handle 1.3×10^5 J/kg (36 We-h/kg). In terms of the parameter of the forecast, α_s, these figures are 2×10^{-6} kg/J and 7.7×10^{-6} kg/J, respectively. It must be noted that the secondary battery is capable of repeated discharge and charge cycles, but the number of successful charge cycles is related to the amount of discharge; the smaller the fraction of the energy removed the larger the number of charge cycles. Costs of primary batteries presently run about \$100/kg (\$0.7/We-h) whereas secondary batteries, because of intensive testing, cost about \$3600/kg (\$100/We-h). Improvements in secondary battery cell technology, such as the development of the nongassing Ni-Cd cell which allows lower battery case mass, could provide, by the 1980s, an α_s of 5×10^{-6} kg/J (55 We-h/kg).

Energy storage by means of stable chemicals to be used in combustion devices is available at the present time at an α_s value of about 8×10^{-8} kg/J with no significant improvement envisioned by 1980.

d. Conversion to Mechanical Energy for Propulsion. The great majority of space missions performed to date, and planned through 1980, have been or will be accomplished using some form of chemical propulsion. By 1980, a large high-pressure main engine burning oxygen/hydrogen will be operating close to the ultimate performance potential of these propellants. Effective exhaust velocity will be 4480 m/s, a 7% increase over that achieved with the oxygen/hydrogen engines of Saturn V.

The technology for small pressure-fed space propulsion elements using space-storable (fluorine/hydrazine) propellants will be available for use on unmanned spacecraft by 1980. Engines operating at an effective exhaust velocity of 3600 m/s, with this propellant combination, will offer 25% improvement over engines burning Earth-storable propellants which are currently used for spacecraft applications. The first use of fluorine will open the door for later use of larger, pump-fed fluorine/hydrogen systems. Fluorine/hydrogen provides energy storage density close to the maximum possible with stable chemicals.

The mass for motor case and nozzles of spacecraft solid propellant motors can be further reduced, by use of improved composite materials and structure design, from present levels of 8 to 9% of propellant mass to 6% in 1980, closely approaching an ultimate asymptote of 4%.

Solar electric propulsion (SEP) could be brought to readiness for first use as primary spacecraft propulsion by 1980. The technology for each of the essential elements of a total SEP system is presently available. System-level integration and extensive functional, environmental and duration testing remain to be accomplished.

Space nuclear reactors of a size needed for primary propulsion (100 to 400 kWe) will not be available by 1980. The time from when a development program is reestablished to prototype system demonstration will be about 10 years.

e. Conversion to Electrical Energy. Power subsystems for spacecraft generally employ both energy conversion and energy storage elements configured specifically to meet the requirements of a particular mission or class of missions. Spacecraft having mission duration requirements exceeding several weeks have usually used photovoltaic solar arrays in combination with a battery, although the radioisotope thermoelectric generator (RTG), which has a very long life capability, is also used in this application. Fuel cells and batteries have been employed without solar arrays for missions under two weeks. The detailed configuration of the power subsystem is configured to optimize weight, volume, power, storage requirement, lifetime, and cost.

Conversion elements in common use today include solar arrays, fuel cells, power conditioning equipment, and RTGs. Present day solar arrays produce 30 We/kg (α_c = 0.033 kg/We) at 1 AU and cost about \$500/We (\$15,000/kg). Fuel cells produce about 14 We/kg (α_c = 0.07 kg/We) and cost about \$700/We (\$10,000/kg). Power conditioning equipment for planetary and other unmanned spacecraft presently operate at 0.06 kg/We and cost \$1200/We (\$20,000 kg). RTGs produce about 3.8 We/kg (α_c = 0.26 kg/We) and cost about \$15,000/We (\$58,000/kg). Because of lower cost, the solar array has clearly been the preferred source of energy for long-duration missions; however, for missions to Jupiter and beyond, RTGs have become a necessary substitution.

Development programs underway today will provide some improvement in capability of some of the conversion elements mentioned above by 1980. The feasibility of using solar arrays producing 110 We/kg (α_c = 0.009 kg/We) has been established and large, lightweight arrays having this capability, or perhaps even greater, should be available by the 1980s. Other technological improvements, not a part of the feasibility asserted above, which contribute to the efficacy of solar arrays as conversion devices are improved radiation resistance of solar cells which has the effect of reducing the area required and thus the total mass, and an increase in efficiency of perhaps 10% which will also reduce the area.

Little change is expected in fuel cell technology for space application, although RTGs are expected to become more efficient by about a factor of two, thus increasing their performance figures of merit from 3.8 to 8 We/kg (0.26 to 0.13 kg/We). This should also significantly reduce the cost, since the isotope cost is a large fraction of the total cost. No new conversion devices are expected to come into use by 1980.

2. Forecasts for 1980 to 2000 (What is Possible)

In the following paragraphs, technology forecasts concerning space power and propulsion are presented in tables which include: (1) the device code number as shown in Table 4-2, (2) present technology status, (3) the year of first availability (technology readiness) if the device is not presently available, (4) the year for which the parameters are stated, (5) the performance parameters, and (6) the cost parameters. If the device is presently available or is forecast to be available early in the 1980 to 2000 period and if significant change is forecast, two lines of parameter and cost forecasts are shown: the first line represents either the present values or values corresponding to the first availability date and the second line is the forecast for the year 2000. If there is no change in forecast, only one line of parameter and cost forecast are shown.

The parameters forecast represent "what is possible" at some specified time in the future, as opposed to "what will be." For concepts which are not currently in use, the "what is possible" consideration must be applied to the technology readiness date as well as to performance levels. This approach was taken because the great majority of system developments identified are space-peculiar in nature. Hence the availability of these devices is dependent not so much on passage of time but rather on programmatic resources and emphasis applied, projections of which were beyond the scope of this study.

The terms in the technology status column were defined for the forecasters as follows: "In use" is self-explanatory. "In development" implies that such a device is being developed or is ready to be developed for an application. "On the technology frontier" implies experimental research and advanced development is (or has been) active along definite lines that are expected to yield proof of a coherent idea, with possibly some related basic physics and chemistry research supporting it, but it is too early to engage in proof of concept experimentally. "Conceptual" refers to those concepts which must have a large amount of fundamental research performed before firm performance parameters can be projected.

a. Transmission. Forecast parameters for energy transmission are shown in FC 4-12.

(1) Laser Beaming (Code 1.1). Transmission of energy by laser beam involves consideration of transmitter power required as well as beam generation, pointing, degradation, and reception.

The transmitting system to receiver coupling parameter is the power density at the receiver. Power density can be considered to be proportional to laser power divided by the square of the product of beam divergence and range. Beam divergence must be limited to a value near the diffraction limit for long range transmission. Power is dependent upon the mission as well as whether the laser beam generator is Earth-based or space-based. For example, Earth-based missions may require power in the 100 to 200 MWe range for short periods of time. Five-to-ten megawatt power may be required for long-term space-based laser generator applications.

A critical design problem of the transmitting system is the beam directing system including size, mass, drive requirements, and type of drive. The required tracking precision must be well below a small fraction of the aperture diffraction angle. These requirements can be alleviated to some extent by use of adaptive optics both for Earth-to-space and space-to-space applications.

Total average power requirements for most conceivable laser missions using an Earth-based transmitter are compatible with the output capacity of available conventional power plants. Energy storage devices may be used to advantage to provide large amounts of power for short periods of time. Operational lifetime would be limited by component degradation and laser media contamination (which on the ground is not serious because the lasant can be continuously exchanged). Atmospheric transmission poses the largest restraint on use of an Earth-based system. Clouds, dust, and precipitation can absorb or scatter the beam rendering the system useless. Dephasing caused by turbulence and/or thermal blooming can be improved by adaptive techniques. A safety problem exists when beaming energy over large distances. If the propagation space is not controlled, there is the possibility of beam interception. An obvious mission (trajectory) restriction to Earth-based transmission is that the receiver must be in the line-of-sight of the transmitter.

A space-based laser generator would be restricted in size by the amount of power available in orbit. For example, since the laser will probably never be more than 50 percent efficient, at least 20 MWe of conditioned power is required to obtain a 10-MWe laser beam. At this power level, the obvious long-term power sources are nuclear and solar. Lifetime again is limited by component degradation and media contamination but in a space environment this is a more serious problem. Based upon current experience, the

FC 4-12. Parameter Estimates for Energy Transmission (What Is Possible)

Device Code No. (Ref. Table 4-2)	Description	Present Technology Status	Year of First Availability	Year of Stated Parameters	System Performance Parameters (Ref. Table 4-3)		System Cost Parameters (Ref. Table 4-3) $-\alpha_c c_c$ ($/We)
					α_c (kg/We)	η_c	
1.1.1	Laser Beam Generator (Space-based)	On the Technology Frontier	1995	1995	- - - -	0.3(b)	- - - -
1.1.2	Laser Beam Generator (Ground-based)	On the Technology Frontier	1985	1985	N.A.	0.2(a)	- - - -
1.2.1	Microwave Beam Generator (Space-based)	In Development	1990	1990	7×10^{-4}(b)	0.8(a)	10^{-1}(b)
1.2.2	Microwave Beam Generator (Ground-based)	In Development	1980	1980	N/A	0.8(a)	10^{-1}(b)
1.2.3	Microwave Receiver (Rectenna) (Space-based)	In Development	1990	1990	2×10^{-3}(b)	0.9(a)	10^{-1}(b)
1.2.4	Microwave Receiver (Ground-based)	In Development	1980	1980	N/A	0.9(a)	10^{-1}(b)

DISCUSSION

System performance and cost parameters shown here do not include the all-important Power System, which dominates for **space-based** transmission systems (see Code Nos. 5.3 and 5.6 for appropriate space power system parameters). **Availability dates** shown here are possible dates, assuming increased resources to achieve the required high power levels **and cost** reductions. Preproject and first-application costs will be primarily those of the Power Systems.

NOTES:

Uncertainty and/or variation due to range in secondary parameters:

(a) = ±20%

(b) = 1/2 to 2 times value shown

operating life limits for high-power lasers forecast for the year 2000 is about six months. For space operations a closed-cycle device will be used to minimize total system mass. This restricts the types of lasers which can be considered. For a given laser medium, the laser beam generator total volume and mass will probably scale as a total system in proportion to beam power, based on present high-technology systems. The transmitter optics will scale directly with power and with the reciprocal of the wave length. A typical space-based diffraction-limited power transmission from low Earth-orbit to synchronous orbit would produce a 30-meter spot using a 30-meter transmitter operating at 10.6 micrometers wave length. Prohibitive mass requirements result for conventional transmitter antenna construction. Alternate acceptable concepts will involve deployable, deformable, segmented, or continuous mirrors.

The power levels available for continuous-wave laser-beam generators for the year 2000 could be as high as 5 MWe in space and 100 MWe on Earth. Lasers could probably be made to accommodate these power levels. For both cases, the rate of performance growth of laser beam-generator capability is essentially limited by the investment capital provided.

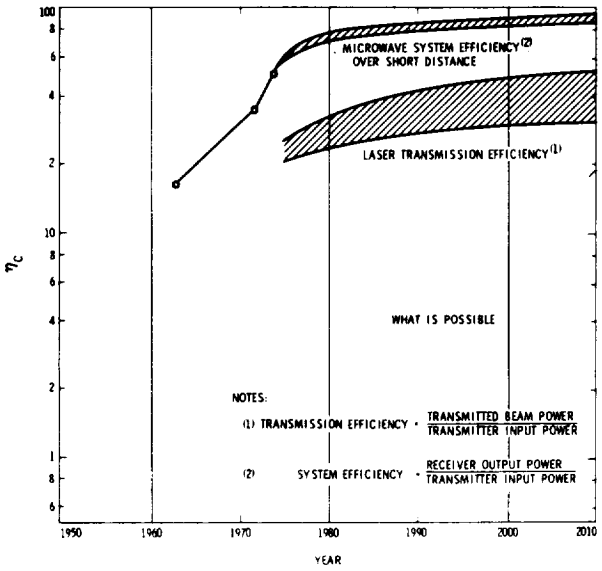
(2) Microwave Beaming (Code 1.2)

High-efficiency transmission of power by means of beamed microwaves of the order of 10 cm wavelength can be anticipated. The microwave energy transmission system consists of (1) conversion of dc power to microwave power, (2) a means for forming a concentrated microwave beam (transmitting antenna) and (3) a means for collecting and rectifying the received power to produce dc power output (rectenna). The microwave generator being forecast is a crossed field device. The level of specific mass attributed to the generator by 1975 is drastically reduced from prior levels. This has been achieved by use of a new material which reduces magnet mass by a factor of 10 and by specific design for the vacuum of space. Further reductions predicted for space transmitter specific mass by the year 2000 will be due primarily to mass reductions in the active phased array used as a transmitting antenna.

The receiver mass is dominated by the rectenna, an array of half-wave dipole antennas each terminated by a Schottky barrier diode used as a rectifier. The device will be deployed in space in a roll-out mode. This device provides a high-energy capture efficiency which is independent of the illumination patterns and dependent on pointing only by the cosine function.

(3) Efficiencies of Laser Beaming and Microwave Beaming. For space-based beam transmission systems (microwave or laser), the dominant mass is that of the power generator needed to form the beam. Hence, the forecast for specific mass of the entire system depends on the forecast for space power systems and on the efficiency η_c of conversion from electric power to beam power. The forecast values η_c are shown in FC 4-13 The specific mass of the entire system is thus roughly α_c (power system)/ η_c. The cost also is dominated by the cost for the power generation system, both for development of prototypes and for testing and launching of flight hardware. (See paragraph E-5 for discussion of space-based power supplies).

FC 4-13. Efficiency of Energy Transmission



b. Collection. Energy collection forecasts presented in this section relate to photon collection for thermal conversion, collection of material for reactants from the surface or atmosphere of other bodies, and antimatter production. The photovoltaic devices are presented in D-2-e-(3)-(a).

Forecast 4-14 summarizes forecast parameters for energy collection.

(1) Photon Collectors (Code 2.1). Mass and cost estimates for photon collectors are included in Solar Energy Conversion Devices (Code 5.3). A forecast for this device is also presented separately, however, to allow ease of comparisons. Forecasts of paraboloid photon collector state of the art indicate that collectors capable of 1400°K temperature will be built of a graphite-epoxy matrix. These collectors are estimated to have near-term costs of \$110 per kg based on an area density of 0.035 kg/m^2. The cost is expected to be halved by 2000 as these materials become more plentiful. Specific mass of 4.3×10^{-3} kg/W_t (W_t = thermal Watts) may drop to 3.5×10^{-3} kg/W_t by the year 2000 for collectors used to concentrate solar energy at 1 AU.

(2) Extraterrestrial Surface Materials (Code 2.2). Forecasts were made for three indigeneous material processing plants previously documented in the open literature. These include a processing plant to obtain O_2 from moon rocks, a Lunar processing plant to obtain O_2, H_2O, H_2 and electricity from below-surface thermal wells, and a water-ice processing plant suitable for use on a satellite of Jupiter or Saturn. These forecasts were normalized to obtain estimates of α_a (equipment mass/unit power out) and η (power out/ power in) by assuming combustion of O_2 and H_2 at an α_q of 0.08×10^{-6} kg/J. Note that Device Code Nos. 2.2.1 and 2.2.3 appear to have smaller values for α_a than 2.2.2. However, the Lunar thermal station obtains power in addition to chemicals from the thermal reservoir assumed, while additional power must be supplied to the other devices. If one assumes a nuclear system with an α_c of 0.25 kg/We (see paragraph C-2-(e)-(5)) and the efficiencies noted, then the combined α values for Code Nos. 2.2.1 and 2.2.3 are 1.5 and 1.0 kg/We respectively.

Cost estimates are for development and production; they do not include transportation to the site or operational maintenance required on site. The processes identified are conceptually straightforward, but their remote location adds significantly to their complexity. The Lunar rock system (Code No. 2.2.1) must provide for the removal of 70% of the input raw material as slag.

(3) Extraterrestrial Atmospheric Materials (Code 2.3). Future exploration of the planets may generate a requirement for making atmospheric measurements over extended periods. A balloon system could be used at Venus. Another concept for possible use at Venus and also the outer planets is an "air" breathing engine. FC 4-14 summarizes performance and cost parameters for Venus and Jupiter engines. The concepts envisioned are a turboprop engine at Venus burning Be powder with atmospheric CO_2 and a turbojet engine burning fluorine with indigenous hydrogen in the Jovian atmosphere. Note that even with the use of CO_2, a relatively weak oxidizer, the Venus device is forecast to provide a specific fuel consumption α_q a factor of 2 to 3 better than conventional storable propellants used to drive a smaller engine. The forecast at Jupiter is not so optimistic. The low mass obtainable from the atmosphere, the resulting high specific fuel consumption, and the low atmospheric molecular weight and high gravitational attraction all tend to make atmospheric cruise a more difficult problem as indicated by the endurance forecast.

(4) Antimatter Production (Code 2.4). Work by elementary particle physicists on antimatter production, storage, and reaction may ultimately lead to an energy source with available energy per unit mass two orders of magnitude greater than fusion. Antimatter particles are currently created in high energy accelerators; the estimated present rate of production in this country is 0.5×10^{-6} g/ yr, about 6 orders of magnitude too low for useful propulsion applications. Storage is maintained in magnetic rings. Energy conversion and control devices have received only cursory attention at this time. It is forecast that use of antimatter is well behind fusion in terms of application. This would make its application well beyond the 1980 to

FC 4-14. Parameter Estimates for Energy Collection (What Is Possible)

Device Code No. (Ref. Table 4-2)	Description	Present Technology Status	Year of First Availability	Year of Stated Parameters	System Performance Parameters			System Cost Parameters			Remarks
					α_q (kg/J)	α_a (kg/W)	η_c	c_a ($/kg)	First Costs: Pre-Project (10^6)	First Costs: First Applic. (10^6)	
2.1	Photon Collectors	In Development	1975	1975 2000		4.3×10^{-3}(a) 3.5×10^{-3}(a)		100(b) 50(b)			Specific mass at 1 AU
2.2.1	Lunar Rock Processing for O_2	On the Technology Frontier	1980	1980	N/A	0.6(c)	0.27(b)	300(c)			Based on plant designed for 91 kg O_2 per day. Numbers do not include power supply. α_a = kg plant/W out. η = power out/power in. (See text.)
2.2.2	Lunar Thermal Processing for O_2, H_2, H_2O, electricity	On the Technology Frontier	1985	1985	N/A	2.4(c)	N/A	200(c)			Based on life support plant for 20 people. System draws power from below-surface thermal reservoir.
2.2.3	Outer Planet Satellite Ice Processing for H_2-O_2	On the Technology Frontier	1990	1990	N/A	0.4(c)	0.40(c)	300(c)	100(c)	30(c)	Based on electrolysis plant with capacity of 220 kg O_2 per day, 27 kg H_2 per day. Numbers do not include power supply. α_a = kg plant/W out. η = power out/power in (see text).
2.3.1	Venus Atmospheric Cruise Propulsion	On the Technology Frontier	1985+	1985+	0.1×10^{-6}(a)	0.007(b) (Engine only)	N/A	5000(c)	1(c)	20(c)	Costs for engine only. Endurance estimated 280 hours for 4:1 initial to final mass ratio. α_q = specific consumption of on-board fuel.
2.3.2	Jupiter Atmospheric Cruise Propulsion	On the Technology Frontier	1985+	1985+	0.25×10^{-6}(a)	0.007(b) (Engine only)	N/A	5000(c)	1(c)	20(c)	Costs for engine only. Endurance estimated at 2.4 hours for 4:1 initial to final mass ratio. α_q = specific consumption of on-board fuel.
2.4	Matter-Antimatter Reaction	Conceptual	2000+	2000	0.2×10^{-16}(a)	Large					α_{sp} also very large for antimatter storage.

NOTES:

Uncertainty and/or variation due to range in secondary parameters:

(a) = ±20%

(b) = 1/2 to 2 times value shown

(c) = 1/10 to 10 times value shown (order of magnitude)

2000 period of interest, but significant advances in knowledge on the subject should occur in this time frame.

c. Storage. The parameter forecasts for devices defined in the energy storage category are presented in FC 4-15. Included are (a) mechanical - flywheels, (b) superconductors, (c) batteries - primary and secondary, and (d) chemical - stable reactants and metastable reactants. Parameters for nuclear energy storage and conversion devices are presented in paragraph D-2-e. An overall storage summary including nuclear device parameters is included in paragraph E-3.

(1) Flywheels (Code 3.1). Although flywheels have been in use for many years, their application, as long-term energy storage devices, has not yet become a reality. Upon the development of high-strength fiber composites and implementation of new concepts in fabrication, these devices can become effective elements for long-term energy storage. The performance factor, α_s (kg/J) is an overall value and includes the converters necessary to produce electrical energy, speed controls, bearings and the flywheel support structure. Assuming the use of magnetic bearings and electro-mechanical energy coupling techniques, lifetimes of 30 years or more should be achievable.

(2) Superconductors (Code 3.2). This device consists of a superconducting magnet with associated cryogenic equipment, a magnet support structure, and associated power conditioning equipment. The cryogenic equipment presently requires a continuous source of liquid helium but it is anticipated that LH_2 will be used for future superconductors.

(3) Primary Batteries (Code 3.3). Primary battery forecasts are presented in FC 4-15, under four general categories. The first class is based on a low-energy-density couple and includes such types as the Leclanche, alkaline-manganese, mercury, and silver-zinc batteries. The second classification, high-energy-density couples, includes the magnesium and lithium batteries. Batteries in the third class are high-energy-density couples using a solid ionic conductor as an electrolyte while the fourth class of batteries is made up of those requiring high temperatures to activate the couple.

(4) Secondary Batteries (Code 3.4). Secondary battery forecast parameters are also presented in FC 4-15, under four general categories. The first class uses an aqueous electrolyte with water as the solvent and an acid or alkaline inorganic as the solute. Representatives of this class include nickel-cadmium, silver-cadmium, silver-zinc, and nickel-zinc batteries. The second classification uses an aqueous electrolyte, and a gas is one of the cell reactants. Typical batteries of this type use the nickel-hydrogen or silver-hydrogen couple.

A third class of secondary batteries uses organic solvents containing inorganic solutes as the electrolyte while the fourth classification requires high temperatures to activate the battery.

Further note should be made of the requirement for a secondary battery to survive hundreds to tens of thousands of charge/discharge cycles. In order to attain these cycle lifetimes, less energy must be taken from the battery on each discharge cycle than the battery has the capability of supplying. Thus, a nickel-cadmium battery (representing the class of aqueous batteries) will withstand approximately 200 charge/discharge cycles without a performance (mass/cost) penalty. However, the specific mass and cost increases by a factor of 2 for 2000-3000 cycles and by a factor of 4 for 10,000-15,000 cycles.

(5) Stable Chemicals (Code 3.5). This device includes the chemical reactants as well as tanks for storing the chemicals, pumping and pressurizing equipment and tankage support. The stable chemicals fall into the two general categories of cryogenics (e.g., LH_2 - LO_2) and storables (e.g., N_2O_4 - MMH).

(6) Metastable Chemicals (Code 3.6). This device includes the metastable substance, the container, magnetic field stabilization equipment and cryogenic equipment. The metastable substance is hydrogen containing above 15% of atomic hydrogen.

d. Conversion to Mechanical Energy for Propulsion. As previously mentioned, the propulsion devices are arranged according to the type of energy from which conversion is made, viz., electrical, photonic, chemical, and nuclear. Pertinent performance and cost parameters are presented in FC 4-16 for each device or system forecasted. These parameters will allow determination of system mass and cost for various program options.

(1) Conversion from Electrical Energy (Code 4.1). Parameters are forecast for electrostatic and electromagnetic thrusters. Electrostatic thrusters are further subdivided into electron bombardment and colloid thrusters. Electron bombardment thrusters (Code 4.1.1), using mercury propellant, have reached an advanced development state in two size ranges - 3 kWe per thruster for primary propulsion and 0.15 to 0.5 kWe per thruster for auxiliary propulsion. System optimization studies dictate a preferred exhaust velocity of about 3×10^4 m/s for primary thrusters with desired values toward 10^4 m/s for auxiliary thrusters. Forecast parameters summarized in FC 4-16 represent thrusters with expected operating lifetimes of 15,000 to 20,000 hours. The conversion mass term includes the basic thruster, as well as mass for structural assembly and thrust vector control.

As specific mass values for power acquisition and/or storage decreases, the optimum exhaust velocity tends to increase. This increase can be achieved by increasing the acceleration voltage, hence electrical power to the device. A possible future use for electric propulsion thrusters for stationkeeping of satellite power systems requires an optimum exhaust velocity of about 8×10^4 m/s. Propellant requirements for such a system are so large that cost considerations may well drive the system to use of a light gas propellant such as argon. Parameters for such a system are forecast at a power level of 7.5 kWe per thruster.

FC 4-15. Parameter Estimates for Energy Storage (What Is Possible)

Device Code No. (Ref. Table 4-2)	Description	Form of Energy Output	Present Technology Status	Year of First Availability	Year of Stated Parameter	System Performance Parameter α_s (kg/J)	System Cost Parameters		
								First Costs	
							c_s ($/kg)	Pre-Project ($10^6)	First Application ($10^6)
3.1	Flywheels	Electrical							
	4 to 400 MJ Units		In Development	1980	1980 2000	1.5×10^{-6}(b) 1.0×10^{-6}(b)	7×10^{1}(b) 1.6×10^{1}(b)	0.3(b)	2(b)
	40,000 MJ Units		In Development	1980	1980 2000	1.2×10^{-6}(b) 8×10^{-7}(b)	3.5×10^{1}(b) 8(b)	5(b)	25(b)
3.2	Superconductors	Electrical							
	10 MJ Units		In Development	1980	1980 2000	6×10^{-5}(b) 1.3×10^{-5}(b)	2.8×10^{2}(b) 2×10^{2}(b)	10(a)	20(a)
	1000 MJ Units		In Development	1980	1980 2000	2×10^{-5}(b) 4×10^{-6}(b)	1.7×10^{2}(b) 1.3×10^{2}(b)	20(a)	100(a)
3.3	Primary Batteries	Electrical							
	Low Energy Density		In Use	N/A	1975 2000	2.0×10^{-6}(b) 1.5×10^{-6}(b)	1×10^{2}(a) 5×10^{2}(b)	---	---
	High Energy Density		In Development	1980	1980 2000	1×10^{-6}(b) 4×10^{-7}(b)	1.3×10^{2}(a) 5×10^{2}(b)	7(a)	1.5(a)
	Solid Electrolyte		In Use	N/A	1975 2000	5×10^{-5}(b) 6.5×10^{-5}(b)	1×10^{2}(a) 5×10^{2}(b)		
	Thermal Cells		On the Technology Frontier	1985	1985 2000	6.3×10^{-6}(b) 8×10^{-7}(b)	1.6×10^{2}(a) 5×10^{2}(b)		
3.4	Secondary Batteries	Electrical							
	Aqueous		In Use	N/A	1975 2000	8×10^{-6}(b) 4.3×10^{-6}(b)	3.5×10^{3}(b) 4.5×10^{3}(a)	---	---
	Aqueous + Gas Reactant		In Development	1975	1975 2000	4.4×10^{-6}(b) 3.3×10^{-6}(b)	1.0×10^{4}(b) 8×10^{3}(b)	---	1(b)
	Organic		On the Technology Frontier	1982	1982 2000	3.2×10^{-6}(b) 2×10^{-6}(b)	1.3×10^{4}(b) 6.4×10^{3}(b)	3.5(b)	1(b)
	Thermal Cells		On the Technology Frontier	1982	1982 2000	3×10^{-6}(b) 1.2×10^{-6}(b)	1.1×10^{5}(b) 7×10^{4}(b)	10(b)	5(b)
3.5	Stable Chemicals	Mechanical (Kinetic Energy of Exhaust)							
	$H_2 - O_2$ (Large Stage)		In Use	N/A	1975 2000	8.1×10^{-8}(a) 8.1×10^{-8}(a)	4.0(b) 4.0(b)	---	---
	$H_2 - O_2$ (Small Pressure-Fed Stages)		In Use	N/A	1975 2000	8.1×10^{-8}(a) 8.1×10^{-8}(a)	1.5×10^{2}(b) 1.5×10^{2}(b)	---	---
	Storables (Large Stage)		In Use	N/A	1975 2000	1.2×10^{-7}(a) 1.2×10^{-7}(a)	7.5(b) 7.5(b)	---	---
	Storables (Small Pressure-Fed Stages)		In Use	N/A	1975 2000	1.3×10^{-7}(a) 1.3×10^{-7}(a)	1.6×10^{2}(b) 1.6×10^{2}(b)	---	---
3.6	Metastable Chemicals	Mechanical (Kinetic Energy of Exhaust)	Conceptual	1985	1985 2000	1.0×10^{-7}(c) 8×10^{-8}(c)	2.5×10^{4}(c)	20(c)	50(c)

NOTES:

Uncertainty and/or variation due to range in secondary parameters:

(a) = ±20%

(b) = 1/2 to 2 times value shown

(c) = 1/10 to 10 times value shown (order of magnitude)

FC 4-16. Parameter Estimates for Energy Conversion to Mechanical Energy for Propulsion (What Is Possible)

Device Code No. (Ref. Table 4-2)	Description		Present Technology Status	Year of First Availability	Year of Stated Parameter	System Performance Parameters				System Cost Parameters				
						α_{sp} (kg/kg)	α_c (kg/We)	η_c	V_e (m/s)	c_p ($/kg)	c_{sp} ($/kg)	c_c ($/kg)	First Costs: Pre-Project (10^6)	First Costs: First Application (10^6)
4.1	From Electrical													
4.1.1	Electron Bombardment Electrostatic Thrusters	Primary Hg Propellant	In Development	1975	1975 2000	1.5×10^{-2}(a) 0.85×10^{-2}(a)	5.0×10^{-3}(a) 3.5×10^{-3}(a)	0.7(a)	2.9×10^4(a)	12(b)	1.5×10^2(b) 1.5×10^1(b)	4.0×10^3(b)	4(b)	6(b)
		Primary-Light Gas Propellant	In Development	1975	1975 2000	0.3(a) 0.17(a)	2.0×10^{-3}(a) 1.5×10^{-3}(a)	0.7(a)	7.3×10^4(a) 2.1×10^5(a)	0.4(b)	1.5×10^2(b) 1.5×10^1(b)	4.0×10^3(b)	4(b)	6(b)
		Auxiliary-Hg or Cs Propellant	In Use	1975	1975 2000	1.5×10^{-1}(a) 0.7×10^{-1}(a)	2.0×10^{-2}(a) 1.3×10^{-2}(a)	0.7(a)	10^4 for Cs(a) 2.9×10^4 for Hg(a)	12(b)	1.5×10^2(b) 1.5×10^1(b)	2.5×10^4(b)	4(b)	6(b)
4.1.2	Colloid Electrostatic Thruster (Auxiliary)	Glycerol Propellant	In Development	1977	1977 2000	2.5×10^{-2}(a)	2.5×10^{-3}(a)	0.6(a)	1.3×10^4(a) 1.9×10^4(a)			3.3×10^4(b) 1.7×10^4(b)	0	2(b)
		Cesium Propellant	In Development	1985	1985 2000	1.6×10^{-2}(a)	0.9×10^{-3}(b)	0.65(a)	2.9×10^4(a) 10^5(a)			3.3×10^4(b) 1.7×10^4(b)	2(b)	2(b)
4.1.3	Electromagnetic Accelerator(d)	Quasi-Steady (10 kW) (e)	On the Technology Frontier	1980	1980 2000	0.3(a) 0.17(a)	2.0×10^{-3}(b)	0.15(a) 0.4(a)	10^4 Adjustable	1.6×10^{-2}(b)	1.5×10^2(b) 1.5×10^1(b)	6.0×10^2(b)	25(b)	10(b)
		Steady (1 MW)	On the Technology Frontier	1985	1985 2000	0.3(a) 0.17(a)	1.5×10^{-4}(b)	0.3(a) 0.5(a)	10^4 Adjustable	1.6×10^{-2}(b)	1.5×10^2(b) 1.5×10^1(b)	50(b)	20(b)	15(b)
4.2	From Electromagnetic													
4.2.1	Beamed Energy Driven Thermal Rocket Engine		On the Technology Frontier	1985 - 90	1985 - 90	0.05(a)	10^{-4}(c)	0.2(b)	10^4(b)	1.0(a)	50(a)	10^2(c)	10^3(c)	500(c)
4.2.2	Solar Sails		On the Technology Frontier	1981	1981 2000	N/A	2.0×10^{-6}(b) 0.7×10^{-6}(b)	η_c equals $\frac{1+r}{2}\cos^2\beta$ r=reflectance	3.0×10^8(a)	N/A	N/A	10^3(b) 0.3×10^3(b)	0.7(b)	20(b)
4.2.3	Solar Electric Propulsion System (Mercury Propellant)		In Development	1980 +	1980 + 2000	1.5×10^{-2}(a) 0.85×10^{-2}(a)	40.0×10^{-3}(a) 20.0×10^{-3}(a)	0.63(a) 0.70(a)	2.9×10^4(a) 4.0×10^4(a)	12(b)	1.5×10^2(b) 1.5×10^1(b)	30.0×10^3(b)	15(a)	40(a)
4.3	From Chemical													
4.3.1	Liquid Propellant Rockets	Pump Fed	In Use/In Development	O_2-H_2 now, advanced propellants 1985-1995	1985-1995 2000	0.05(a)	6.0×10^{-7}(a)	0.95(a)	4.6×10^3(a) 5.5×10^3(a)	1.0(b) for O_2-H_2 to 50(b) for advanced propellants	50(b) for largest stages	5.0×10^3(b) at F = 40,000 N	20(b)	70(b)
		Pressure Fed Primary Propulsion	In Use/In Development	Storables now, fluorine propellants 1980-1985	1980-1985 2000	0.10(a)	3.0×10^{-6}(b)	0.95(a)	3.0×10^3(a) 3.6×10^3(a)	5.0(b) for storables to 20(b) for fluorinated	10^3(b) for spacecraft size systems	3.0×10^4(b) at F=400N 10^3(b) at 40,000 N	2(b)	5(b)
		Pressure Fed Auxiliary Propulsion	In Use	N/A	1975	0.15(a)	5.0×10^{-6}(b)	0.85(a)	2.0×10^3(a) monopropellants 3.0×10^3(a) bipropellants	10(b)	10^3(b)	3.0×10^4(b)	---	---
4.3.2	Solid Propellant Rocket Motors	Propellant Mass 10^2 kg	In Use	N/A	1975 2000	0.09(a) 0.04(a)	Included in α_{sp}	N/A	2.9×10^3(a) 2.9×10^3(a)	($/kg of total motor mass) 320(a) 320(a)			0.6(a)	
		10^4 kg	In Use	N/A	1975 2000	0.09(a) 0.04(a)		N/A	2.9×10^3(a) 2.9×10^3(a)	35(a) 35(a)			10(a)	
		10^6 kg	In Use	N/A	1975 2000	0.09(a) 0.04(a)		N/A	2.9×10^3(a) 2.9×10^3(a)	5(a) 5(a)			150(a)	

NOTES:

1. Uncertainty and/or variation due to range in secondary parameters:
   - (a) = ±20%
   - (b) = 1/2 to 2 times value shown
   - (c) = 1/10 to 10 times value shown (order of magnitude)
2. Values quoted for α_{sp}, c_p, c_{sp} assume N_2 propellant (other materials may be used)
3. Quasi-steady device also requires energy storage. $\alpha_s = 10^{-2}$ kg/J(b); $c_s = 60$ $/kg (b)

Device Code No. (Ref. Table 4-2)	Description		Present Technology Status	Year of First Availability	Year of Stated Parameter	System Performance Parameters				System Cost Parameters				
						α_{sp} (kg/kg)	α_c (kg/We)	η_c	V_e (m/s)	c_p ($/kg)	c_{sp} ($/kg)	c_c ($/kg)	First Costs: Pre-Project (10^6)	First Costs: First Application (10^6)
4.3.3	From Chemical (contd) Detonation Propulsion	----	On the Technology Frontier	1980 2000	1980 2000	0.10(b) 0.10(b)	10^{-4}(b) 10^{-5}(b)	0.4(a) 0.5(a)	2.0×10^3(a) 3.0×10^3(a)	2(b) 2(b)	100(b) 100(b)	75×10^3(b) 75×10^3(b)		
4.3.4	Metastable Chemical Rocket H-H_2	Magnetic Stabilized(d) 10^3 kg Propellant mass	Conceptual	1990	1990 2000	5(b) 9(b)	----	----	4.0×10^3 9.0×10^3(a)	2(b)	100(b)	50×10^3(c)	20(c)	50(c)
		10^5 kg Propellant mass	Conceptual	1990	1990 2000	1.5(b) 3.7(b)	----	----	6.5×10^3 17×10^3(a)	2(b)	100(b)	50×10^3(c)	50(c)	100(c)
		Solid Matrix Stabilized(e) 10^3 kg Propellant mass	Conceptual	1995	1995	0.25(b)	----	----	5.0×10^3(a)	2(b)	100(b)	50×10^3(c)	20(c)	50(c)
		10^5 kg Propellant mass	Conceptual	2000	2000	0.18(b)	----	---	5.0×10^3(a)	2(b)	100(b)	50×10^3(c)	50(c)	100(c)
4.4	From Nuclear Fission						α_c/η_c (kg/We)						Engine Costs Only	
4.4.1	Solid Core Nuclear Rocket	F=70,000N	In Development	1985	1985	0.05(a)	7.0×10^{-7}(a)		9.0×10^3(a)	1.0(a)	50(a)	160×10^3(b)	100(b)	300(b)
		F=300,000N	In Development	1985	1985	0.05(a)	6.5×10^{-7}(a)		9.0×10^3(a)	1.0(a)	50(a)	55×10^3(b)	100(b)	600(b)
		$F=10^6$N	On the Technology Frontier	1990	1990	0.05(a)	6.0×10^{-7}(a)		9.0×10^3(a)	1.0(a)	50(a)	25×10^3(b)	200(b)	1000(b)
4.4.2	Dust Bed Nuclear Rocket	F=20,000N	Conceptual	1990	1990	0.05(a)	7.0×10^{-6}(b)		1.1×10^4(a)	1.0(a)	50	4.0×10^4(c)	100(b)	500(b)
		F=45,000N	Conceptual	2000+	2000+	0.05(a)	3.0×10^{-6}(b)		1.1×10^4(a)	1.0(a)	50	7.0×10^4(c)	150(b)	700(b)
4.4.3.1	Nuclear Light Bulb Rocket	F=500,000N	Conceptual	1990	1990	0.05(a)	2.0×10^{-5}(c)		2.0×10^4(b)	1.0(a)	50	10^4(c)	100(b)	800(b)
		$F=10^6$N	Conceptual	2000+	2000+	0.05(a)	1.0×10^{-5}(c)		3.0×10^4(b)	1.0(a)	50	10^4(c)	250(b)	1000(b)
4.4.3.2	Nuclear Gas Core Rocket	F=250,000N	Conceptual	1990	1990	0.05(a)	3.0×10^{-5}(c)		4.0×10^4(b)	1.0(a)	50	10^4(c)	100(b)	500(b)
		F=450,000N	Conceptual	2000+	2000+	0.05(a)	2.0×10^{-5}(c)		6.0×10^4(b)	1.0(a)	50	10^4(c)	150(b)	700(b)
4.4.4	Nuclear Electric Propulsion	Thermionic 120 kWe to 240 kWe	On the Technology Frontier	1985-1995	1985-1995	10^{-2}(a)	3.0×10^{-2}(b)	0.65(a)	4.0×10^4(a)	12(b)	150(b)	8×10^3(c)	300(c)	600(c)
		1 MWe		2010	2010	10^{-2}(a)	2.0×10^{-2}(b)	0.7 (a)	6.0×10^4(a)	12(b)	150(b)	3×10^3(c)	600(c)	1500(c)
		MHD 1 MWe	On the Technology Frontier	1990	1990	10^{-2}(a)	2.0×10^{-2}(b)	0.65(a)	4.0×10^4(b)	12(b)	150(b)	3×10^3(c)	500(c)	1000(c)
		10 MWe		2010	2010	10^{-2}(a)	1.0×10^{-2}(b)	0.7(a)	6.0×10^4(b)	12(b)	150(b)	10^3(c)		1500(c)
4.5	From Nuclear Fusion													
4.5.1	Fusion Rocket Engine	Jet Power = 200 MW to 1 GW	Conceptual	2000-2010	2000-2010	0.17(b)	10^{-3}(c)	0.25(b)	10^4-10^6(c)				2000(c)	5000(c)
4.5.2	Fusion Microexplosions		Conceptual	1990-2000	1990-2000	0.17(b)	10^{-4}(c)	0.15(b)	10^5(c)				300(c)	1000(c)

NOTES:

1. Uncertainty and/or variation due to range in secondary parameters:
   - (a) = ±20%
   - (b) = 1/2 to 2 times value shown
   - (c) = 1/10 to 10 times value shown (order of magnitude)
2. Values quoted for α_{sp}, c_p, c_{sp} assume N_2 propellant (other materials may be used).
3. Quasi-steady device also requires energy storage. $\alpha_s = 10^{-2}$ kg/J(b); $c_s = 60$ $/kg (b)

Colloid thrusters (Code 4.1.2) use an electrically conducting liquid fed to the accelerating grids, rather than a vapor as used by the electron bombardment thrusters. Colloid thrusters using glycerol propellant are under development for use as auxiliary propulsion on Earth-orbiting satellites at a power level of 70 We per thruster. Advanced thrusters of this type using cesium propellant may be available by 1985.

The electromagnetic accelerator (Code 4.1.3) passes a large current through an injected stream of propellant. Interaction of this current with its self-induced magnetic field produces a body force which acts directly on the ionized propellant to accelerate it to a usefully high exhaust velocity. This magnetoplasmadynamic (MPD) accelerator is characterized by exhaust velocities of 5 to 50 km/s and thrust densities of 0.05 to 50 N/cm^2.

The self-field MPD arc is a low-voltage (100s of volts), high-current (10^4 amps) plasma which can be operated in either a steady or quasi-steady mode. In steady operation, it requires direct connection to a large, steady, space power supply (100 kWe to 10 MWe). In the quasi-steady mode, a smaller power supply can be used (1 kWe to 100 kWe) in conjunction with an energy storage system which draws power continuously from the power supply and periodically discharges it through the accelerator, at much higher instantaneous power.

Parameter forecasts for the device, presented in FC 4-16, are for quasi-steady operation at 10 kWe average power and steady operation at 1 MWe power. The device may operate with a variety of propellants, solid, liquid, or gaseous.

(2) Conversion from Electro-Magnetic (Photon) Energy (Code 4.2). Photon energy from the Sun or a laser beam may be converted to propulsive energy. The first device (Code 4.2.1) is the beam heated thermal rocket engine. A laser beam source located on the ground or in orbit about Earth (see Code 1.1, Energy Transmission) is aimed at a collector on the spacecraft. This collector then focuses the energy through windows in a thrust chamber where it is absorbed by a propellant (e.g., H_2) which is heated and exhausted through a nozzle. Exhaust velocities of the order of 7.5×10^3 to 2×10^4 m/s are possible if the hydrogen can be heated to temperatures of 2500 to 10,000°K. Critical developments required for this device, in addition to beam generator technology, are windows for high-intensity beam transmission, means for energy absorption by the propellant, and chamber thermal protection.

Solar sails have been considered for years as a possible means of low-cost propulsion. Shuttle operations would provide the first opportunity for relatively low-risk on-orbit deployment of the required extensive light-weight structure. The concept described as Code 4.2.2 uses a stiffened mylar structure with vanes for attitude control. Performance parameters forecast correspond to 1 AU with the sail normal to the vehicle Sun-line. The accelerating pressure varies as the square of the cosine of the Sun-probe-sail centerline angle (β) and inversely as the square of the Sun-probe distance. Acceleration at zero payload is obtained from the parameters given with the formula

$$a = \frac{\eta_c}{\alpha_c \times (\text{speed of light})}$$

The forecasts can also be applied to laser beams by relating the beam energy to the solar intensity at 1 AU.

The third entry under photon energy conversion represents a composite summary of solar electric propulsion (Code 4.2.3). Parameters for photovoltaic cells and power processors (Codes 5.3.1 and 5.1.2) are combined with mercury bombardment thrusters (Code 4.1.1). Laser beam conversion by electric propulsion may also be evaluated by relating laser energy to solar energy at 1 AU.

(3) Conversion from Chemical Energy (Code 4.3). Rocket motors now used for propulsion use the stored electronic energy in the chemical bond, released through a combustion process, to provide thermal expansion and high-velocity exhaust of the combustion products. Forecasts are presented for liquid propellant rocket motors, solid propellant rockets, and a conceptual system using metastable hydrogen as a propellant.

Liquid propellant rocket engines (Code 4.3.1) are divided into two major subclasses — pump fed and pressure fed. Parameters forecast for pump-fed engines are based on current technology O_2-H_2 engines with possible growth to advanced technology propellants such as F_2-H_2 or O_2-H_2-Be. Pressure-fed engines are further subdivided into primary and auxiliary propulsion categories. Primary propulsion forecasts are based on current storable technology (e.g., N_2O_4-MMH) with growth to propellants using a fluorinated oxidizer in the early 1980s. Auxiliary propulsion forecasts are based on monopropellant hydrazine for small systems (0.5 N to 250 N) and current technology bipropellants for larger engines (100 N to 400 N). Parameters presented in FC 4-16 include propellant storage parameters from Code 3.5 in addition to the rocket engine parameters.

Solid propellant rocket motor (Code 4.3.2) parameters are forecast to cover a range of motor sizes from 10^2 to 10^6 kg. The parameters forecast are for "conventional" solid motors used for space applications. Extremely-high-acceleration motors used for some military applications would have different characteristics. Single mass and cost parameters are used, rather than the multiple parameters used for the liquid systems. Cost is presented as a function of total motor mass. Special requirements on a motor (e.g., integral thrust vector control, thrust termination, and extreme temperature limits) will have some effect on the parameters listed. Solid motors have been operated successfully after storage for 10 years between 0 to 100°F temperature limits.

Detonation propulsion (Code 4.3.3) is designed for application in high-density planetary atmospheres and employs a detonating propellant fired in a pulse mode in a nozzle. The propulsion system utilizes the momentum of the products of

detonation and ambient gas set into motion by the explosion. Typical pressures developed by the detonation range between 20-200 kbar, so that ambient pressures of a few hundred bars or even a kilobar will not appreciably affect the process. Because of the pulsing mode of operation, such high pressures do not have to be contained statically; thus structures can be designed to withstand the detonation forces. Regulation of average thrust can be obtained over a wide range by either controlling the size of the charges or varying the frequency of the firings (or both). Conventional chemical rockets, because of material strength limitations in the combustion chamber, operate at inefficient expansion ratios in high-pressure environments of the outer planets and therefore produce lower specific impulse than a detonation propulsion system.

A significant increase of energy storage and release from chemical bonds is conceptually represented by the metastable hydrogen rocket motor (Code 4.3.4). This device is an $H\text{-}H_2$ mixture frozen at 1°K in a solid-propellant-like chamber. Thrust is the result of evaporation and recombination followed by expansion through a nozzle. Large concentrations of H are conceptually possible ; all hydrogen stored as H atoms could yield an exhaust velocity of $\approx 1.6 \times 10^4$ m/s. However, a magnet with field strength of 10 T is projected to be required for H concentrations above 25%, and the resulting mass would tend to counter performance gained from the high exhaust velocity. Consequently, matrix stabilization with lower concentrations, less than 25% H, and with exhaust velocity of 4 to 6.5×10^3 m/s may offer the most interesting possibilities.

Other metastable substances, not forecast but under investigation, include the metallic state of hydrogen and electronically excited states of helium and of oxygen.

(4) Conversion from Nuclear Energy (Code 4.4). The nuclear systems offer extremely large energy densities compared to chemical systems (see paragraph E-3) but the mass and cost considerations associated with nuclear propulsion development have kept these systems in the categories ranging from "conceptual" to "in development" for some time. As indicated by the cost parameters for nuclear propulsion systems, a large resource commitment to the development of nuclear propulsion will be required to change that situation.

Extensive development testing has occurred over the past 10 years on solid-core rocket engines (Code 4.4.1) in the thrust range of 250,000 to 300,000 N. Material temperature constraints limit the exhaust velocity of the hydrogen propellant to about 9×10^3 m/s. Conceptual schemes for obtaining increased exhaust velocity include the fluidized or "dust bed" engine, the nuclear light bulb engine, and the gas-core engine (Codes 4.4.2 and 4.4.3). All of these concepts offer means for removing the material temperature limitations of the solid-core rocket by containing the reactor fuel in a vortex flow. However, each of these devices has significant technological problems which must be overcome. Among these are heat transfer to the propellant, losses of nuclear fuel inventory, and chamber cooling.

Nuclear electric propulsion (Code 4.4.4) offers the potential for low-thrust propulsion at a very high exhaust velocity ($V_e \approx 4$ to 6×10^4 m/s), as with solar electric propulsion, but with a system that is independent of solar distance. Parameters forecast for the 120 kWe to 1 MWe power levels are consistent with use of thermionic or fluid dynamic conversion devices (Codes 5.6.2 through 5.6.5) electric propulsion power processors (Code 5.1.2) and mercury electron bombardment thrusters (Code 4.1.1). Although detailed studies of 1 to 10 MWe systems have not been accomplished, it is anticipated that dynamic conversion or magnetogasdynamic cycles (Codes 5.6.4 and 5.6.5) would be applicable to that size range.

As do the advanced fission reactors, the fusion reactor offers increased exhaust velocity, but does so at a penalty in energy storage and conversion mass. Parameters are forecast for a direct heated fusion system (Code 4.5.1) in which the products of fusion are injected into a thrust chamber to mix with and heat propellants. Wall temperature control is provided by containing the plasma in a magnetic field. Jet power levels of 200 MW to 1 GW can be considered.

Another approach to fusion energy release use is the fusion microexplosions device (Code 4.5.2). Pellets of material are ejected from the rocket and imploded to fusion temperature and pressure by focused laser beams. The reaction products from the resulting fusion explosion act against a pusher plate, thus imparting thrust to the rocket.

e. Conversion to Electrical Energy. Parameters forecast for conversion to electrical energy are summarized in FC 4-17. Efficiencies are not given except for conversions in the same energy domain; e.g., electrical to electrical because, except for that case, efficiency is not a primary subsystem parameter. In effect, efficiency is included in α_c since the power referenced is output power.

(1) Conversion to Electrical Energy from Electrical Energy. This class of device converts electrical energy from one form to another; changing voltage level, wave form, regulation, frequency or other such characteristic. Forecasts have been made for static devices only.

(a) Power Conditioning for Science/Housekeeping (Code 5.1.1). Performance and costs are forecast for this device at two separate power levels. The device is shielded against EMI and equipment redundancy is included to enhance reliability. There is no allowance, however, for nuclear radiation shielding or thermal control devices. This forecast, however, includes an allowance for wiring and cabling common to a power distribution system.

(b) Power Conditioning for Electrical Propulsion (Code 5.1.2). The forecast shows three different scales of power level. Temperature regimes are limited to -15°C to +60°C. Shielding against EMI is included, but there is no allowance for redundancy, nuclear radiation shielding, or thermal control devices.

FC 4-17. Parameter Estimates for Energy Conversion to Electrical Energy (What Is Possible)

Device Code No. (Ref. Table 4-2)	Description	Technology Status	Year of First Availability	Year of Stated Parameter	System Performance Parameters		System Cost Parameters			
									First Costs	
					α_c (kg/We)	η_c	c_c ($/kg)	$c_c\alpha_c$ ($/We)	Pre-Project (10^6)	First Application (10^6)
5.1	From Electrical									
5.1.1	Power Conditioning Equipment (Science/ Housekeeping)									
	0.2 - 2 kWe Units	In Use	N/A	1975 2000	6.0×10^{-2}(a) 3.8×10^{-2}(a)	0.90(a) 0.90(a)	2.0×10^{4}(b) 1.2×10^{4}(b)	1.2×10^{3}(b) 4.6×10^{2}(b)	0.3(b)	3(b)
	10 kWe Units	In Development	1975	1975 2000	1.1×10^{-2}(a) 7.2×10^{-3}(a)	0.90(a) 0.90(a)	2.0×10^{4}(a) 1.2×10^{4}(b)	2.2×10^{2}(b) 8.6×10^{1}(b)	0.3(b)	3(b)
5.1.2	Power Conditioning Equipment (Electrical Propulsion)									
	3 kWe Units	In Development	1980	1980 2000	5.5×10^{-3}(a) 1.2×10^{-3}(a)	0.91(a) 0.95(a)	8.2×10^{3}(a) 3.0×10^{3}(b)	4.5×10^{1}(a) 3.6(b)	5(a)	1(a)
	20 kWe Units	In Development	1985	1985 2000	3.6×10^{-3}(a) 1.2×10^{-3}(a)	0.92(a) 0.95(a)	6.4×10^{3}(b) 3.0×10^{3}(b)	2.3×10^{1}(b) 3.6(b)	10(b)	3(b)
	1000 kWe Units	In Development	1985	1985 2000	1.8×10^{-3}(a) 6.0×10^{-4}(a)	0.92(a) 0.95(a)	6.4×10^{3}(b) 3.0×10^{3}(b)	1.2×10^{1}(b) 1.8(b)	50(c)	20(c)
5.2	From Magnetic									
5.2.1	Energy Tapping of Ambient Fields	In Development for Use in Earth Orbit	1982	1982 2000	1.3×10^{-2}(a) 1.2×10^{-2}(a)		2.5×10^{4}(c) 3.0×10^{4}(c)	3.0×10^{2}(c) 3.0×10^{2}	1(c)	5(c)
5.3	From Electromagnetic									
5.3.1	Photovoltaic Cells									
	<5 kWe Units (conventional)	In Use	N/A	1975 2000	3.3×10^{-2}(a) 2.1×10^{-2}(a)		1.5×10^{4}(a) 1.6×10^{4}(a)	5.0×10^{2}(a) 3.4×10^{2}(a)	---	---
	5-100 kWe Units (lightweight)	In Development	1975	1975 2000	1.5×10^{-2}(a) 7.6×10^{-3}(b)		5.2×10^{4}(a) 5.5×10^{3}(b)	7.8×10^{2}(a) 4.2×10^{2}(b)	3(a)	6(a)
	>100 kWe Units (low cost)	On the Technology Frontier	1985	1985 2000	5.0×10^{-3}(b) 3.2×10^{-3}(b)		1.0×10^{4}(b) 6.5×10^{3}	5.0×10^{1}(b) 2.1×10^{1}(b)	3(b)	6(b)
5.3.2	Thermionic									
	0.5 kWe Units	In Development	1975	1975 2000	7.3×10^{-2}(a) 3.2×10^{-2}(b)		1.2×10^{2}(b) 5.2×10^{1}(b)	8.8(b) 1.7(b)	10(b)	30(b)
	5 kWe Units	In Development	1975	1975 2000	6.2×10^{-2}(b) 2.8×10^{-2}(b)		1.2×10^{2}(b) 5.2×10^{1}(b)	7.4(b) 1.5(b)	20(b)	40(b)
5.3.3	Dynamic Cycles									
	Brayton Cycle (0.5-15 kWe Units)	In Development	1975	1975 2000	1.3×10^{-1}(a) 1.2×10^{-1}(a)		1.3×10^{4}(a) 7.9×10^{3}(b)	1.7×10^{3}(a) 9.5×10^{2}(b)	20(a)	100(a)
5.3.4	Dielectric Solar Converters	In Development	1980	1980 2000	4.0×10^{-3}(c) 4.0×10^{-4}(c)		5.0×10^{3}(c) 5.0×10^{3}(c)	2.0×10^{1}(c) 2.0 (c)	0.2(b)	2(c)
5.4	From Chemical									
5.4.1.1	Primary Fuel Cell (H_2-O_2)	In Use	N/A	1975 2000	6.8×10^{-2}(a) 4.1×10^{-2}(b)		1.0×10^{4}(a) 7.0×10^{3}(b)	6.8×10^{2}(a) 2.9×10^{2}(b)	29(a)	44(a)
5.4.1.2	Regenerative Fuel Cell (H_2-O_2)	In Development	1975	1975 2000	8.6×10^{-2}(a) 5.5×10^{-2}(b)		13(a) 7(b)	1.1(a) 3.9×10^{-1}(b)	80(a)	120(a)
5.4.2	Dynamic Cycles									
	50-h Unit	In Development	1975	1975 2000	1.9×10^{-2}(b) 1.3×10^{-2}(b)		1.9×10^{5}(b) 2.3×10^{4}(b)	3.6×10^{3}(b) 3.0×10^{3}(b)	2(b)	5(b)
	500-h Unit	In Development	1975	1975 2000	1.0×10^{-1}(b) 4.5×10^{-2}(b)		3.6×10^{5}(b) 6.7×10^{4}(b)	3.6×10^{3}(b) 3.0×10^{3}(b)	3(b)	7(b)
5.4.3	MGD System (H_2-O_2)									
	5 MWe Unit	On the Technology Frontier	1980	1980 2000	1.5×10^{-3}(b) 2.5×10^{-4}(b)		2.0×10^{5}(c) 1.0×10^{5}(c)	3.0×10^{2}(c) 2.5×10^{1}(c)	50(b)	100(b)

NOTES:

Uncertainty and/or variation due to range in secondary parameters:

(a) = ±20%

(b) = 1/2 to 2 times value shown

(c) = 1/10 to 10 times value shown (order of magnitude)

FC 4-17 (Contd)

Device Code No. (Ref. Table 4-2)	Description	Technology Status	Year of First Availability	Year of Stated Parameter	System Performance Parameters		System Cost Parameters			
									First Costs	
					α_c (kg/We)	η_c	c_c ($/kg)	$c_c \alpha_c$ ($/We)	Pre-Project (10^6)	First Application (10^6)
5.5	From Nuclear (Radioisotope)									
5.5.1	Thermoelectric									
	0.1-10 kWe Units	In Use	N/A	1975 2000	2.6×10^{-1}(a) 9.0×10^{-2}(b)		5.8×10^4(a) 8.9×10^4(b)	1.5×10^4(a) 8.0×10^3(b)	2.5(b)	25(b)
5.5.2	Thermionic									
	0.1-10 kWe Units	In Development	1985	1985 2000	1.7×10^{-2}(b) 1.4×10^{-2}(b)		1.9×10^5(b) 1.1×10^5(b)	3.3×10^3(b) 1.5×10^3(b)	20(b)	20(b)
5.5.3	Dynamic Cycles									
	Brayton Cycle 1.5-15 kWe Units	In Development	1975	1975 2000	1.6×10^{-1}(a) 1.3×10^{-1}(a)		1.1×10^5(a) 8.8×10^4(a)	1.8×10^4(a) 1.1×10^4(a)	55(a)	70(a)
5.6	From Nuclear (Fission)									
5.6.1	Thermoelectric									
	3 kWe Units	In Development	1985	1985 2000	2.6×10^{-1}(a) 9.3×10^{-2}(b)		5.4×10^2(a) 8.6×10^2(b)	1.4×10^2(a) 8.0×10^1(b)	30(b)	3(b)
	1000 kWe Units	In Development	1985	1985 2000	2.6×10^{-1}(a) 9.3×10^{-2}(b)		5.4×10^2(a) 8.6×10^2(b)	1.4×10^2(a) 8.0×10^1(b)	300 (b)	30(b)
5.6.2	Thermionic									
	40 kWe Units	On the Technology Frontier	1985	1985 2000	3.8×10^{-2}(a) 1.7×10^{-2}(a)		4.0×10^3(b) 8.8×10^2(b)	1.5×10^2(b) 1.5×10^2(b)	300(a)	100(b)
	400 kWe Units	On the Technology Frontier	1985	1985 2000	2.5×10^{-2}(a) 1.2×10^{-2}(a)		3.0×10^3(b) 6.3×10^2(b)	7.5×10^1(b) 7.5×10^1(b)	300(a)	100(b)
5.6.3	MHD System									
	Liquid Metal 300 kWe Unit	In Development	1990	1990 2000	5.4×10^{-2}(b) 2.7×10^{-2}(b)		1.5×10^3(c) 1.5×10^3(c)	8.0×10^1(c) 4.0×10^1(c)	500(b)	250(b)
5.6.4	MGD System									
	1 MWe Units	On the Technology Frontier	1995	1995 2000	5.0×10^{-3}(b) 5.0×10^{-3}(b)		1.0×10^4(b) 1.0×10^4(b)	5.0×10^1(b) 5.0×10^1(b)	500(b)	500(b)
	10 MWe Units	On the Technology Frontier	1995	1995 2000	3.6×10^{-3}(b) 3.6×10^{-3}(b)		2.1×10^3(b) 2.1×10^3(b)	7.5(c) 7.5(c)	500(b)	500(b)
	100 MWe Units	On the Technology Frontier	1995	1995 2000	3.4×10^{-3}(b) 3.4×10^{-3}(b)		3.0×10^2(c) 3.0×10^2(c)	1(c) 1(c)	500(b)	500(b)
5.6.5	Dynamic Cycles									
	Brayton Cycle 5-100 kWe Units	In Development	1975	1975 2000	5.8×10^{-2}(b) 5.8×10^{-2}(b)		1.8×10^4(c) 1.3×10^4(c)	1.0×10^3(c) 7.5×10^2(c)	300(b)	150(b)
5.6.6	Gas/Fluid Core									
	Reactor/Converter									
	Thermionics									
	400 kWe Unit	On the Technology Frontier	1980	1980 2000	1.0×10^{-1}(b) 1.6×10^{-2}(b)		4.8×10^3(b) 2.5×10^4(b)	4.8×10^2(b) 4.0×10^2(b)	12(b)	75(b)
	MGD System									
	10 MWe Unit	On the Technology Frontier	1982	1982 2000	2.6×10^{-2}(b) 5.0×10^{-3}(b)		2.0×10^2(c) 1.0×10^3(c)	5(c) 5(c)	12(b)	500(b)
5.7	From Nuclear (Fusion)									
5.7.1	Fusion Energy	On the Technology Frontier	2000+	2000	2.0×10^{-3}(b)		1.25×10^2(b)	2.5×10^{-1}(b)	2000(b)	4000(b)

NOTES:

Uncertainty and/or variation due to range in secondary parameters:

(a) = ±20%

(b) = 1/2 to 2 times value shown

(c) = 1/10 to 10 times value shown (order of magnitude)

(2) Conversion to Electrical Energy From Magnetic Energy. This class of device converts magnetic energy to electrical by relative motion of an electrical conductor through a magnetic field perpendicular to the conductor.

Energy Tapping of Ambient Fields (Code 5.2.1). This device consists of long insulated electrical conductors attached to the spacecraft, conductor support (via boom mounting, gravity gradient tensioning or propulsion system tensioning at separate ends of the conductor) and a means of collecting current from the conductor. The operating lifetime of this device is dependent on the orbital decay due to particle drag in low planetary orbit and on the loss of gravitational energy of the spacecraft needed to overcome electrical drag forces.

(3) Conversion to Electrical Energy from Electromagnetic (Photons). A number of different systems are available for converting the energy of photons to electrical energy. All parameters are forecast for the solar constant at 1 AU; allowance must be made for the inverse square dependence of intensity with Sun – spacecraft distance. Power level or range is given where it has an important effect upon the performance parameters. Note that thermoelectric devices are not among those forecast. The conversion efficiency of solar thermoelectric conversion is too low for useful application, compared to other conversion devices used in similar applications.

(a) Photovoltaic Cells (Code 5.3.1). For spacecraft application three categories of solar arrays are shown; their potential power level is the essential difference: (1) evolving conventional technology ($\leq$ 5 kWe), (2) evolving lightweight technology (5 to 100 kWe) and (3) low-cost array technology (>100 kWe). The arrays in the forecasts include cells, protective coating, substrate, and supportive structure, but do not include deployment or orientation mechanisms. It is anticipated that the ERDA low-cost solar array program will impact the space program and will reduce the cost of cells and arrays as shown in FC 4-17 under low-cost units greater than 100 kWe. Reductions in cost beyond this point may be brought about by large-scale production of both terrestrial and space arrays of megawatt size.

(b) Thermionic (Code 5.3.2). The thermionic device listed includes the solar concentrator, heat receiver, radiator, and structure as well as the converter itself. This prediction is predicated on the expectations of an 1800°K device. Two levels of power are forecast.

(c) Dynamic Cycles (Code 5.3.3). This forecast is based on the use of collected electromagnetic radiation as an energy source for a dynamic heat engine to drive electrical generators. Of the thermodynamic cycles available, the bias for space use is toward a Brayton cycle device. The system, as described in FC 4-17, includes a solar concentrator, heat receiver, Brayton rotating unit (including generator), recuperator, radiator, ducting, and support structure. Energy storage is not included. Present lifetime based on a single unit has been demonstrated to be 2 years. A lifetime of 5 to 10 years is predicted by 2000. Additionally, the solar collector must be oriented toward the Sun within an accuracy of 3 minutes of arc.

(d) Dielectric Solar Power Converter (Code 5.3.4). The dielectric solar power converter, along with such devices as photoconversion using resonant absorption, photon engines, and optical diodes, was among the more exotic conversion devices examined. None of the experimenters contacted felt it appropriate to forecast parameters for device concepts at this early stage except for the dielectric solar power converter. This latter device consists of a thin film of dielectric material with electrically conducting cover layers. The film is bonded to the surface of the spacecraft. The device operates by alternate heating and cooling of the dielectric which might be achieved by rotating the spacecraft.

(4) Conversion to Electrical Energy from Chemical. This category of converters includes such devices as fuel cells, dynamic cycle engines, and magnetogasdynamic systems.

(a) Primary Fuel Cell (Code 5.4.1.1). Cost and performance parameters for the primary fuel cell are based on a device consisting of the fuel cell module, radiators, structure, and cryogenic tankage capable of holding a one-year supply of reactants. Lifetimes of 5000 to 10,000 hours are predicted.

(b) Regenerative Fuel Cells (Code 5.4.1.2). Regenerative fuel cell forecasts are based on a device which contains a fuel cell module, electrolysis cell module, storage tanks, radiator, and structure. A power source, needed to regenerate the fuel-cell products in the electrolysis cell, is not included. Lifetimes of 5000 to 10,000 hours are predicted.

(c) Dynamic Cycles (Code 5.4.2). Forecasts are based upon a device containing the turbine, electrical generator, controls, and structure, as well as dry tankage capable of holding a 50 to 500-hour supply of reactants. These reactants may be: storable monopropellants, (hydrazine) or cryogenic bipropellants (LH_2/LO_2). Current lifetimes are 50 hours, increasing to 500 hours with future development effort.

(d) Magnetogasdynamic Cycle (Code 5.4.3). The equipment forecast includes combustor, superconducting magnet subsystem, and control elements. Reactants used are cryogenic (LH_2/LO_2).

(5) Conversion to Electrical Energy from Nuclear Isotope Sources. Devices considered viable candidates for space applications, which convert energy derived from nuclear isotopes to electrical energy, utilize the principles involved in thermoelectrics, thermionics, and dynamic cycles.

(a) Thermoelectric (Code 5.5.1). Radioisotope thermoelectric generators (RTG), as forecast herein, contain the isotopic heat source, the thermoelectric converters, minimal shielding, and radiators. Lifetime of generators

is dependent upon the half life of the fuel used, and the degradation of the thermoelectric converters. It should be noted that the RTG can be regarded as a conversion device or as a storage device. FC 4-17 shows it as a conversion device. As a storage device the performance parameters are discussed in the energy storage summary paragraph E-3. The parameters given in FC 4-17 for the year 2000 are based upon the assumption that Cm^{244} or low-cost Pu^{238} fuel is used. These fuels, especially the Cm^{244}, greatly increase the radiation which implies that increased shielding may be required, depending on mission constraints.

(b) Thermionic (Code 5.5.2). The device forecast consists of an isotopic heat source, the thermionic converter, limited shielding, and a radiator. Lifetime of the device is dependent on isotope fuel half-life and the degradation of the thermionic converter. The isotope used as a fuel is Pu^{238}.

(c) Dynamic Cycles (Code 5.5.3). The essential difference between this class of device and the device forecast in 5.3.3 is the source of heat energy. As pointed out in that summary, the Brayton cycle is the leading dynamic cycle contender for space use. (Rankine cycle systems offer performance and cost factors only slightly less attractive.) The system forecast herein includes the isotope heat source, the Brayton rotating unit, recuperator, radiator, ducting and support structure. Design lifetime is 5 to 10 years.

(6) Conversion to Electrical Energy from Nuclear Fission Sources. This category of device couples the energy conversion device to a reactor heat source. Devices examined include thermoelectric, thermionic, liquid metal MHD, magnetogasdynamic, and dynamic cycles. Limits on lifetimes of reactors are common to all devices in this class.

(a) Reactor Thermoelectric (Code 5.6.1). The device contains a reactor heat source, shielding (for manned mission applications), controls, heat exchangers, thermoelectric elements, radiators, pumps, piping, and structure.

(b) Reactor Thermionics (Code 5.6.2). The thermionic device contains a nuclear reactor heat source, shielding (rated for a nuclear-electric propulsion mission), thermionic converters, heat pipes, radiators, piping, pumps, and structure. Operating lifetimes of 20,000 to 30,000 full-power hours or 60,000 to 100,000 hours at reduced power levels are expected.

(c) Liquid Metal MHD (Code 5.6.3). A liquid-metal MHD device will consist of a nuclear reactor heat source, shielding (shadow shielding for an unmanned mission), a liquid metal MHD converter, radiator, piping, pumps, and structure. Operating lifetimes of 1 to 2 years are presently anticipated. These lifetimes, however, are primarily limited by reactor fuel burnup.

(d) Magnetogasdynamics (Code 5.6.4). The MGD cycle device contains a nuclear reactor heat source, shielding (rated for a manned mission application), MGD converter (including superconducting magnet system), heat exchangers, turbine compressor, radiator, ducting, and structure.

(e) Dynamic Cycle (Code 5.6.5). The dynamic cycle equipment is essentially the same (Brayton cycle), as in the dynamic cycles discussed above for the other energy sources. In this case, however, the energy source is a nuclear reactor and associated shielding. The shield is rated for an unmanned mission application.

(f) Gas/Fluid-Core Reactor/Converter (Code 5.6.6). The device contains a fluid-core reactor heat source, shielding (for nuclear electric propulsion mission applications) controls, radiators, heat exchangers, power conversion elements, pumps, piping, and support structure. Power conversion is via a thermionic or an MGD device.

(7) Conversion to Electrical Energy from Nuclear Fusion Sources (Code 5.7). Since controlled fusion energy release is still to be demonstrated, an examination of particular methods of converting fusion energy to electrical energy for space applications is premature. The forecast shown (Code 5.7.1) is for the performance and cost of the heat source (fusion reaction container, magnetic field system and surrounding blanket) only.

E. SUMMARY

The summaries drawn from the forecasts for the space power and propulsion fields are presented for each of the five categories used for the forecasts.

1. Transmission

Beamed-energy transmission has possible NASA applications for communication, power transmission, and propulsion. Both space-based and Earth-based transmission systems may be of interest. The communication application, however, is considered in Part Three, Section III; hence, only systems suitable for transmitting large power levels are considered in this forecast. Only laser and microwave beam systems were found to fall within that category. Because of the rather large divergence angles of electron beams, and their susceptibility to deflection by magnetic fields, this approach to energy transmission was judged not to be of interest when compared with microwave or laser beams.

With respect to availability of beam transmitters, the microwave beam technology is in the development stage, whereas the high-power laser beam is on the technology frontier. Availability of microwave beam technology is forecast for 1975 and 1990, respectively, for Earth-based and space-based systems. Availability of high-powered laser beam technology is forecast for 1985 and 1995, respectively, for Earth-based and space-based systems. Technology readiness demonstration in terms of efficiency and power density for laser beams is forecast to be available without major application of NASA resources. This forecast is based on the fact that ERDA and DOD are providing substantial support to laser development. Microwave transmission technology continues to require support.

The cost is dominated by the cost for the power generation system, both for development of prototypes and for testing and launching of flight hardware. (See paragraph E-5 that follows for discussion of space-based power supplies.)

For Earth-based beam transmission systems, specific mass is not as important a parameter as for space-based transmitters but the power generation systems still dominate cost of the transmission system.

Microwave beams can be collected by means of high-efficiency rectennas (specific mass in the range of 1 to 4 x 10^{-3} kg/We of beam power received) which convert received energy to electrical energy to provide on-board power or to drive electric thrusters (see paragraph E-4). Note that because of the relatively longer wavelength of microwaves, the beam divergence will limit their use to Earth-orbital distances.

Laser beams can be collected by photovoltaic cells (see paragraph E-5) and converted to electrical power which can be used to drive electric thrusters. Laser beam energy can also be used to heat propellant and thus provide propulsion (see paragraph E-4). This approach is not attractive for microwaves because absorption of microwave frequencies by the propellant is poor and means of focusing to high power densities are not available.

Use of laser beams for propulsion systems for launch from Earth against the Earth's gravitation appears improbable. If hydrogen were to be the heated propellant, neither the quantity of energy-expensive hydrogen nor the volume of the launch vehicle would be significantly less for systems using externally supplied laser energy than for systems using internally supplied energy in the form of hydrogen/oxygen chemical reaction. Thus, there will be little advantage, if any, to offset the large capital investment in the needed laser beam generaor, e.g., 40 to 60 GWe input power for Shuttle-size payloads.

Laser-beam energy used to heat hydrogen propellant may be of interest for space propulsion, where thrust-to-mass ratio can be effective at levels much less than the acceleration of gravity at the Earth's surface (see paragraph E-4).

2. Collection

Collection and concentration of solar photons for thermal conversion may play a role in space power. A major advantage of this approach over photovoltaic conversion is resistance of the collection system to degradation from high-energy particles; e.g., radiation belts.

Use of extraterrestrial materials, atmospheres, or surface materials for energy storage and release will be developed as Lunar and planetary operations become more extensive. The major pacing factor in use of surface materials for chemical energy components will be development of solar or nuclear energy sources, in situ, to support the gathering and processing of chemicals. In general, the energy available from the chemical reactants produced in this manner will be considerably less than the energy used to produce them. For example, electrolysis of water ice to make chemical reactants for power or propulsion requires an input energy approximately 2.5 times the energy that can be recovered by later reaction of the chemicals. Nevertheless, the availability of simply stored chemical energy and of rocket propellants for large-scale operations in the vicinity of an extraterrestrial ground station may be of crucial importance. The investment in producing and transporting the power station to the site need not be charged to chemical energy collection since the station will have many other uses as well.

Production and storage of antimatter for energy will probably not be feasible by the year 2000. Significant advances in manufacture and storage techniques may have occurred by 2000 such that antimatter storage as a means of storing energy for space propulsion and power can be considered for possible application some decades after 2000.

3. Storage

A first-order comparison of the mass required to store a unit of deliverable energy is presented in Table 4-9. Also shown is the cost per unit-mass of the various classes of devices. For purposes of comparison, the devices listed are

Table 4-4. Energy storage: summary comparison of possible technology advances

Device	Power Levels (kWe)	α_s (kg/J)		c_s ($/kg)		$\alpha_s c_s$ ($/J)
		1975 - 1985	2000	1975 - 1985	2000	2000
Flywheels	0.1 - 100	1.5×10^{-6}	8.0×10^{-7}	7.0×10^{1}	8.0	6.4×10^{-6}
Superconductors	0.1 - 1000	6.0×10^{-5}	4.0×10^{-6}	2.8×10^{2}	1.3×10^{2}	5.2×10^{-4}
Batteries						
Primary	0.1 - 100	5.0×10^{-6}	4.0×10^{-7}	1.0×10^{2}	5.0×10^{2}	2.0×10^{-4}
Secondary	0.1 - 100	8.0×10^{-6}	1.2×10^{-6}	3.5×10^{3}	6.4×10^{3}	7.7×10^{-3}
Chemicals						
Stable	1.0 - 10,000	1.0×10^{-7}	1.0×10^{-7}	6.0	6.0	6.0×10^{-7}
Metastable	1.0 - 10,000		8.0×10^{-8}		10 to 10^{3}	10^{-6} to 10^{-4}
Radioisotope						
Thermoelectric	0.1 - 10	1.7×10^{-9}	2.9×10^{-10}	5.8×10^{4}	8.9×10^{4}	2.6×10^{-5}
Thermionic	0.1 - 10	1.1×10^{-10}	5.4×10^{-11}	1.9×10^{5}	1.1×10^{5}	5.9×10^{-6}
Dynamic cycles	0.5 - 15	1.0×10^{-9}	4.1×10^{-10}	1.1×10^{5}	8.8×10^{4}	3.6×10^{-5}
Fission Reactor						
Thermoelectric	1.0 - 1000	3.6×10^{-9}	5.9×10^{-10}	5.4×10^{2}	8.6×10^{2}	5.1×10^{-7}
Thermionic	1.0 - 1000	5.3×10^{-10}	7.6×10^{-11}	3.0×10^{3}	6.3×10^{3}	4.8×10^{-7}
MHD system*	100 - 100,000	~	1.7×10^{-10}	~	1.5×10^{3}	2.6×10^{-7}
MGD system*	1000 - 100,000	~	2.2×10^{-11}	~	2.9×10^{2}	6.4×10^{-9}
Dynamic cycles	5.0 - 100	7.7×10^{-10}	3.7×10^{-10}	1.8×10^{4}	1.3×10^{4}	4.8×10^{-6}

*First available after 1985.

Notes:
1. Uncertainties for all parameters should be assumed to range over a factor of two (x or ÷) from the value shown, except as otherwise noted.
2. Isotope devices are assumed to have 5-year life in 1975-1985 and 10-year life by 2000.
3. Reactor devices are assumed to have 20,000-hour (2.3-year) life in 1985 and 5-year life by 2000.

assumed to deliver energy as electrical energy. Thus, the values for devices originally forecast for mechanical energy output (stable and metastable chemicals) have been reduced by 50% to account for mechanical to electrical energy conversion. A number of broad observations can be drawn from Table 4-4 in regard to storage of energy in space.

The specific mass factors (α_s) for primary batteries, stable chemicals, and flywheels appear to be competitive. It does not appear that superconductors have the potential of supplanting the battery or of eventually competing with flywheels. Present-day batteries are just about as effective as storage elements as the most favorable forecast for superconductors. In this group, stable chemicals show potential for lowest cost-per-unit-energy-stored ($\alpha_s \times c_s$).

Forecasts for metastable chemical storage devices indicate that their energy storage capabilities are not better than the capabilities of stable chemical storage devices. The metastable chemical device forecast atomic hydrogen mixed with molecular hydrogen was based on the assumption (unproven as yet) that metastable chemicals will require magnetic field containment to retain the metastable state of the reactant. It is possible that the mass of cryogenic superconductor magnetic field equipment included in the mass estimate can be reduced for a given atomic hydrogen concentration. In this case metastable chemicals could show energy storage advantages.

The nuclear devices, when shown as storage elements, project to much better mass performance than other forms of energy storage (by three or more orders of magnitude), and thus appear to be the prime means for increasing energy storage capacity in the future. Radioisotope systems compare closely with the fission reactor systems on an energy-per-unit-mass basis. However, cost per unit of energy stored projects is to be about one order of magnitude greater for the isotope storage. Fission reactor

systems promise the lowest cost per unit of deliverable-energy, matching that of the stable chemical systems.

Another consideration, which is not easily represented by simple specific mass parameters, is the capability of secondary batteries, flywheels, and superconductors to operate reversibly, that is to charge or discharge. This capability, when used in conjunction with other energy acquisition or converting devices, may prove extremely valuable for complete space energy systems.

4. Conversion to Mechanical Energy for Propulsion

There is no one parameter or set of parameters that can characterize the performance of all propulsion devices. For this reason, the appropriate forecast parameters for each device have been displayed in tabular form. These parameters, together with mission destination and duration as developed separately in the Outlook for Space Study, can be used to make direct predictions of performance and cost of the propulsion device considered. Short of carrying out this process, several general implications can be drawn directly from the parameter forecasts and from the prior studies referenced in the forecasts, as follows:

(1) Chemical propulsion will continue to be used extensively through the year 2000. With devices of this type, energy is stored on board the spacecraft in the form of separate, stable, chemical reactants or in a metastable monopropellant having very long storage life. The stored energy is released in chemical reactions and the reactants serve as the propellant. The relative ease with which energy can be stored and converted to kinetic energy leads to systems which are characterized by relatively very low inert-to-propellant mass ratio, very low cost per unit hardware mass and low cost per unit propellant mass. Also, because most of the nonrecurring development costs have already occurred, little additional resources are required to develop new devices for new applications. Thus, chemical propulsion systems are likely to remain the cost-effective choice for any mission of modest velocity increment.

(2) Theoretically, by increasing the number of stages, chemical propulsion could be used to achieve any desired velocity increment. However, the mass of required hardware and propellant increases exponentially with velocity increments unless energy storage density can be increased. Existing and projected chemical propulsion systems are already functioning at near the fundamental limit of energy that can be stored in the bonds of stable chemicals. Thus, for very energetic missions, the cost of using chemical propulsion will become prohibitive even though the cost per unit mass is low. Clearly, if we are to accomplish missions with velocity increments of greater than, say, 3 or 4 times the maximum effective exhaust velocity (specific impulse) of stable chemicals (approximately 5000 m/s) and if we are to do so at a reasonable cost, some way must be found either to collect energy from sources external to the spacecraft or to store energy at much higher densities.

(3) The concepts for using electrical energy to accelerate propellants to very high exhaust velocities offer means for using collected energy, viz, solar photons or transmitted laser photons with photovoltaic conversion to electrical energy. The large mass-per-unit-power of such conversion systems leads to optimum designs at very low thrust-to-system-mass ratio and to restrained exhaust velocities (in the vicinity of 30,000 m/s). Solar electric and laser electric systems should show cost advantages over chemical systems for energetic interplanetary missions, such as comet rendezvous, and for energetic Earth-orbital operations, such as orbit raising from low altitude to synchronous altitude and return. This will be true even though the hardware cost per unit-mass is expected to remain much higher than chemical propulsion hardware. The technologies for solar photon electric systems are essentially ready for development and could be carried into use in the near term with a modest additional investment.

(4) The solar sail concept is another means for using collected energy for propulsion. At one AU from the Sun, the energy collected per unit area is so small that even with extremely lightweight structures the thrust-to-mass ratio (acceleration) will be very small. Nonetheless, absence of propellant mass and the intermediate cost per unit-mass of hardware promises cost advantages for solar sails in performing highly energetic missions such as out-of-the-ecliptic probes in the regions not much greater than about 1 AU from the Sun. This technology could be brought into use in the early 1980s.

(5) The concept of storing large concentrations of metallic or atomic hydrogen in a matrix of solid molecular hydrogen offers one way to greatly increase chemical (electronic) energy storage density, albeit in a metastable state. Typical of the concepts for storing high-energy metastables, this concept requires use of a refrigeration system for maintaining the substance at less than 1°K (below the background temperatures of space) and a large magnetic field maintained by superconducting magnets. While the effective exhaust velocity can be large (of the order of 10,000 m/s), this advantage may be partly offset by large specific mass and cost for propellant containment.

(6) The strongest prospects for storage capability significantly greater than that possible with stable chemicals is to store energy in the nuclear states of matter. An approach to storing and releasing nuclear energy for propulsion, which is one of the closest to realization, is the fission nuclear electric rocket. Here, heat energy released in a solid-core fission

reactor is converted to electricity by any of a number of means: thermoelectric diodes, thermionic diodes, magnetohydrodynamic cycles, or liquid metal Rankine or gas Brayton cycles with rotating machinery. The electric energy is then processed into voltages and currents needed for driving electric thrusters (electrostatic or electromagnetic). Here, as with the solar-electric concept, the relatively large specific mass for energy conversion leads to optimum designs with very low thrust-to-mass ratio and restrained exhaust velocity (approximately 40,000 m/s). This circumstance also implies a need for very long functional lifetimes, periods of up to five years of continuous unattended operation in space. Thrusters and power processors are nearly ready for application with reasonably small additional investment required. Considerable advanced development has also gone into design of lightweight, spaceborne reactors and electric generators such that an additional investment of one-half to one billion dollars could bring a nuclear electric propulsion and power device into being by 1990. It is likely that only one such design, perhaps in the scale of multi-hundred kWe, would be developed prior to the year 2000. Such a development of nuclear electric propulsion could enable extensive unmanned exploration of the outer reaches of the solar systems and could at the same time provide long-life power systems, either singly or in multiple units, for power at say a Lunar base.

(7) Another class of fission nuclear devices for space propulsion covers various means for directly heating a low-molecular-weight propellant (hydrogen) and expanding the hot gas to high velocity through an expansion nozzle, as is done with the chemical rockets. This class of nuclear device can be characterized by the same performance parameters as the chemical rocket: effective exhaust velocity, specific mass for energy conversion (reactor/thruster) and specific mass for propellant storage. The latter factor is somewhat poorer for the nuclear rocket, since the entire propellant load is very-low-density liquid hydrogen. Also, the reactor/thruster is very much heavier. However, propellant kinetic energy and hence exhaust velocity can be very much greater; limited only by the temperature to which the hydrogen can be heated without destroying the reactor and nozzle. Of the devices considered for direct-heating nuclear rockets, the solid-core reactor/thruster is closest at hand; large technology investments have already been made and actual hardware has been tested. Another 400 million dollars is forecast as being required to bring a small (80,000 N thrust) device of this type through first application. Effective exhaust velocity, nearly twice that achievable with chemical rockets, can be demonstrated. Use of solid-core nuclear stages, in place of chemical stages, could reduce the required total mass in Earth orbit by as much as a factor of three or four for certain high-energy planetary missions. Even then, however, the higher specific cost of the nuclear rocket hardware may obviate any net cost advantage over chemical systems if predicted low Earth-to-orbit costs are realized.

(8) Three more advanced versions of the direct heating fission rocket are forecast for possible first use by the year 2000. These have been considered as methods for raising the hydrogen temperature, and hence exhaust velocity, to levels much higher than that possible with the solid core. In the dust bed concept, solid or liquid fissioning particles are suspended in a vortex with hydrogen propellant flowing through the swarm of particles. The gas-core concept is similar in description, but would be operated at a higher temperature with the fissioning material being fluid dynamically stabilized in the gas phase. The third concept, the "nuclear light bulb," has the fissioning material contained in a swirling neon gas vortex which is surrounded by a cooled, transparent chamber. Thermal radiation passes through the wall and is absorbed by hydrogen propellant flowing on the outside. Hydrogen temperatures in the gas phase schemes are as high as 10,000°K, yielding effective exhaust velocities upwards to 45,000 m/s. The nature of the gas-core and light bulb concepts requires that they operate at very high power (>10 GWe or equivalently at thrust on the order of 5×10^5 N).

(9) The investment required to bring any of the advanced fission devices through first application is predicted to be the order of one billion dollars. If such developments were realized they would enable delivery of very large payloads to and from the outer planets with trip times held to several years. Manned missions to the near planets might then be considered with trip times less than a year.

(10) A number of concepts which could open whole new prospects for space operations are forecast to be on the technological horizon by the year 2000. One concept is to use energy released from the fusion reaction of stored deuterium and helium-3 to heat hydrogen propellant. The reacting plasma, operating at 50 to 500×10^6°K, is contained in a magnetic field maintained by superconducting magnets. Fusion energy release appears primarily as the kinetic energy of protons and helium-4 ions. These particles are then diluted with hydrogen to form the propellant plasma, which is allowed to escape at very high exhaust velocities (upwards to 1% of the speed of light).

(11) Another concept for use of fusion-derived energy is to initiate a series of micro-explosions with concentrated laser beams. One method of forcing the very high-speed product of the explosions to escape preferentially in one direction is to absorb and

reflect particles with a pusher plate attached to the rocket.

(12) Perhaps the ultimate in energy storage and conversion for propulsive effect is envisioned by the storage of antimatter and its subsequent annihilation with matter to yield direct beams of photons as the propellant.

(13) Fusion, antimatter or other advanced propulsion concepts may be under active development by the year 2000. It will be through these concepts, which might yield effective exhaust velocities at significant fractions of the speed of light, that we can begin to consider direct exploration beyond the solar system.

A perspective on the above implications, drawn from the forecasts for energy conversion to mechanical energy for propulsion, is provided by Figs. 4-8, 4-9, and 4-10 (taken directly from Ref. 4-5).

It must be emphasized that these are forecasts of "What is possible," provided by way of enabling propulsion technology. If a trend extrapolation were used in 1975 to predict "What will be," only a small increase in capability would be predicted for the year 2000 beyond the further development of chemical propulsion and solar electric propulsion. Propulsive capability with chemicals will soon reach the asymptote imposed by the energy storage capability of stable chemicals. In recent years, work on systems using nuclear energy storage has been reduced to a level which is inconsistent with the use of reactors in space by the year 2000. Even the first step beyond chemical propulsion, solar electric propulsion, has been delayed by resource limitations to an extent that it may not see first application as primary propulsion until after 1980.

The availability of propulsion capability beyond that provided by stable chemicals and solar electric devices appears to depend on the advent of high-energy missions so compelling that the commitments of large resources can be sustained over extended periods, solely for the purpose of enabling such missions. While developments for applications outside of the space program (e.g., laser-induced nuclear fusion) will contribute to the picture, the needs for low specific mass are so unique to space operations that most of the resources (billions of dollars) must be invested in the name of a space payoff. Further, the technologies involved are so diverse and complex that much of the investment must be sustained over lead times of 10 to 20 years before any direct payoff will be evident.

The lack of precedent for the investment of such large resources, with such long lead times for purposes of exploring for unknown benefits, forces a rather conservative prediction of what will be available by way of space propulsion capability in the years up to 2000: (1) chemical propulsion will be used in wide variety of sizes and types, ranging from monopropellants for low-velocity applications to fluorine and hydrogen propellants for the most energetic missions that can be accomplished with chemicals; (2) solar electric propulsion in perhaps two or three size classes will find first use early in the period; (3) solar sails will be used for certain low-cost scientific missions in the vicinity of 1 AU from the Sun, and (4) a space nuclear fission power source will be developed in the 100 to 500 kWe-size range. Used with electric thrusters this latter device will be used to begin unmanned exploration of the outer reaches of the solar system.

5. Conversion to Electrical Energy

Summary conclusions for this set of forecasts will be drawn for each of the conversion categories examined, as well as for the total set.

(1) Conversion of Electrical Energy to Electrical. The development of power conditioning equipment has reached the point where order of magnitude changes in performance parameters are not foreseen. In fact, it is only with great optimism that factors of two or three reduction in specific mass are seen to be possible. The figures shown in FC 4-17 for the electrical propulsion conditioning equipment represent equipment module performance only; whereas the figures on spacecraft science/housekeeping equipment represent power subsystem interconnection and distribution functions as well as equipment redundancies. There is an implication also that larger systems will have a smaller specific mass.

(2) Conversion of Magnetic Energy to Electrical. Spacecraft in low planetary-orbit (with such orbits having a low inclination relative to any magnetic field equator) may be able to extract useful quantities of energy from the planetary magnetic and electric fields. The major limitation appears to be the ability to sustain the spacecraft in orbit for reasonable times without excess quantities of propellant needed to overcome particle and field drag effects on the extraction device.

(3) Conversion of Photon Energy to Electrical. In those mission circumstances where the conversion of solar to electrical energy is a viable option, the basic choice is between devices which use concentrated solar energy and those devices which function in the ambient intensity. The forecasts show that, for spacecraft use, photovoltaic devices will remain the viable and effective conversion device from the point of view of specific mass. Solar thermionic converters (used with concentrators) have the potential of competing at power levels less than 100 kWe, but the pointing accuracy required adds an additional complication. Dielectric solar converters have the potential of order of magnitude reductions in specific mass. This latter device, however, requires extensive research effort to achieve the efficiency levels forecast. Additionally, applications of the dielectric device are limited to situations where insolation can be repeatedly turned on and off, such as a rotating spacecraft.

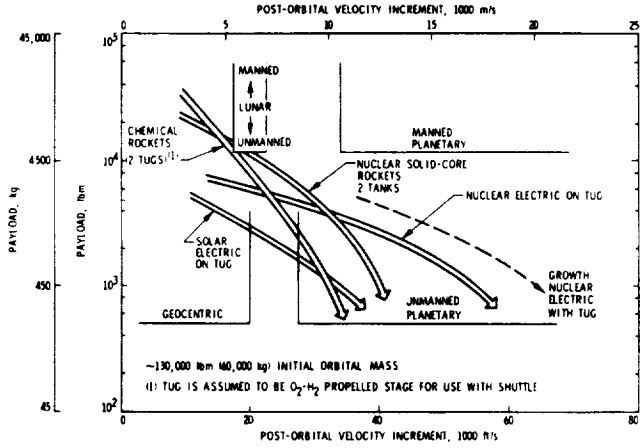


Figure 4-8. Mission performance projections (2-Shuttle launches)

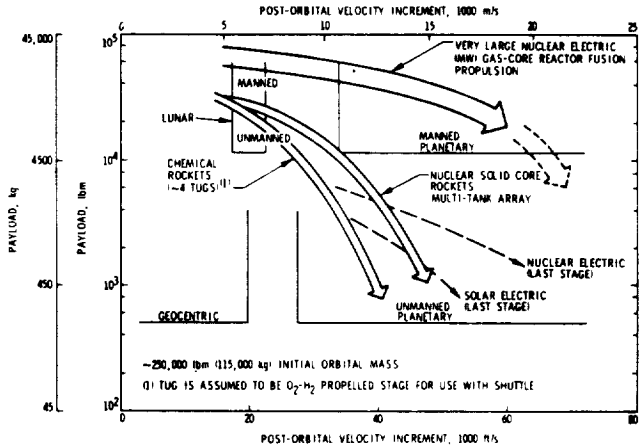


Figure 4-9. Mission performance projections (4-Shuttle launches)

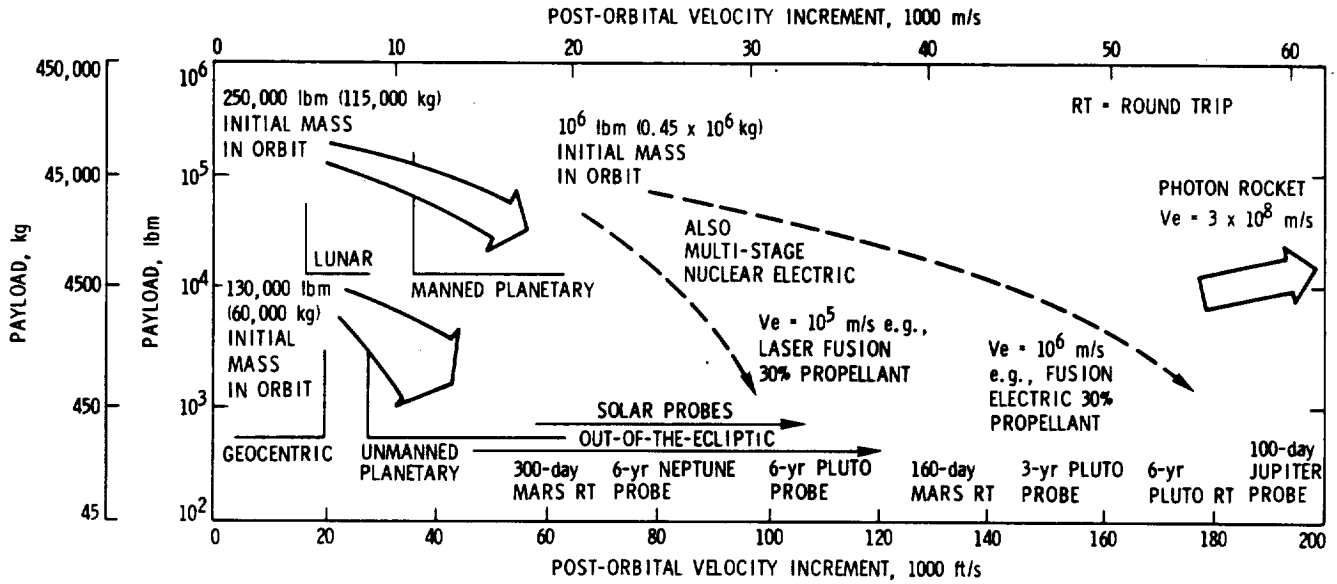


Figure 4-10. Projection of future propulsion system capabilities

(4) The photovoltaics cell technology program for space applications will profit from the NSF/ERDA terrestrial program which has as its objective the reduction of terrestrial cell costs by three orders of magnitude. Space arrays, wherein low mass is an important consideration, will continue to be more costly than terrestrial arrays.

(5) Conversion of Chemical Energy to Electrical. Fuel cells and dynamic cycles are projected to achieve rather minor improvements by 2000. Magnetogasdynamics could possibly provide a specific mass two orders of magnitude better than the fuel cells or the dynamic cycles; however, the likelihood of this achievement is remote unless technology investments of the order of $100 million to $200 million can be made available. Development of terrestrial applications may provide some of the needed funding and technology.

(6) Conversion of Nuclear Isotope Energy to Electrical. Conversion elements coupled with isotope heat sources are inherently heavier than the conversion elements discussed above. There appears to be little to choose from between thermoelectrics and Brayton in terms of specific mass. The simplicity of the RTG would seem to give that device an edge. Future developments in radioisotope thermionic converters (RTIG) may decrease the specific mass by an order of magnitude below that of the other devices.

(7) Conversion of Nuclear Fission Energy to Electrical. The magnetogasdynamic cycle appears to offer the greatest promise for low specific mass in this category of energy converters. In general, fission nuclear power will require large development costs (of the order of one billion dollars).

(8) General Summary. For each of the categories of conversion devices discussed above, those devices with the more favorable specific mass are compared in Table 4-5.

Table 4-5. Conversion to electrical energy summary

Conversion Device	α_c = kg/We	
	1975 - 1985	2000
Ambient field tapping	1.3×10^{-2}	1.2×10^{-2}
Solar photovoltaic	3.3×10^{-2}	7.6×10^{-3}
Solar thermionic	7.3×10^{-2}	2.8×10^{-2}
Solar dielectric	4.0×10^{-3}	4.0×10^{-4}
MGD system (chemical) (5 MWe) (excludes reactants)	1.5×10^{-3}	2.5×10^{-4}
RTIG (thermionics) (includes isotope)	1.7×10^{-2}	1.4×10^{-2}
MGD system (fission) (100 MWe) (includes reactor)		3.4×10^{-3}

F. PARTICIPANTS

The Coordinators express their appreciation to those who so willingly and enthusiastically shared their experience by contributing to this study. Their inputs are maintained in a microfilmed version (see G below). The Contributors are members of the Energy Management Coordinating Committee who assisted in the formulation and writing of this report. Appreciation is also extended to those others who are not listed below whose many conversations helped focus the activity to the important areas treated in this report.

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A FORECAST OF SPACE TECHNOLOGY

Part Five. MANAGEMENT OF MATTER

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under the direction of
Outlook For Space Working Group V

PART FIVE GLOSSARY

ATS	Applications Technology Satellite
AU	Astronomical Unit
CCD	Charge coupled device
CMGS	Control moment gyros
CMOS	Complementary - MOS (transistors)
ΔVLBI	Differential very long baseline interferometry
DOD	Department of Defense
DSN	Deep Space Network
EFL	Emitter follower logic
EGRS	Extragalactic radio source
EOS	Earth Observation Satellite
ERTS	Earth Resources Technology Satellite
EVA	Extra-vehicular activity
FEP	Fluorinated ethylene propylene
FET	Field effect transistor
I^2L	Integrated injection logic
IC	Integrated circuit
IPPQ	Iso polyphenyl quinoxaline
IUE	International Ultraviolet Explorer
JO	Jupiter Orbiter
JO/SL	Jupiter Orbiter Satellite Lander
LRV	Lunar Roving Vehicle
LSI	Large-scale integrated circuit
LST	Large Space Telescope
MJS	Mariner Jupiter Saturn
MJU	Mariner Jupiter Uranus (proposed)
MM'71	Mariner Mars 1971 mission
MNOS	Metal-nitride-oxide-silicon (transistors)
MOR	Modulus of rupture
MOS	Metal oxide silicon (technology)
MVM'73	Mariner Venus Mercury 1973 Mission
NDT	Nondestructive testing
NMOS	N - channel MOS (transistors)
MTBF	Mean Time Between Failure
OAO	Orbiting Astronomical Observatory
OD	Orbit determination
OGO	Orbiting Geophysical Observatory
OSO	Orbiting Solar Observatory
PMOS	P - channel MOS (transistors)
PPQ	Polyphenyl quinoxaline
QVLBI	Quasi very long baseline interferometry
RAM	Random access memory
RF	Radio frequency
SMM	Solar Maximum Mission
SO	Saturn Orbiter
SO/SL	Saturn Orbiter Satellite Lander
SOS	Silicon on sapphire (technology)
SSIC	Small-scale integrated circuit
T^2L	Transistor-transistor logic
TDRS	Tracking and Data Relay Satellite

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Section I. INTRODUCTION

A. R. Hibbs

A. SCOPE

The technology of the Management of Matter is taken to include the formation of new materials and their assembly into structural forms as well as advances in theory which lead to improvements in either of these activities. Thus, for example, it would include the possibility of new types of composites, ceramics, alloys, etc., as well as new types of semiconductors, advances in microminiaturization, structural design and test procedures, techniques of insulation or of heating and cooling. It also includes the treatment of techniques for the management of animate matter, both plant and animal; thus, life support systems, biological processing, and closed ecological systems involving photosynthetic organisms.

On the other hand, it does not include the technology of "end use." That is, it does not involve the assembly of new semiconductors into computers or information storage systems, nor the technology of instrument assembly, instrument design or the technology of propulsion system development. For example, in the Management of Matter category, one would consider the future availability of new materials and processes from which propellant tanks could be made, but would not consider the technology of propulsion systems.

As in all of the other categories, there are a vast number of separate technologies which could be investigated. Therefore it has been necessary to concentrate on those specific technical problems which would appear to present some sort of limit on future capabilities in space missions. This judgment — that is, sorting out the critical items — must be made primarily on the basis of intuition.

B. ORGANIZATION AND APPROACH

Figure 5-1 shows the way in which this category has been further subdivided into separate areas for more detailed study. Note that the functions of "acquiring," and "processing," were lumped together. However, within these functions there has been a further subdivision into subcategories of matter: first, animate vs inanimate; and, second, within the inanimate branch, microstructures and macrostructures.

It was not felt that this subcategory breakdown was necessary for the function of transferring matter, but the breakdown between animate and inanimate was maintained in considering the function of "storing."

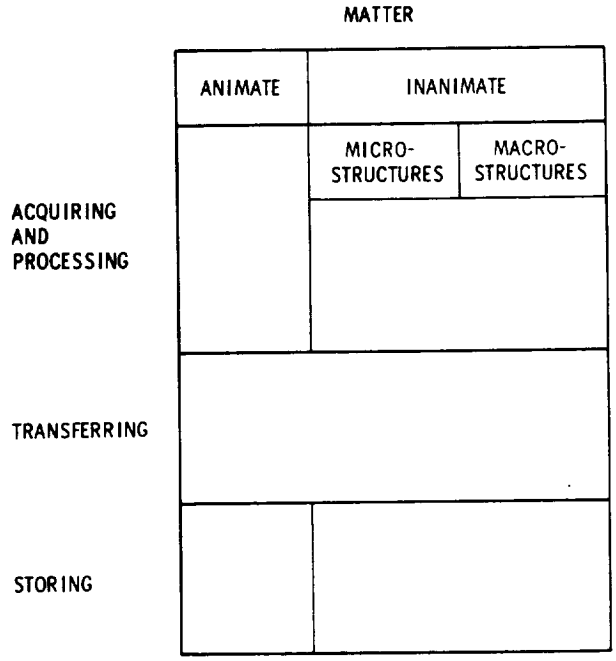


Figure 5-1. Management of matter

Technology related to life support systems was divided between two groups working in the separate areas in a rather arbitrary manner. Under the functions of acquiring and processing of animate matter, questions of the technology of space medicine were considered, as well as the technology of providing a closed ecological system by means of introducing various plants or other organisms into a biological cycle, including man. Other problems of maintaining a life support system such as shielding and insulation were considered under the function of storing of animate matter. This latter area also included the assessment of various mechanical devices which might be introduced into such a system to provide recycling of waste products. This rather arbitrary separation was based primarily on convenience, and in recognition of the background and experience of the various contributors and consultants in the separate areas. Thus, in brief, purely biological processes (including space medicine) are considered in the area of acquiring and processing of animate matter. Processes which are not purely biological (mechanical, electrical, chemical-physical, etc.) which bear on the maintenance of a crew (or any other biological object) in space are considered in the area of storing of animate matter.

C. TRENDS AND TECHNOLOGICAL OBSTACLES

In the subareas of microstructures and macrostructures, the outlook for technology as it applies to potential space use is quite encouraging. Even without major NASA support, continued commercial advances will bring to the engineer an increasingly powerful array of new materials and electronic components. For example, semi-conductor devices will provide about 10^7 gates on a single chip, and optical memories will provide much more than 10^{11} and up to 10^{15} bits of storage, with a storage density of 10^{14} bits per cubic meter. Furthermore the costs of semiconductors, measured in dollars per bit, will decrease by 2 to 3 orders of magnitude, and the power requirements for such things as charge coupled devices (CCD) may decrease by 3 to 4 orders of magnitude. For superconductive components, the decrease in cost will be about 5 orders of magnitude.

In the area of macrostructures, a broad spectrum of improvements in metal materials, new composites and new polymers is foreseen, all leading to increases in cost effectiveness for space structures. For example, new composite structures for launch vehicles, reentry vehicles, and spacecraft will result in a 50% saving in structural weight and a two order-of-magnitude decrease in thermal distortion of large structures such as antennas. In addition, major breakthroughs in fabricating and assembling large erectable space structures will occur. Also possible are polymer fibers with moduli approaching 90 million psi and refractory alloys with a 1200°C use temperature.

In the area of space-processing of materials, it would seem that a number of potential opportunities exist. It would also seem that none of these is limited by problems of space technology itself. The problem then is how to take advantage of these opportunities, such as an order-of-magnitude improvement in homogeneity of semiconductor materials and processing purity of materials with unique mechanical and electrical properties. For such developments, the technological support will be available.

The investigation of the technology of Transferring of Matter has been directed primarily at the accuracy with which a spacecraft or a surface explorer can be positioned at its planned location. These investigations indicate that the normal course of technical developments will enable us by the year 2000 to deliver payloads to any point in the Solar system with as much accuracy as would appear to be required, land payloads, manned or otherwise, on the surface of Mars or the Moon, traverse such surfaces with mechanical vehicles with high precision, and, in free-fall, stabilize and point large antennas or other spacecraft structures.

Investigation of the technology of Storing of Matter indicated that the technology necessary for storing of equipment in a space environment or providing it with a suitable environment for its activities (e.g., temperature control of instrumentation) will not involve any serious technical limitations. One way to state this is that, for every problem considered, there seems to be at least one, and in most cases, several "work around" techniques to solve the problem with today's technology or with the technology which can be confidently predicted to be available in the time period in question.

Nevertheless, in this area, as well as in the area of Acquiring and Processing of Animate Matter, one critical technical area appeared. This had to do with the maintenance of life-support systems. Between now and the year 2000, the life-support problem will remain critical. This conclusion bears principally on manned flights of extended duration where the question of expendables becomes important. There are a number of conceptual techniques for regenerating human waste products — gases, liquids, and solids — and producing from them oxygen, water, and food. However, there are serious problems involved with any one (or any combination) of the techniques so far suggested. No electromechanical (or physical-chemical) system so far suggested or envisaged could guarantee 100% regeneration. However, by the turn of the century, such techniques might decrease resupply requirements to 10% of those required if no regeneration were involved.

Although it is conceivable that an extensive and complex biological ecosystem could provide 100% regeneration, just as it does in the Earth's biosphere there is not enough experimental evidence to demonstrate that a limited closed system, including men, would actually operate for an extended period of time in a stable manner. Most of the closed-biological systems which have been tested involve algae or perhaps algae and one or two strains of bacteria. Some of these have been maintained for hundreds of days, and in a few cases, mice have been a part of the system. It has been demonstrated, however, that algae is not a suitable human food. Tests of more complex closed systems involving leafy plants which would offer a suitable human diet have simply not been done. Added to this problem of recycling are the many problems of space medicine. In free-fall, there is a problem of calcium loss from bones for which there is at present no solution and no guarantee that it will be solved within the period encompassed by this forecast. Even considering a lunar colony, or a rotating spacecraft with artificial gravity, there are still questions of psychology and other factors which are presently unresolved.

It would seem possible that if suitable experimentation were addressed to such problems as these, in 10 to 15 years one would be able to design an almost-closed system which could maintain a suitably selected crew for an extended period of time (several years). Using a conservative approach, this implies 10 to 15 years to do the research to begin the design, and then another 10 years before the resultant system could actually be placed into a space mission; and this takes us to the year 2000. It might be more desirable to attempt earlier missions based on early research results, refining the operational system as new information came to light. But even with this less-conservative approach, the time scale to a reliable system is long.

The significant conclusion is this: if there is any reason to contemplate an extended manned mission before the close of this century, then the time to begin research on regenerative systems and space medicine is now.

Section II. ACQUIRING AND PROCESSING ANIMATE MATTER

A. R. Hibbs

A. SCOPE

The animate matter discussed in this section includes both human and nonhuman species, as well as various biological products; both those produced deliberately (e.g., space processing) and those produced accidentally (e.g., noxious products of humans or plants in closed ecological systems). Problems of space medicine technology are also considered in this area, although it would have been equally reasonable to include space medicine under the area of Storing of Matter. The decision to consider it here was made primarily for convenience, based upon the interests and backgrounds of various contributors and consultants working in this area. (See Section VI of this part, "Storing of Matter," for related subjects such as space suit design.)

B. ORGANIZATION AND APPROACH

1. Organization

a. Technology of Space Medicine. There are two major problems with which the technology of space medicine must cope, in responding to the requirements of potential space missions in the future: (1) the maintenance of crew health, or the health of colonists at some permanent space station or lunar station; and (2) the possibility of using orbiting stations as space "hospitals," thereby taking advantage of the free-fall environment. In the second consideration, it is conceivable that an orbiting station could enhance certain medical research activities, or provide more traditional hospital services for the treatment of certain diseases with perhaps more effectiveness or lower cost (or both) than an Earth-based facility. This report is concerned only with identifying those technological problems which would be deterrents to such undertakings, with estimates of when solutions might reasonably be expected.

b. Biological Materials. Technical problems related to the acquiring and processing of biological materials (other than human beings) were further divided into two major subcategories. The largest of these had to do with the possibility of creating a closed ecological system using plants (and perhaps animals) to provide food, recycle wastes, and replenish the gaseous environment.

The second subcategory concerns the technology of exploiting the space environment to process biological materials with the primary aim of using these biological materials on Earth. For example, a free-fall environment might enhance the possibility of cell separation, with the resultant separated cell strain being used on Earth as seeds for pure cell cultures to produce clinically useful amounts of enzymes, hormones, or other types of biologically active molecules.

c. Contaminants. As the investigation of the foregoing progressed, it became clear that any activities involving the acquisition and processing of biological materials, human or otherwise, in space, would invariably involve the potential production of noxious material. It was judged important to consider whether or not the technology available in the projected time period would be capable of dealing with such contaminants in long-term closed-system space stations or lunar stations.

Another potential biological type of contaminant is epitomized by a sample returned from Mars. This particular technical problem is given consideration under the category of Storing of Matter, since it was judged that the primary purpose of acquiring any such sample would be for its scientific value, rather than to support crew health or provide a useful biological product on Earth.

2. Approach

a. Contributors and Consultants. Contributors to this area (listed in subsection E) were individuals at JPL and Caltech who have requisite backgrounds in biology and medicine to address the type of technical problems evaluated in this section. Consultants came from NASA centers and from other organizations. Additional information was gathered from informal discussions with various experts in relevant fields.

b. Selection of Parameters. Obviously, a huge number of separate technical problems bears on each of the subcategories mentioned above. It was necessary here, as in other categories, to try to define those particular parameters which seem best to encompass a large variety of technical questions in a small number of meaningful measures.

(1) Space Medicine. Considering the host of problems which bear on the question of space medical technology, one question appears to be dominant: How long can a crew be maintained in a state of physical and mental health which allows them to function effectively in a space environment?

It is understood that in the manned missions, as in any truly innovative undertaking, the possibility of risk cannot be excluded but must be understood as completely as possible and minimized.

(2) Biological Materials. In considering the possibility of maintaining a closed ecological system (including humans) with the use of growing plants, there are two variables which seem to be basic requirements for this particular technological capability: the diversity of species necessary to maintain a stable system, and the total area of a space "farm" required to support one man in a completely closed system. Specification of these variables requires data as in such crucial unknowns as plant viability in a space environment (e.g., less than 1 g), the possibility of developing new species, etc.

(3) Contaminants. Technology related to this area must be concerned with three problems: (1) identification, or prediction, of all potentially harmful agents; (2) measuring levels of all potential toxic products in a closed space environment, including for example, gases, bacteria, and viruses; and (3) removing them or at least limiting their concentration below some acceptable safe level. Numerical parameters are inappropriate for this area. The forecast is presented in the text.

C. FORECASTS

1. Background, Present Status, and Forecasts of 1980 Improvement

The stability of living systems is a basic consideration in any discussion of biological activities in space, hence of the related technology.

The significant characteristics of humans, plants and animals change with the time-scale of evolution. We might look forward to the development of new varieties of food plants, better adapted to, say, lunar gravity and a 28-day light cycle than anything currently available, or to experiments with different varieties of algae which may overcome some of the difficulties experienced with algae cultures so far. But in general we must assume that fundamental biological parameters will undergo little change between now and the year 2000. If we seek to find ways for improving those aspects of technology which bear on biological processes in space, our search must be directed toward a better understanding of biological processes as they occur today, rather than a search for ways to make significant modifications of those processes. Thus, we may reasonably hope to develop crop plants that are intrinsically nitrogen fixers.

a. Space Medicine. The following four general precepts underlie the remainder of the discussion of Space Medicine:

(1) Clearly, the better our understanding of the basic physiology of humans on Earth, the better we can predict, understand and study changes that may occur in space. In this sense, any advance in knowledge of physiology will to some degree support manned space missions. Conversely, studies of human and appropriate experimental animal subjects during space missions of various types will provide a new approach to the study of physiology. With respect to the period 1980 to 2000, those physiological changes most likely to limit the duration or nature of future missions are those that have been documented by or inferred from data obtained from manned missions already completed. At present we see no insurmountable technical obstacles that would make it impossible to perform in space any physiological or clinical studies that could be carried out on Earth.

(2) The most acute physiological demands are likely to occur during the transition phases of a mission, e.g., during launch, transition from one g to zero g, during reentry, and so forth. We refer to these sudden severe demands as acute stress. Most acute stresses will call upon existing adaptive mechanisms. Once the transitional phase of the mission is over, the individual will again (i.e., soon) be in homeostasis at a functional level that may be somewhat different from that maintained on Earth, but one that permits effective functioning and does not consistently require adaptation to acute stress. Where this is in question, the success of long missions is in question. This type of uncertainty is of central importance in the hierarchical ordering of risks.

(3) The major psychological stress will occur among crews on very long missions and when the mitigating effect of the pioneering spirit no longer prevails. This situation has not yet occurred in manned space missions.

(4) The ability to tolerate existence at less than one g for long periods and to function well emerges as the overriding consideration in terms of missions during the period 1980 to 2000. For this reason it is essential that those physiological effects that appear most likely to limit mission duration or success be studied as a function of time at several levels of gravitational force between zero g and one g.

Given the above four precepts, it is possible to identify certain key medical problems relative to manned space missions during the period 1980-2000:

(1) Bone Resorption: At present the major physiological (non-physchological) variable limiting the duration of manned space missions through the year 2000 is resorption of trabecular bone under conditions of less than one g.

The main danger is calcium loss $\geq$ approximately 20% of total body calcium; i.e., osteoporosis severe enough that even moderately vigorous or sudden movement may result in fracture(s) of the spine. Renal calculus (kidney stone) formation is a related problem.

Presently available information about the mechanisms controlling bone resorption and remodelling is not adequate for planning preventive or corrective therapy for bone resorption occurring at rates as rapid as those observed in Skylab

astronauts if the rates are, in fact, as high as the data suggest and if they are sustained.

In the past few years there has been a series of significant new findings about the biochemical role(s) of vitamin D, the role of prostaglandins, the interaction of various hormones and the role of various dietary forms of calcium and of dietary calcium/phosphorous ratios in regulating bone growth and maintenance. The piezoelectric properties of bone are receiving increasing attention and several conceptual models of trabecular bone homeostasis have been proposed. Nevertheless, the key questions with respect to bone resorption at < one g (and, indeed, in earthly varieties of osteoporosis) remain incompletely answered (Refs. 5-1 – 5-7)*.

(2) Psychological Problems: Most informed opinions agree that beyond missions of a few months, psychological problems could become severe. There are some data on crew selection, reaction to confinement, group dynamics, and the like from volunteers closely confined in fallout shelters, studies of submarine crews, and crews stationed in Antarctica, but these are not entirely translatable to manned space missions. At the present time, it appears that it will probably be necessary to complete a series of missions of increasing length and various crew sizes before the questions about optimum crew size, psychological "profiles," and structural and operational characteristics of the spacecraft required for a successful long mission (i.e., years) can be answered with an acceptable degree of confidence. (Refs. 5-1, 5-2, 5-8, and 5-9).

(3) Cardiovascular Changes and Fluid Balance: Changes in cardiovascular function and fluid balance during the Skylab missions have been well documented (Ref. 5-1). They appear to stem from (1) marked and sudden shift of blood from the lower extremeties to the upper body and (2) cardiovascular deconditioning.

The fluid shift that occurs following abrupt transition from one g to zero g triggers a complex series of physiological adaptations to reduce the circulating blood volume and stabilize the circulation. Ultimately, "excess" water is lost through diuresis and red blood cell production is temporarily "turned off" long enough to allow the red cell mass to drift down to an appropriate level. It then resumes and the hematocrit stabilizes. The net effect is equivalent to removal of whole blood in an amount equal to that shifted from the legs to the upper body.

More rapid adjustment might be achieved if an equivalent volume of whole blood were removed and banked for re-infusion after splash down. It has been suggested that legless astronauts might be at an advantage at < one g, and that the rigorous physical conditioning that the astronauts undertake before the missions may be unnecessary and possibly deleterious.

Several of the cardiovascular changes observed in the Skylab astronauts cannot be accounted for on the basis of changes in blood volume and hematocrit alone. These changes are probably analogous to the cardiovascular deconditioning that has been clearly demonstrated through bed rest studies on normal human volunteers and on patients in Coronary Care Units.

To avoid serious cardiovascular deconditioning, exercise on a routine basis will probably be essential on long space missions at < one g. It will also be important to have monitoring techniques for evaluating electrocardiograms of astronauts periodically during long missions. Astronauts should be taught basic physiology of the heart and circulation. They should understand the effects of key cardiovascular drugs and the proper use of these drugs therapeutically as necessary for cardiovascular changes that develop during long flights. No truly new technology would be required to meet these requirements.

(4) Muscle Mass and Neuromuscular Coordination: Loss of muscle mass from the leg muscles was observed in all Skylab astronauts (Ref. 5-1). It is less certain that other muscle groups developed significant loss of muscle mass. Abnormalities of gait, posture, and balance were also observed after splashdown. Some of these changes reverted to normal only after several weeks at one g. Although there was no notable decrement in the astronauts' abilities to perform their tasks during the mission, the changes observed after splashdown do raise questions about how well neuromuscular coordination would be maintained during very long flights. Until control of bone resorption can be assured, however, questions about muscle mass and neuromuscular coordination are not likely to limit mission duration or complexity.

(5) Radiation Effects: Existing or foreseeable technology is adequate for measuring and shielding against most types of radiation that would be encountered during most types of missions, assuming realistic trade-offs between mission duration, complexity, and so forth, and crew safety. Furthermore, the biological effects of various doses and dose rates are reasonably well understood and continue to be studied intensively. The methodology for such studies is not a problem. The major exceptions to the above statement

*References may be found at the end of Part Five.

relate to nuclei of high atomic number (e.g., iron) and the extremely high energy protons from solar flares (Refs. 5-1, 5-10, 5-11, 5-12, and 5-13). The newer accelerators may be expected to improve our understanding of this aspect of radiobiology. Ultimately, however, additional physical and biological data representing real missions will be required before acceptable exposure levels for very long missions can be arrived at. None of these requirements exceed existing or foreseeable technology, and, in any case, the more urgent problems for the period under consideration are those of bone resorption, psychosocial problems, cardiovascular "deconditioning" and neuromuscular function.

(6) Aging: If space flight is to last for a period of years, aging will be an important factor. Most astronauts who have been chosen for space flight are in their 40s, and on flights of 10 years or longer may be expected to develop some degree of age-related pathology. Precept number 1 (set forth above) is especially germane to this consideration. In fact, plans for prolonged manned missions would justify NASA-sponsored evaluation of work now in progress on mechanisms of cell aging and how aging, in general, affects organ function in humans at a clinical level.

The idea of using a zero-gravity environment for medical work, either research or therapy, raises a number of interesting questions, all of which seem to be medical at this time rather than problems of space technology. That is, there seems to be no technological factor which would limit capabilities to perform medical research or medical treatment in space. Rather, the issue revolves around (1) questions of relative benefits and cost between space and Earth-based facilities, and (2) the possibility of posing medical questions that would require a zero-gravity environment to answer. Therefore, there seems to be no value in attempting to make purely technological forecasts in this area.

b. Biological Materials. In this area, the study has concentrated primarily on the question of whether or not a completely closed ecological life-support system could be maintained in a space environment for an indefinite period. Two broad categories were considered: a highly limited system involving, for example, one variety of algae and one or two varieties of bacteria, and a highly diverse system involving 50-100 different species of plants, animals and bacteria.

Over the past several years, a considerable amount of work has been done with alga cultures. Most of these have centered on the alga Chlorella (Ref. 5-14) which is small, relatively easy to culture at high density on enriched media, has very little cellulose, and has a high rate of photosynthesis per unit biomass. More recently work has been carried out with Oocystic polymorpha. Systems using this alga turn out to be quite "clean" in comparison to Chlorella cultures. The alga does not stick or clump, and is not highly susceptible to contamination. It is estimated that a culture of this species could provide enough photosynthesis to interchange oxygen with one person given a culture volume of 60-80 liters and an illuminated surface area (solar illumination) of 8 sq. meters. In contrast other algae species cannot survive such concentrations, and require culture systems employing culture volumes as high as 3,000 liters per capita and up to 15 sq. meters of illumination per capita. Although the systems are subject to contamination by microorganisms, continuous successful operation has been achieved for periods of up to several hundred days (Refs. 5-15 and 5-16).

At one time, it had been thought that the algae produced in a photosynthetic gas exchanger could be used as a complete food stuff for humans, but later research has proven this belief untenable. There are definite digestibility problems, and the nutritional values are unacceptable (Ref. 5-17). For example, algae are 40-60% protein (dry weight), whereas the human diet should contain less than 20% protein. Another problem that has yet to be solved is that of maintaining a proper balance in the gas exchange loop between humans and algae.

Algae cultures in closed systems cannot successfully convert human waste products (Refs. 5-18 and 5-19). Algae cannot live on unprocessed human feces and urine. Proper waste treatment requires either some sort of mechanical equipment or the introduction of one or more additional species (e.g., a bacteria-fungi combination) capable of decomposing waste products into materials which can be utilized by the algae. However, no work to date indicates that such theoretically possible algae-based system would actually operate in a closed environment with a human for any extended period of time.

Certain varieties of leafy plants have been suggested as alternatives to algae as potential members of a single-species closed system. Here again, experimental evidence is lacking.

As a matter of fact, the only experimental evidence we have on "closed" long-life ecological systems is the biosphere itself, a system of great complexity and diversity. Thus, to properly describe the present status of technology for achieving closed ecological systems using biological processes, one would have to say that a great diversity of species is required, involving leafy plants as well as algae, and decomposers (bacteria, protozoa, and perhaps some simple animal species).

Selection of higher plants in a life support system is highly acceptable from a psychological and physiological standpoint. Minimum innovative processing is necessary and analysis of the food value of most crop plants can be found in agricultural handbooks. The majority of research in botany is on the Angiosperms, true flowering plants (including familiar food plants), so growth characteristics, pathogens, and chemistries are fairly well known.

The criteria for selection of Angiosperms on a space flight (Refs. 5-20, 5-21, and 5-22) are: (1) high photosynthetic efficiency under available light conditions; (2) production of edible parts

under low light conditions; (3) resistance to relatively high osmotic pressures; (4) no (or controllable) production of pharmacologically active substances; (5) maximum leaf to minimum stem surface; and (6) elimination of plants that flower readily irrespective of photoperiod since oxygen production declines with flowering.

Various studies have concentrated on different plants. Peanuts, lima beans, topinambar (ground pear), leaf cabbage, potatoes, maize, lettuce, collards, tomatoes, yeast, Chinese cabbage, endive, and tampela have been studied in some detail (Refs. 5-22 – 5-26).

Questions and problems regarding the use of angiosperms stem from the lack of enough information on growing plants in a space environment. Information now available is on short-term culture. Growth for the entire life cycle, the effect of radiation and the effects of zero gravity, or 1/6 g on the Moon, are not known. Substances could be given off by plants in a Lunar or space environment that could not be foreseen from experiments on Earth. Also substances that dissipate in the Earth's atmosphere may cause problems in a small closed system such as a space ship or Lunar station.

Each of the biological life support systems that have been studied so far has advantages and disadvantages. For a mission exceeding about one year, however, the advantages seem to be greater. A combination system with bacteria, higher plants, and perhaps algae, would provide a system that would be most bioregenerative. Using algae and bacteria as parts of a waste recycling system and partly in a diet to complement higher plant foods would take care of CO_2, most of the human waste products, generate water and, perhaps, partially decontaminate the atmosphere. Perhaps 25-50 different species would be required and 25% to 50% of the product would be available as food. However, taking a conservative approach, one would conclude that stability of the system requires a much greater degree of diversity, involving hundreds of interacting species. Only a small fraction of the total product of the system, perhaps less than 5% (dry weight) would be available to humans to supply their needs of food and oxygen. The rest of the product would maintain the overall system.

This, in turn, implies a "farm" area of about 1 hectare per capita based on existing Earth technology (Refs. 5-27 and 5-28), even though the theoretical lower limit is less than 0.1% of this, assuming highly efficient photosynthesis in plants, and 100% conversion to food. Even this 1-hectare estimate must be taken as optimistic if it is believed to represent the present status, because in fact, no one has actually put together such a closed system and operated it for any extended period.

Between now and 1980 it might be possible to at least test the concept that a closed ecological system is feasible at all. One could visualize a somewhat heroic set of experiments in which various candidate systems were set up and sealed off, complete with their (presumably volunteer) human populations, and then tested for equilibrium operation for a period of at least one year, but preferably several years.

Gravity becomes an important factor when considering the use of higher plants in a space system. There are no data to show that a complex ecosystem could be maintained at zero gravity. Such a system might, therefore, require a rotating space station to survive in free-fall.

c. Space Processing of Biological Materials. The technological problems in this area seem to be rather straightforward. A typical space processing task is scheduled for the Apollo Soyuz Test Project mission. An experiment has been designed by Abbott Laboratories, under the direction of the Marshall Space Flight Center, for the electrophoretic separation of human kidney cells. If successful, one strain of the separated mixture can be used as seed material for tissue culture on Earth for a highly efficient production of urokinase, a hormone of considerable medical significance. It is important to note that the technological demands for this experiment are modest. The equipment is essentially "off-the-shelf," although, of course, special packaging is required for the space mission. This particular mission is judged to be characteristic of biological space processing missions foreseen for the 1980-2000 time period. That is, it is judged that space technology will not in any way be limiting for this type of endeavor. Future activities in this area would seem to depend primarily on our ability to pose crucial biological problems whose solution requires a space environment. The pacing element therefore is basic biological knowledge itself, not the limitations of space technology. Assuming that this is the proper conclusion, there will be no forecast or further discussion of this particular area of technology.

d. Contaminants.

(1) Definition. A contaminant is defined here as any chemical compound or biological organism which appears for some reason in any part of a closed ecosystem in which it was not originally present. The contaminant, defined this way, need not be harmful to the ecosystem. The contaminant must, however, like all the other chemicals and biological organisms be monitored.

(2) Problem. The problems concerned with contamination of the atmosphere and other parts of an ecosystem are manyfold. A very large ecosystem can cope with a greater variety and greater concentration of contaminants than can a small or critically balanced one. An artificially designed ecosystem is by definition "critical" since by necessity, the variety of species will be limited. It is impossible at this point to state quantitatively the effect of specific contaminants on an arbitrary ecosystem; first, a suitable closed ecosystem of plants and animals necessary to support a space colony for a long period of time (> 1 yr) is not defined, and second, insufficient information is available concerning the tolerance of most plants to various contaminants. In addition, some plants release chemicals as waste products which are toxic to certain species of other plants.

Spacecraft and space station construction must be carefully planned with respect to the materials to be used for various functional parts (Ref. 5-29). Construction materials can release various toxic substances into the atmosphere as a

result of radiation and contact with low levels of various gas phase chemicals. Soil can also be contaminated through water which has been circulated through pipings that release inorganic ions necessary in trace concentrations but lethal to plants at seemingly low concentrations. A classic example of this is copper.

Contamination through improper handling of animal wastes can also be a problem. Various gases like H_2S can end up, through a likely series of reactions, as serious problem chemicals like sulfuric acid, which is a corrosive acid to metals, a very toxic chemical to plants and a respected burning agent to animals.

All of these results of the presence of contaminants must be addressed. Basic to this, is the need for sensitive, reliable, and redundant means of contaminant detection in all phases existing in an ecosystem, gas phase, liquid phase and in soil type mixtures. Then, means must be available to eliminate or reduce to acceptable levels toxic contaminants.

(3) Detection. A study on the volatile compounds evolved by a number of vegetables revealed that between 9 and > 60 such chemicals were excreted by various common fruits and vegetables (Ref. 5-30). Most of these were hydrogen, lower hydrocarbons, aldehydes, alcohols, acetone, etc. These were specified for certain plants under ordinary earthbound growing conditions. On Earth, due to tremendous plant variation, these compounds remain dilute enough so that no toxicity problem exists. In a critical ecosystem this could prove a problem, since plant varieties will be chosen for food value, waste usage, and biomass conservation considerations; hence, lesser variety. An obvious and natural result is that such a well chosen system cannot in its initial evolutionary stages satisfy all the total stability requirements which now exist on Earth.

The problem of toxic contaminant buildup is then extremely important to the survival of both plant and animal life (Refs. 5-29 and 5-30).

Since there exist hundreds of chemicals which must be monitored in the atmosphere alone, means must be available to measure, qualitatively and quantitatively, all chemicals. Some of these will be life support gases, like O_2, and CO_2 (always present). Others may be contaminants which suddenly appear either through accidents, or as waste products from the biosystem. It is impossible and undesirable to program for the detection of specific chemicals if the aim is to eliminate eventually those which are toxic. To program for certain chemicals is to say that all possible toxic contaminants are known; this is not the case.

The monitoring system should then be at least doubly redundant for each class of chemical compounds. The sensitivity should be in the parts per billion (ppb) range. To process the data rapidly a computer evaluation system should be developed and utilized. Monitoring of contaminants should be a continuous operation so that occasional accidents can be immediately identified. Since the food supply and $CO_2 - O_2$ gas cycle are needed to support all life, any contaminant which can render the plant kingdom functions inoperable is an important chemical to monitor (Ref. 5-31). It imposes important considerations.

Atmospheres and liquids can be tested by several methods. All of these now exist but a modest effort must be undertaken to render these techniques more sensitive, portable and automated. Redundancy of measurement capability is required for several reasons:

(1) Certain methods separate mixtures better than others. Redundancy will, therefore, lower the probability that a contaminant will exist undetected.

(2) Certain methods are more sensitive than others for given classes of chemicals, thus again lowering the probability of the existence of an undetected contaminant.

(3) Redundancy also guards against a catastrophe in case of an instrument failure.

Most volatile organic compounds can easily be detected by gas chromatography (Ref. 5-30) and mass spectrometry in the parts per billion range; infrared spectroscopy and nuclear magnetic resonance will also be valuable. Non-polar diatomic molecules such as O_2, N_2, etc., can be detected by mass spectrometry. Polar gaseous molecules such as CO, CO_2, NH_3, H_2O, H_2CO, SO_2 are easily detected by mass spectrometry and microwave rotational absorption spectrometry (Refs. 5-32 and 5-33). The limits of detection of both of these methods are in the ppb range and the latter method is being developed for better sensitivity, diversity and hand portability. The above mentioned detection methods have the range and adaptability to measure redundantly and quantitatively all expected classes (Ref. 5-29) of volatile compounds which will probably enter the atmosphere of a closed ecosystem. They (IR, gas chromatography, mass spectrometry) are in most cases, also important detectors for liquids.

Metals in soil can be detected with a sensitivity greater than ppb by atomic absorption spectrometry.

(4) Elimination of Toxic Contaminants. Once detected and quantified, the problem shifts to either eliminating the contaminants from the recyclable system or converting them to usable products. Thus far, during short duration space flights, the effort has been towards eliminating undesirable gaseous wastes and supplying O_2, food, and everything else from Earth.

A trade-off study has been made concerning the problem of adsorption contaminant removal systems (Ref. 5-34). More work must be done on these and conceptually new systems so that recycling rather than removal is the main method. A total ecosystem would rely on recycling for the most part, but for the interim stages, a complementary chemical removal system whose products can later be recycled chemically and reclaimed by the biosystem must (or should) be developed.

2. Forecasts of the 1980 to 2000 Period

The technology forecasts of the critical items that have been judged as having the potential of presenting specific technical problems that could place limits on future capabilities in space missions are depicted on the following pages. These forecasts include:

(1) Maximum Mission Duration at 0 g — Calcium-Loss Limited.

(2) Mission Duration at 1/6 g (Lunar Surface) - Calcium-Loss Limited.

(3) Number of Species Required for Stable, Closed Ecosystem.

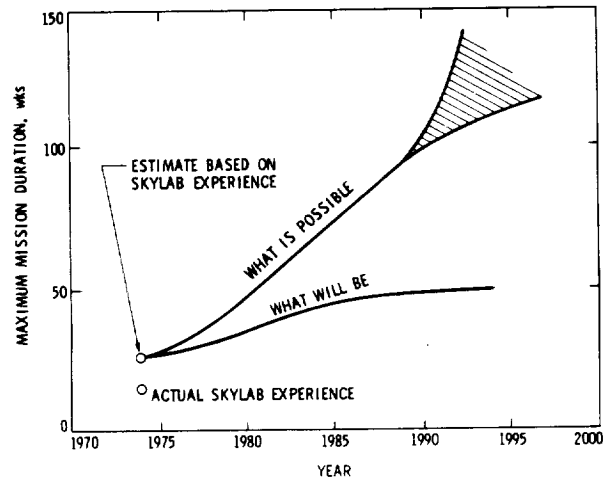
(4) Farm Area Required in a Completely Closed System to Support One Person.

(5) Availability of New Plant Species Suitable for Growing in Space.

(6) Sensitivity of Instrumentation for the Determination of Contaminant Levels.

ACQUIRING AND PROCESSING ANIMATE MATTER FORECASTS

FC 5-1. Maximum Mission Duration at 0 g - Calcium-Loss Limited



DISCUSSION

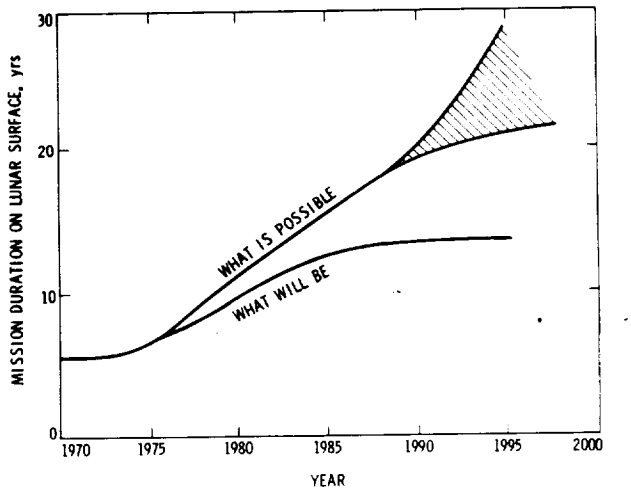
The starting point in 1974 corresponds to twice the length of the longest Skylab mission and is based on medical information gained during that mission. The data indicate that under Skylab conditions, a duration of 24 weeks would have been feasible.

The "What Will Be" curve assumes Skylab conditions would be improved by optimizing diet (e.g., total Ca and Ca/P ratio) and exercise based on data obtained from completed Skylab missions.

The "What is Possible" curve assumes that intensive work on experimental animals and humans under appropriate conditions, will yield data on which clinical management for calcium loss could be based (presently available data are not adequate). Thereafter, it is assumed that there would be a carefully supervised treatment of astronauts with those hormones, vitamins and minerals that are directly involved in the maintenance of normal bone.

The uncertainty as to what is possible after 1990 presumes that research has indicated techniques for maintaining normal bone formation in the absence of gravity. The possibility of such artificial stimulation (e.g., application of precisely controlled magnetic fields and/or weak electric currents) is quite speculative at present; thus, the uncertainty at the later time period.

FC 5-2. Mission Duration at 1/6 g (Lunar Surface) - Calcium-Loss Limited

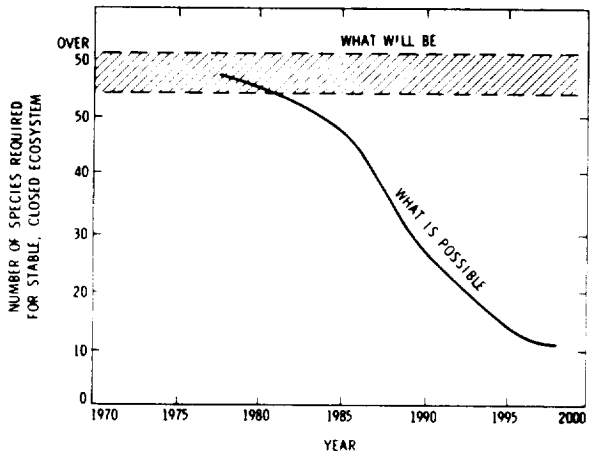


DISCUSSION

At 1 g, 35 years is a reasonable estimate of average time to become osteoporotic after age 40, at normal adult levels of calcium loss. It is assumed that the same total loss would occur in 1/6th the time under lunar gravity of 1/6 g. This assumption accounts for the initial position of the curve.

Assumptions for the "What Will Be" and "What is Possible" curves are the same as those used for the previous forecast, 5-1.

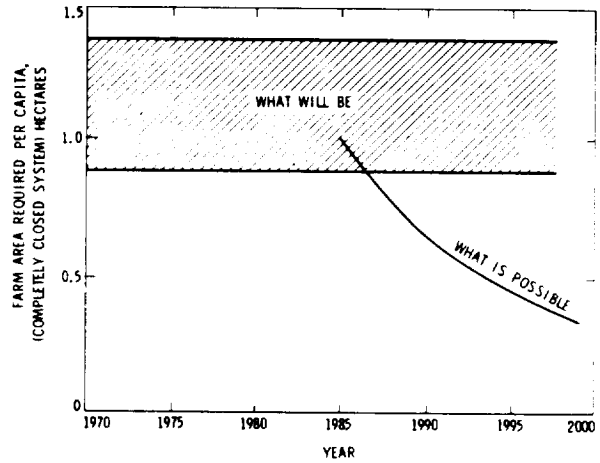
FC 5-3. Number of Species Required for Stable, Closed Ecosystem



DISCUSSION

Background information and the current state of knowledge on this parameter are quite uncertain, since no attempt has ever been made to maintain human beings in a closed ecosystem with a limited number of species for an extended period of time. Best estimates appear to be that somewhere between 25 and 50 different species would be necessary. The curve indicating "What Is Possible" indicates that if a research program in this area were undertaken, then over the time period in question, it would be possible first to identify the number of species required on the basis of present knowledge, and then by selective testing, gradually trim down this number to some lower level. It is presumed that the goal of minimum species diversity is valuable for efficiency, from the point of view of supporting humans; that is, a greater proportion of the biological product would be available for human use in a stable equilibrium.

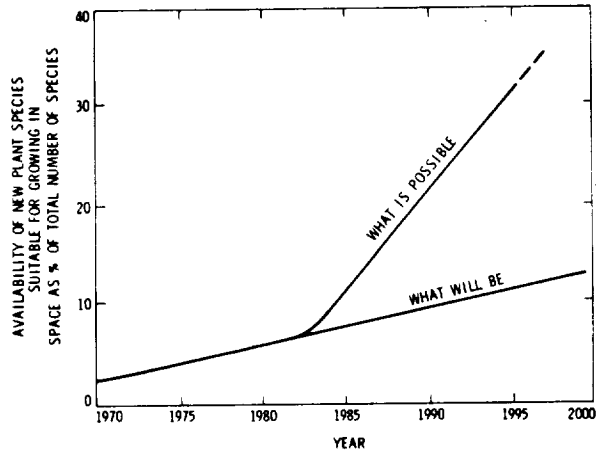
FC 5-4. Farm Area Required in a Completely Closed System to Support One Person



DISCUSSION

The present value of this parameter cannot actually be defined, since it is not certain whether or not it is even possible to make a completely closed system of limited volume. Therefore the prediction is based on the assumption that such a possibility does exist, but will require the order of 10 years of research to demonstrate conclusively. Such early research would be devoted to success of the demonstration, rather than to improvements of efficiency. So the conclusion in 1985 would be a closed system at about 1 hectare per capita. After the concept is demonstrated there could conceivably be very rapid increases in efficiency in the first few years of further work, but it does not seem likely that by the year 2000 we will be at the theoretical lower limit of a few sq meters, per capita.

FC 5-5. Availability of New Plant Species Suitable for Growing in Space



DISCUSSION

New plants will be developed that will more efficiently utilize available nutrients. Subsequently strains that are photoperiod tolerant, and with high nutritional and a high edible proportion will be developed to meet future food needs of the Earth's population. Additional research could clarify the nutrient requirements as related to the biological processes. To date there has not been a systematic study done on dietary nutrient requirements of either plants or animals -- including humans. Some kind of study dealing with this problem must be done before selection of the ecosystem components can be done.

Development of new plant species through intergeneric fusion, parasexual hybrids, and somatic hybrids will be the direction of plant research in the next 10 years (Refs. 5-35, 5-36, and 5-37). Development of plants that are specifically adaptable for space growth and investigations into the feasibility of plant growth in space will be done only for space programs. No such studies have been done in this area so far.

FC 5-6. Sensitivity of Instrumentation for the Determination of Contaminant Levels

DISCUSSION

The technological forecast in the area of contaminants is best described as follows:

(1) By 2000, the technology of detection instruments will be advanced, reliable, sensitive and compact enough to sufficiently monitor and detect various contaminants in the ecosystem. Such work is now being funded by air pollution research, but additional funding by NASA will be required to adapt the instruments and test them for space flight. New computer data analysis systems for cross-checking the inputs from the various instruments must be developed.

(2) Botanical research must be undertaken to determine those plants best suited for an ecosystem and to determine their sensitivities to various types of contaminants.

(3) Materials for spacecraft construction must be retested for the effects of prolonged ionizing and UV radiation exposures hence probable contaminant evoluation. These materials should also be tested for reactions which will occur with various gases which may escape into the atmosphere.

D. SUMMARY

In the area of Acquisition and Processing of Animate Matter (defined and limited as described in Section II-A) the critical technical problem is centered around the possibility of maintaining a healthy crew for a long period of time, either on the Lunar surface or in free-fall. The primary medical problem appears to be bone resorption, under conditions of less than normal gravity. Over the next one or two decades, increasing medical knowledge of this problem, as gained in the ordinary course of medical research relative to common types of osteoporosis, might enable the limits of mission duration to be pushed to the order of one year. But to go much beyond that requires much more concentrated effort on this specific problem than any effort which, it is expected, would take place without NASA support. Even if the calcium loss problem can be solved, there are other unknown potentially limiting factors which may prevent missions of several years duration. Here again, the normal course of medical research is not likely to resolve such problems in the next one or two decades; so here again NASA support would be required if these limits are to be removed.

For extremely long-duration missions, such as a Lunar colony or a manned deep-space station, there is a break point at which it would seem more desirable to attempt a completely closed life support system, rather than to carry food, water, and oxygen as cargo and then simply dispose of the waste products ("stow and throw"). This break point has been estimated in other studies as lying somewhere in excess of six months, but less than about two years. Obviously, it depends upon what alternative technologies are being considered.

It is theoretically possible to create a closed system in either of two ways: By the use of various devices to artificially process waste materials and regenerate the required food, water and oxygen, or, by relying primarily on biological processes involving plants, bacteria and other elements of a complete ecosystem. In this area of study, the concentration was on the second of these two possibilities.

It would seem to be perfectly feasible to use a closed biological system to support human beings either on the Moon or in space for extended periods of time, even permanently. However, certain requirements and restrictions must be taken into account. First is the requirement for a highly diverse biological system. In turn, this implies a rather large area for the space "farm," and consequently a different trade-off point for the length of mission at which the closed system becomes less costly than the "stow-and-throw" system. The use of higher plants in such a closed system may or may not require gravity. It is not known whether lunar gravity would suffice, but evidence available so far is not sufficient to guarantee the conclusion that zero gravity would be tolerated. Here again is a definite implication on the complexity of such a system for a free-fall mission. The whole system would possibly have to be spun in order to introduce a suitable g-loading. There are no data available to support any conclusion on the long-term effects of gravity on people and plants.

It must be emphasized that even though all evidence indicates that a 1-hectare-per-capita farm could support a closed space colony indefinitely, this has not, in fact, been demonstrated. Pushing the requirement down to say a fraction of a hectare per capita, or the theoretical lower limit of a few square meters per capita (based on highly efficient food plants and total conversion of plant to human food) obviously requires a considerable amount of research. It does not seem likely that this research would be carried out without NASA support, in spite of potential payoffs for Earth-based agriculture. With NASA support, the results of such research would not only have benefit for space colonies, but also benefits on Earth. The knowledge of how to build more efficient farms is clearly valuable.

E. PARTICIPANTS

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*From JPL, unless otherwise noted.

F. INDEX OF MICROFILMED FORECASTS

The following forecasts, concerning the acquiring and processing of animate matter, are available at the Jet Propulsion Laboratory. This information may be retrieved by calling Mr. George Mitchell at (213) 354-5090 and giving the document number (1060-42) and the Volume number (Vol. V) followed by the correct page reference numbers as listed below:

FC	Title	Page No. (1060-42, Vol. V)
5.1	Maximum Mission Duration at 0 g -- Calcium Loss Limited	5-35 – 5-36
5.2	Mission Duration at 1/6 g (Lunar Surface) -- Calcium Loss Limited	5-37
5.3	Number of Species Required for Stable, Closed Ecosystem	5-38
5.4	Farm Area Required in a Completely Closed System to Support One Person	5-39
5.5	Availability of New Plant Species Suitable for Growing in Space	5-40
5.6	Sensitivity of Instrumentation for the Determination of Contaminant Levels	5-41

Section III. ACQUIRING AND PROCESSING INANIMATE MATTER – MICROSTRUCTURES

J. Maserjian

A. SCOPE

This field encompasses all solid-state structures that require extensive microscopic detail in their fabrication in order to perform their function. Therefore, the field includes microelectronics and any other space-related technologies that can be identified.

The elements forecast in this Section were arrived at through a process of elimination, starting from a candidate list of application categories and technology approaches. One of the main criteria for selecting the key functional elements or specific types of components to be forecast was that they have, in the judgment of the forecasters, a potentially major impact on future NASA capability and cost. Therefore, many types of components were excluded, even though it was believed that they would be needed or their improvement would be of some value. Furthermore, the concern of this forecasting is on the functional capability of the components and not on details such as improvements in materials or fabrication techniques. In some instances, where the impact of such details is great, it is noted.

B. BACKGROUND

A group of experts consisting of people from JPL and NASA Centers, as well as consultants from industry and other institutions, was organized for forecasting this technology. These participants were chosen on the basis that each element under consideration be effectively represented. A tentative list of key elements and their primary parameters, was initially reviewed by the participants. The objective was to include all functional elements or types of components that met the criteria, and to agree on the primary parameters that should be forecast. The outcome of the initial review was that only two application categories, information handling and imaging arrays, contained elements which met the selection criteria. However, the category of imaging arrays has been adequately covered in Part Three, Section II (Acquisition of Information). A more detailed forecast of a narrow portion of the imaging arrays category in the Section would be of limited value, therefore it was not undertaken. The remaining category of information handling is also covered in Part Three, Section IV (Processing and Storing Information) but at a sufficiently higher system level to justify a more detailed forecast of component technology. Therefore, the forecasts in this Section can be considered as backup, at the component level, for the Section on Processing and Storing Information.

C. ORGANIZATION AND APPROACH

The parameters agreed upon for the class of components which apply to the processing and storage of information are as follows:

(1) Density (megabits/meter^3).

(2) Cost (dollars/megabit).

(3) Reliability (failure rate/megabit).

(4) Power (watts/megabit).

(5) Speed (seconds/megabit).

(6) Weight (kilograms/megabit).

The forecasting procedure used here has been to make maximum use of available literature and forecasts and to iterate and update these forecasts as necessary, based on the best judgment of the forecasters. The forecasts presented in this Section represent the third step in this iterative cycle.

The forecasts are divided into three technology categories: (1) semiconductors (processors and memories), (2) magnetics and optics (memories), and (3) superconductors (processors and memories).

D. FORECASTS

1. Background, Present Status, and Forecasts of 1980 Improvement

a. Semiconductors. The technology of semiconductor microelectronics has been rapidly growing for the past decade. Today it has matured to the point of being a large commercial industry which supplies a large number of reliable electronic components for DOD and NASA. At this time, small-scale integrated circuits (SSIC) with less than 100 transistors on a single silicon chip are giving way to large-scale integrated (LSI) chips which have 10,000 transistors on a chip. For example, there are commercially available today entire central processing units on single silicon chips which are only 0.2 cm^2 and cost only tens of dollars. NASA is beginning to look at ways of using this tremendous capability and by 1980 should be building it into its systems. This kind of capability will grow with increasing density of gates on LSI chips for at least the next decade, leading to not only improved sequential systems but also to systems with massive parallelism for high data rates. For example, the emergence of CCD (charge coupled device) and MNOS (metal-nitride-oxide-silicon) technologies, which are presently in advanced stage of development, will by 1980 have great impact on imaging and data handling capability. By 1980 we can expect

at least 10^5 gates on single chips along with new methods of testing those chips, improved reliability, much lower power, higher speed, less weight, and, most significantly, much lower cost. Electron-beam - addressable components (e.g. vidicons) will continue to be available to fill specific requirements and can take advantage of the emerging ultra-high density chip technology.

b. Magnetics. Magnetics has been the primary technology for memories in the past. Magnetic cores, and more recently plated wire which provides main memory for data systems, will undergo some improvement by 1980 and will continue to be used for some years but probably will eventually be replaced by either an emerging magnetic bubble technology or by semiconductor memories such as MNOS or CCDs. Magnetic bubbles, which are presently in advanced development and will be available by 1980, offer high density and lower power. Tape recorders will probably still be needed by 1980 for mass memory, but this need will no longer exist after the mid 1980s when high-density solid-state memories (e.g., CCD, MNOS, or bubbles) can perform the function of disc files for on-board data processing. Again, further improvements will come with extensive parallel processing of image data.

c. Optical Systems. Optical systems using laser read/write techniques are under investigation, involving both x-y scanning and holographic techniques. Such systems offer the possibility of obtaining Fourier transforms within microseconds; providing direct means of performing cross correlations. Optical systems also offer the possibility of archival storage in excess of 10^{12} bits, with information stored in megabit blocks with access time to any block on the order of a few milliseconds and further access to any bit within a block, on the order of tenths of microseconds. This approach offers great potential for extremely massive information handling. However, it is still in an early stage of research involving basic studies of physical phenomena in search of a suitable storage media. No practical systems are likely to be available by 1980.

d. Superconductors. The application of superconductors for computer elements was first considered in the mid-50s and has undergone more intensive research since the advent of thin film techniques in the 60s, when some small working memories were demonstrated. In the past decade, memory elements have improved dramatically in speeds, densities, and potential cost savings and it now appears likely that a working superconducting computer will be reality by 1980. The principal obstacle for practical implementation is the required cryogenic environment of 4.2°K. For this reason, only very large Earth-based systems appear feasible at this time, since the refrigeration system required is nearly independent of computer size. The advantage of such computers over the technologies stems from the intrinsically high speed of superconducting elements.

2. Forecasts of the 1980 to 2000 Period

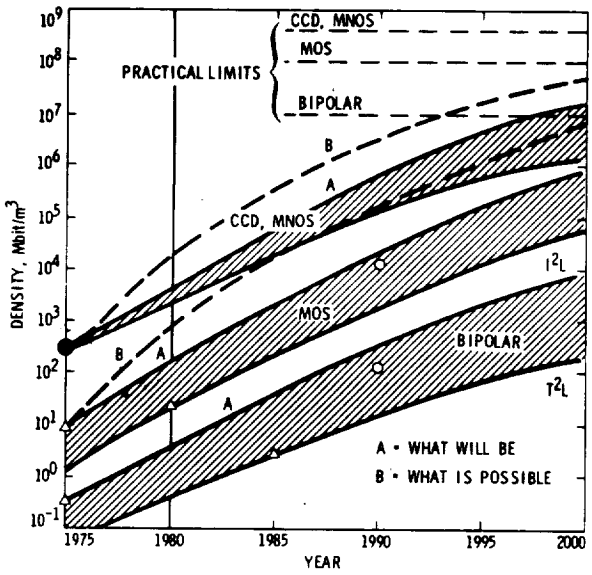
The forecasts shown on the following pages are those elements of Acquiring and Processing Inanimate Matter – Microstructures that were judged to have the most potential impact on future NASA capability and cost. These forecasts are organized as follows:

(1) Semiconductor Systems
   (a) Density
   (b) Cost
   (c) Reliability
   (d) Power
   (e) Speed

(2) Magnetic and Optical Memories
   (a) Density
   (b) Cost
   (c) Reliability
   (d) Power
   (e) Speed

(3) Superconductor Systems
   (a) Density
   (b) Cost
   (c) Reliability
   (d) Power
   (e) Speed

FC 5-7. Density of Semiconductor Systems



DISCUSSION

The "What will be" forecasts are based on commercially driven projections with the shaded bands encompassing a range of device design options (e.g., PMOS, CMOS and CMOS-SOS in MOS band). The "what is possible" curves could result from modest government investments (on the order of millions of dollars) in the early research and development phase of high-density technology to spur industry on.

The projections take into account the system overhead which include power supplies, heat transfer, interconnects, etc. The data point (•) is a developmental CCD system built by RCA (Electronic Design, 1974). The points (o) from Turn (Ref. 5-38) are based on maximum power density (i.e., heat dissipation limitation) and represent a conservative upper estimate corresponding to the anticipated density of gates on silicon chips at the time. The points (Δ) of Martin (Ref. 5-39) are more conservative forecasts based on today's system overhead requirements and can be considered a lower limit. Clearly, the system overhead becomes less important with increasing density of gates on chips.

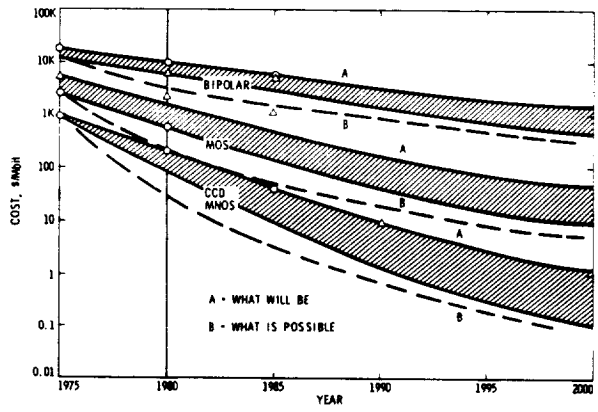
The overall practical limits on density are set by the combination of the maximum density of bits per chip, and the maximum stacking density of chips. The stacking density is limited by practical mechanical considerations. The density on a chip is limited by random fluctuations of device parameters due to the small number of dopant atoms in a small region, and the maximum electric fields that can be tolerated.

The density increases out to 1985 will be primarily due to the development of technology which provides increased density of gates on a chip and some increase in chip size, reaching a limit of about 10^7 gates per chip in CCD or MNOS. This limit will be achieved by high-resolution lithography (e.g., electron beam or x-ray) and the use of thin oxides presently under active research. Beyond that point, increasing system density will continue through the development of more advanced interconnect and packaging techniques, including three dimensional stacking of chips.

CCD and MNOS densities are higher than other MOS technologies (CMOS, PMOS, NMOS, etc.) because of the inherently smaller areas required for a single gate function. Bipolar devices require still more area and also are limited by higher power dissipation, with I^2L (integrated injection logic) offering the highest density.

System weight can be computed by multiplying the system volume obtained from the above forecast by a typical value of mass density, estimated to be 200 Kg/meter^3 in 1980 and increasing to about 500 Kg/meter^3 by the end of the century, as higher packing densities are achieved.

FC 5-8. Cost of Semiconductor Systems



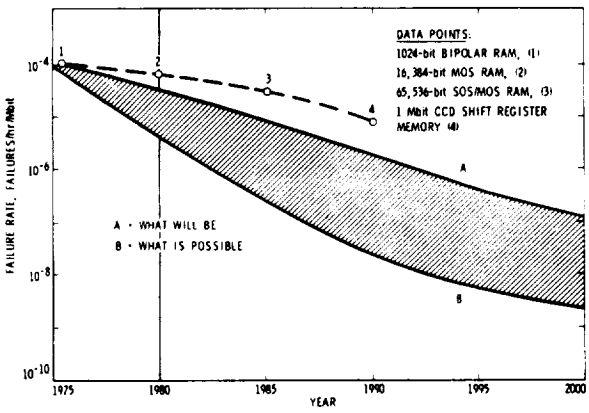
DISCUSSION

The decrease in cost of the "will be" forecasts reflects the effect of increasingly higher density LSI components as well as the effect of a commercially competitive industry. The "what is possible" forecasts depend on how soon or when NASA can develop and implement new procurement and qualification procedures to take full advantage of the emerging high-density LSI technology.

Figures for bipolar and MOS memory technologies are derived from random-access configurations, suitable for both main and mass memories in data processing applications. CCD memories are by nature serially accessed and suitable for mass memory applications.

Cost discrepancy between Turn (o) and Martin (Δ) MOS figures reflect differences of military and commercial markets. It is our contention that this difference will converge rather than diverge because of greater dependence in the future on more reliable commercial LSI components.

FC 5-9. Reliability of Semiconductor Systems



DISCUSSION

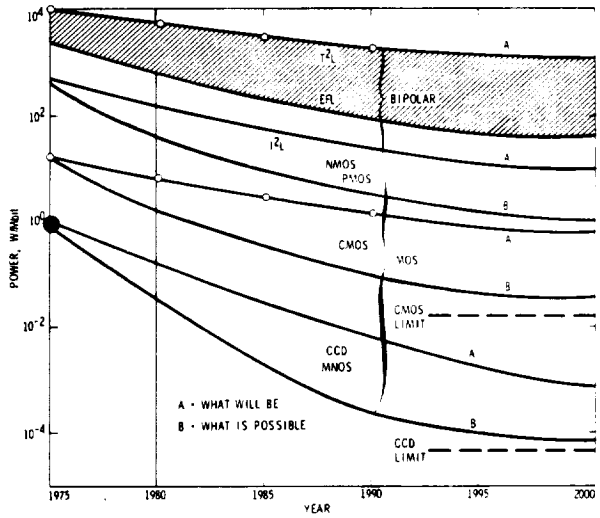
The data points shown above were calculated by applying equation 2.1.4 in MIL-HDBK-217B to the indicated typical devices assuming top-grade MIL-38510 devices. A device failure rate was computed and then multiplied by the number of devices required in a megabit system. Therefore, these calculations are based entirely on present-day processing, testing, and environmental control techniques and this improvement in reliability results entirely from the increased packaging density of the devices.

A more realistic forecast of reliability is indicated in the "what will be" curve above. This additional improvement in reliability will come about because of normal progress in understanding of failure causes and the consequential adjustments and controls in wafer processing and packing.

Further progress (shaded region) is spurred on by a NASA program as well as DOD reliability programs. In addition large industry has recently been more strongly motivated to invest in reliability physics. The maximum rate at which reliability improves "what is possible" curve will depend on the extent on such investments in reliability, as well as the development of new qualification methods appropriate to high density LSI components.

The above forecast makes no distinction between different system organizations which will have large impact on the overall system reliability.

FC 5-10. Power of Semiconductor Systems



DISCUSSION

Data points (o) are from Turn and (•) for an RCA system. The B forecasts correspond to the B density forecasts in FC 5-7.

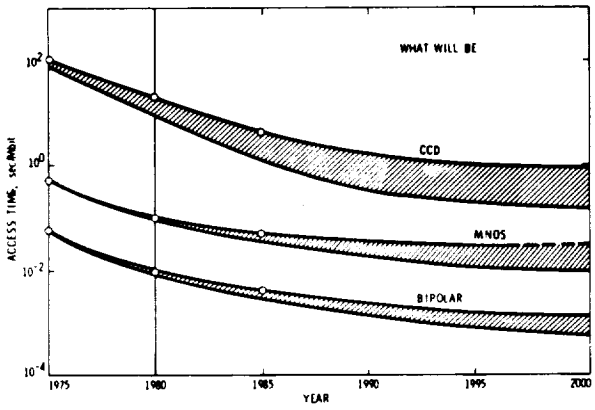
Figures were derived from operating gate power assuming an equivalent of two gates per bit of memory. Standby power for complementary MOS (CMOS) would be lower by about three orders of magnitude.

Power values for bipolar technology memories are based on saturated-logic circuit configurations. New configurations such as integrated-injection logic (I^2L) will achieve power dissipation values approaching 10 watts/megabit.

Indications are that CCD or MNOS memories may be available in the 1985-1990 time frame with power dissipation values approaching milliwatts/megabit. Standby power for CCDs would be lower by a factor of about three and virtually zero for MNOS.

The lower limits on power are determined for each technology by the minimum size of the devices comprising each bit. Thus, the limits given reflect the maximum density of bits per unit area of silicon chip.

FC 5-11. Speed of Semiconductor Systems

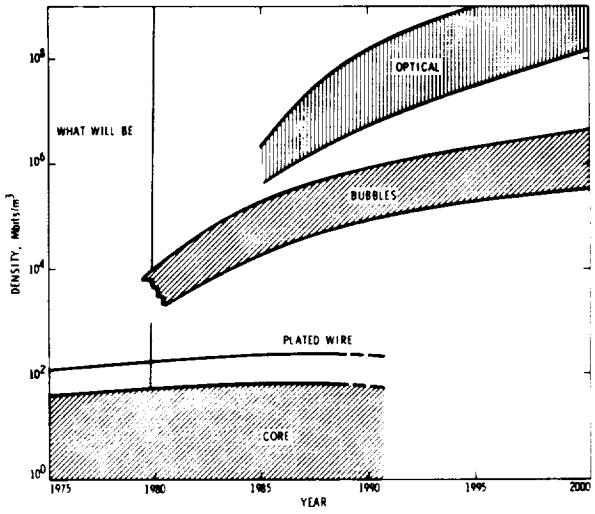


DISCUSSION

The forecasts are for the likely range of speeds (what will be) for typical device options. The data points (o) are from Forecasting International, Ltd. (Ref. 5-40) and Martin (Ref. 5-39) which are in close agreement.

Figures for MOS and bipolar memory systems represent full memory cycle times for random-access organizations. CCDs are serial devices and the access times shown represent inverse shift rates. These graphs relate time per million memory accesses; the actual bit rate is dependent upon the parallelism of the memory structure. Thus a machine with 16 bit words accessing memory one million times per second would have a data rate of 16 million bits/sec. Large scale integration will make practical parallelism of a magnitude greatly exceeding that of present machines; therefore, several orders of magnitude increase in data rate can be expected over that indicated by these graphs alone. The development of content addressable memories will extend this concept to its limit in that the entire memory will be addressable at once although the actual data rate will still be the product of access rate and word size.

FC 5-12. Density of Magnetic and Optical Memories



DISCUSSION

The forecasts represent the likely spread (what will be) for different device options. The optical and bubble forecasts assume increasing commercial drive - that is, bubbles are not supplanted by CCDs, or optical by superconductors.

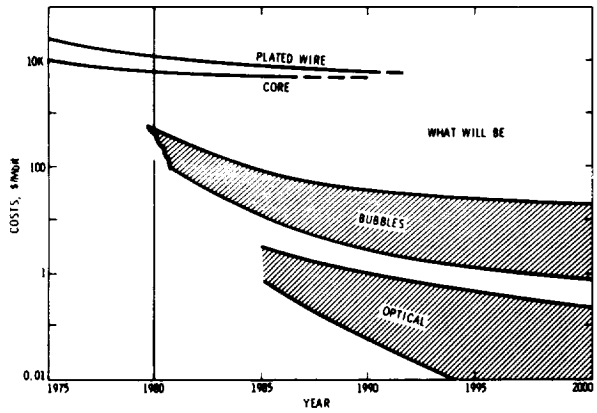
Magnetic cores will decrease in size by 1980 to outer diamters of 10 mils and inner diameters of 6 mils. Practical fabrication limitations will probably prevent further decrease in size after that time. The densities shown include system overhead of drivers, sensors, and power supplies.

Plated wire will also undergo only minor change, decreasing to a size of about 2 mils. The density shown includes system overhead.

Bubble memories are undergoing rapid development. Bit densities on single chips will compete with semiconductor memories using similar lithography and will approach 10^{8} bits/cm^2 by the mid 80s. The overall system density shown includes the system overhead.

Optical memories using laser read/write techniues are still in the research stage at this time. Such memories will probably not be available before 1985 but potentially offer extremely high capacities. A practical system would involve a minimum of 10^{11} bits of storage.

FC 5-13. Cost of Magnetic and Optical Memories



DISCUSSION

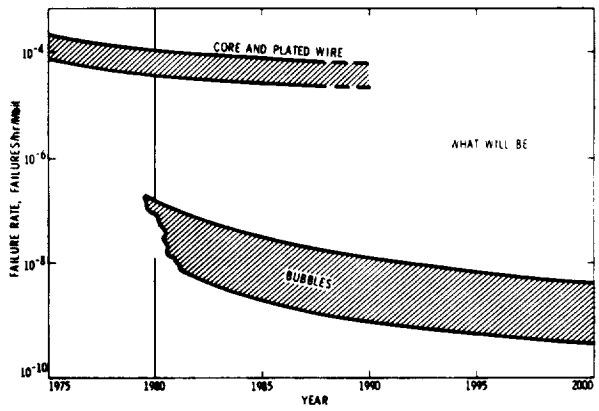
The forecasts are "what will be" for a range of device options, under the assumption that these technologies are driven commercially and survive competition with other technologies.

Plated wire and magnetic cores are matured technologies that will undergo little reduction in cost.

Bubble memories are competing with semiconductor CCD memories to replace disc files. This competition and economic motivation will drive the cost down and will make bubble memories cheaper than disc files by the mid 80s.

Optical memories using laser read/write techniques are considered for extremely high-capacity systems (10^{11} to 10^{15} bits of storage). If a practical technology does emerge (after 1985), we can anticipate the cost of such a system in the millions of dollars, which still represents a very low cost in terms of dollars per megabit of memory.

FC 5-14. Reliability of Magnetic and Optical Memories



DISCUSSION

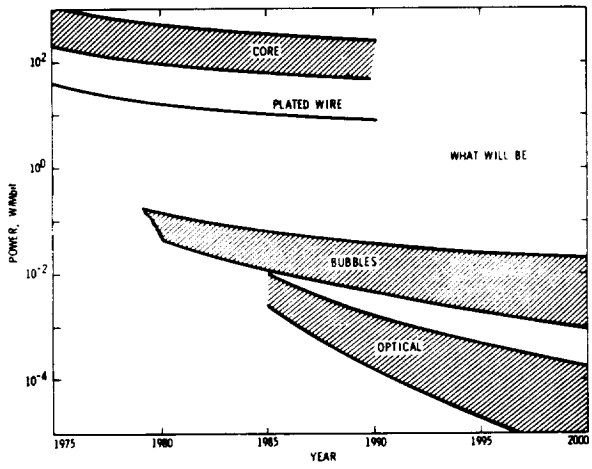
The forecast is "what will be" under the assumption bubbles survive commercial competition with other technologies.

Magnetic cores and plated wire are in themselves reliable components but require high current transistor drivers and interconnects that are the weak links in the system. The reliability shown reflects this limitation, which is not expected to improve significantly.

Magnetic bubbles are still in the development stage with little reliability data available. As bubble technology matures, it can be anticipated, because of the low power involved and the basically stable nature of the magnetic material, that the bubble chips will be very reliable. As in the case of cores, they require semiconductor IC drivers and sensors which limit the system reliability. However in this case, the bubble chips interface efficiently with low-power IC chips, which places the overall system reliability at a level comparable with high-density semiconductors.

Optical memories are too ill-defined to permit any forecasts of reliability.

FC 5-15. Power of Magnetic and Optical Memories



DISCUSSION

The forecasts are "what will be" for a range of device options, under the assumption that these technologies are driven commercially and survive competition with other technologies.

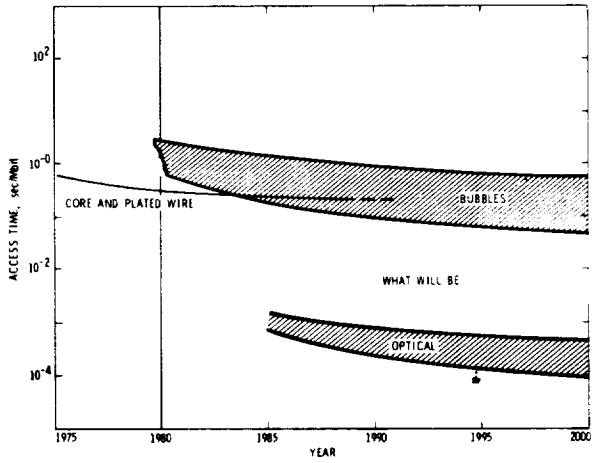
The power requirements for magnetic cores are directly related to their physical size and will not decrease significantly (see density). Depending on how the core memory is organized, a megabit memory will require from 200 watts to 1 kilowatt in the operating mode and from 15 to 100 watts in the standby mode. A three-dimensional organization requires less power but has a slower cycle time (1.5 μsec), and a two dimensional organization requires more power but is faster (0.2 μsec cycle time).

Plated wire will also undergo little improvement. The volume of a plated wire element is much smaller than a core and correspondingly requires less power.

Bubble memories require very little power to shift 10^6 bubbles (about 40 milliwatts) but by the time electronics included for sensing and temperature control, a megabit of memory will require tenths of watts in 1980. Correspondingly less power per megabit is required for larger and more dense memories of the future, where improved interfacing with LSI semiconductor chips can also be expected.

Optical memories with capacities on the order of 10^{12} to 10^{14} bits mean very little power per megabit. The power required for the lasers, sensors, and electronics is shared by this large memory and therefore the power per megabit is very small: on the order of less than 10^{-2} watts.

FC 5-16. Speed of Magnetic and Optical Memories



DISCUSSION

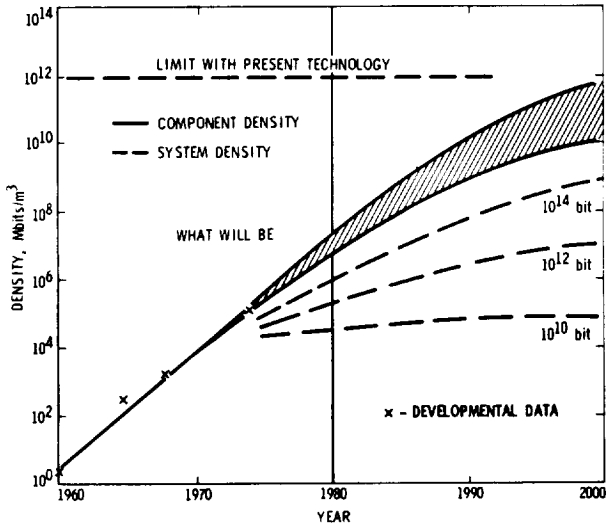
The forecasts are "what will be" for a range of device options, under the assumption that these technologies are driven commercially and survive competition with other technologies.

Read/write times in core and plated wire arrays are of the same magnitude. They are a function of delay times in word drivers, sense amplifiers, and propagation of signals in the array and are not limited by magnetic switching in the elements. Only a small improvement is anticipated by better drive circuitry and IC sensors, and closer spacing within the memory array.

Magnetic bubbles operate as shift registers with shift rates by 1980 on the order of megabits per second. These speeds and their high density make them suitable to fill the memory heirarchy gap existing between cores and disc files. The bubble circuits will probably be shift register loops on the order of 1K bits with access to any one bit in the loop of 1 millisec. No radical improvement in bubble shift rates can be expected beyond this value. However, use of parallel system organization using the above forecasted performance can lead to much shorter access times per megabit than are shown.

Optical systems permit very short access times per megabit because of their organization into large blocks. Since each block may contain a megabit and the access time to a block is on the order of milliseconds, the access time per megabit is very low. As for the case of bubbles and semiconductors, parallel organization can provide still much shorter access times.

FC 5-17. Density of Superconductor Systems



DISCUSSION

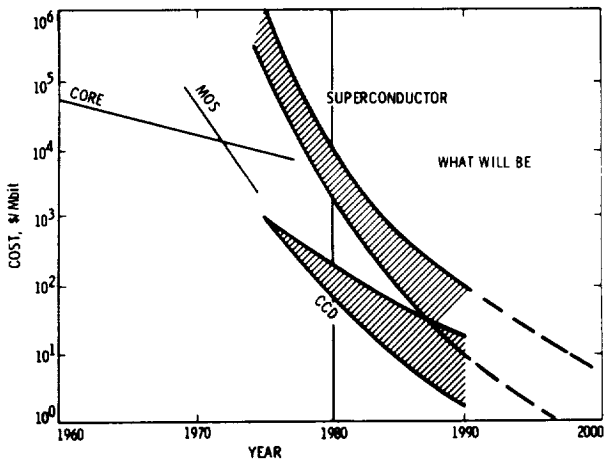
The forecast of superconductive computers is "what will be", under the assumption that this technology is driven commercially and survives competition with other technologies.

The solid curve shows device density, not including interconnections, the dewar necessary for insulation, nor the refrigerator required to provide the cryogenic environment. The dashed curves show system density, including hardware, interconnections, dewar, and refrigerator. These are assumed to total 0.7 m^3 (including hardware inside dewar volume) in 1975, and 0.11 m^3 in 2000. The reduction is due in part to reduction of hardware and dewar size, and in part to reduced refrigerator size. Operation at 4.2°K is assumed in 1975 and at 35°K in 2000. (See discussion under power.) No advance in refrigeration technology beyond presently feasible art is assumed.

It is expected that superconducting device technology will follow semi-conductor technology closely. Single lines of 0.1 μm are now feasible; it is assumed that cells 0.1 x 0.1 μm will be ultimately feasible. Limiting factors are current density and sensitivity to thermal fluctations.

Cells will be fabricated on substrate planes and the planes stacked to form a system. Inter-plane spacing will be determined by need for mechanical support, interconnections, cooling and electromechanical shielding. Superconductors will be substantially better than semi-conductors in the last two parameters. Inter-plane spacing of 0.1 cm is assumed at present and 0.01 at best in 2000.

FC 5-18. Cost of Superconductor Systems

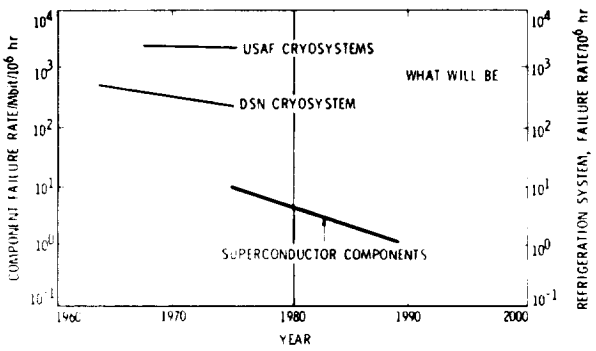


DISCUSSION

The forecast is "what will be", under the assumption that this technology is driven commercially and survives competition with other technologies.

For fully mature technology, superconductor costs are judged to follow CCD costs. Cost estimates are extremely difficult to make, since all superconductor work has been developmental. Costs shown for near term represent high-development investment. For the long term, costs are estimated to be 1/2 to 5 times that of CCD devices. Fabrication costs are estimated to be comparable. External connections will cost more since they must pass through an insulating medium. Refrigeration costs may triple CCD costs for small systems. For large high-performance systems, the greater efficiency of heat transfer may bring cost on a par with CCD systems.

FC 5-19. Reliability of Superconductor Systems



DISCUSSION

The forecast is "what will be", under the assumption that this technology is driven commercially and survives competition with other technologies.

Reliability will depend on two major factors: electronic reliability and cryogenic system reliability.

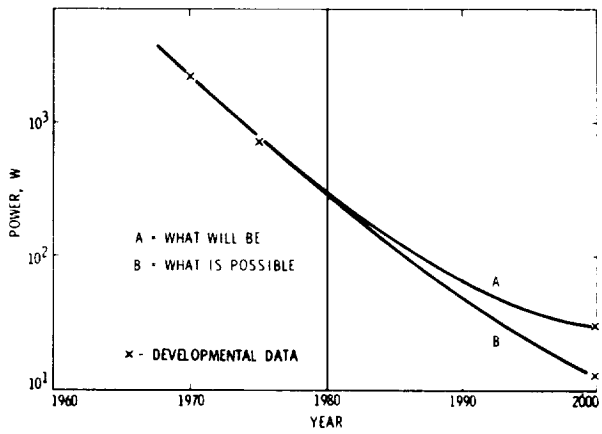
Electronic reliability is assumed to be similar in trend to that of semi-conductor technology. Two factors will modify this: decreased failure rates while at low temperatures since all thermally activated failure mechanisms will be reduced by several orders of magnitude, and increased failure rates due to stresses while thermal cycling, as for repair. On balance, experts in the field feel that low temperature failure rates will be so low that few thermal cycles will be so low that few thermal cycles will be required. Therefore, it is felt that failure rates as low as 0.1 the value of semi-conductors can be expected.

Refrigerator failure rates are much higher. For ground applications this presents no problem. Mean time between failure (MTBF) rates of several thousand hours have been experienced in the Deep Space Network (DSN). With suitable backup, no down time need be suffered. For small, high performance flight systems, however, the USAF reports MTBFs of a few hundred hours. Tradeoffs between light weight and reliability will be required.

For spacecraft operation, the low electronic failure rate at low temperature will favor the super-conductive systems. Most failures could be expected during initial operation and testing. Working systems would probably be kept cold during all subsequent ground handling.

Refrigerator reliability by redundancy of critical parts; e.g., compressors and expanders, may be feasible.

FC 5-20. Power of Superconductor Systems



DISCUSSION

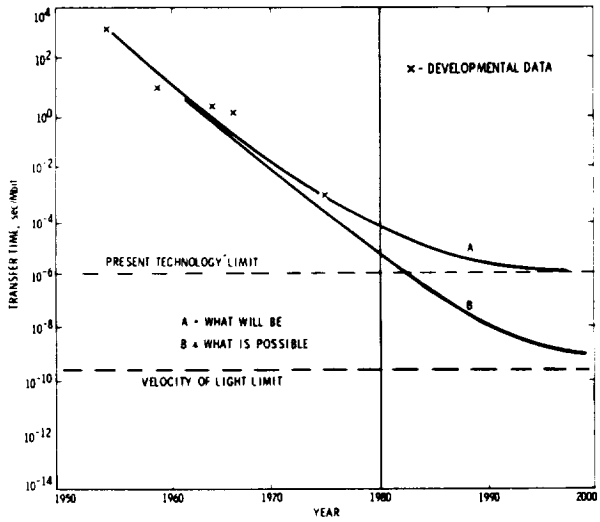
The forecast of "what will be" assumes that this technology is driven commercially and survives competition with other technologies.

The forecast gives the total power, primarily refrigeration power, required to maintain the computer at operating temperature. For typical paramters assumed, power is essentially independent of computer size and speed. Improvement occurs entirely because of development of high-temperature superconductors, leading to reduced refrigeration requirements.

All development of working devices has been on elements operating at 4.2°K (or below). Superconductors with critical temperatures of 23°K are now available and Josephson phenomena have been exhibited at 20°K. It is highly probable that a system operating at 21°K will be feasible by 1990 and at 35°K by 2000, using metallic superconductors. The upper curve shown reflects these values.

A major breakthrough is possible by 2000, in the field of organic superconductors. If so, operation at 77°K would be feasible as shown by the lower curve.

FC 5-21. Speed of Superconductor Systems



DISCUSSION

The forecast of "what will be" assumes that this technology is driven commercially and survives competition with other technologies.

It is assumed that data is transferred serially on a single line and that one data bit is placed on the line in each cycle time.

Transfer time will be highly dependent on system organization, e.g., if a word of N bits is transferred on N lines, time will be reduced by 1/N.

Initial delay time for arrival of first bit is not included; it will be no shorter than transmission line length over the speed of light; i.e., 33 pico sec per cm.

Speed has increased by 7 orders of magnitude in 20 years. Higher speeds will be limited by intercell spacing. We predict intercell spacing of 100 nanometers yielding an ultimate speed of 3×10^{-10} sec/megabit. Workers in the field predict, on the basis of extrapolating present technological limits, speeds on the order of 10^{-6} sec/megabit.

Power density sets a limit on the cycle rate of a single cell. Assuming a cell of 10^{-14} m^2 10^{-20} joules/cell, and a maximum heat transfer to helium of 10^5 watts/m^2, the maximum rate is 10^7 megabits/sec. However, this does not control the data transmission rate, since no one cell will be cycled continuously.

E. SUMMARY

Rapid increases in semiconductor component densities will continue and be accompanied by much lower hardware cost, higher reliability, lower power, and increased speed. These advances are predicted on the basis of established principles and fundamental limits which apply to semiconductor electronic components, coupled with the enormous commercial drive that will continue to exploit these principles. NASA can play a role in stimulating some of these advances during the early phases of development. In particular, emerging technologies such as CCD or MNOS can be more speedily developed into ultra-high density components suitable for mass memories in the 10^8 - 10^9 bit range by the early 1980s.

Magnetic cores and plated wire will continue to be needed for main memories into the 1980s, but will be gradually be replaced by that time with either semiconductor (e.g. CCD or MNOS) or magnetic bubble memories. The predicted performance of bubble memories is similar to CCDs. Consequently, these two technologies compete for a place in the memory hierarchy of computers. An important advantage bubbles have over CCDs is that they are non-volatile, but they suffer by not being a monolithic technology; that is, they require interfacing with semiconductor drivers and sensors.

Optical memories using laser read/write and holographic techniques offer much promise for enormous archival memories in the 10^{11} to 10^{15} bit range. They are still in an early research stage and practical systems cannot be predicted before the late 1980s. Fiber optics for parallel data transfer, in combination with semiconductor arrays and imaging technology, represent an additional possibility for ultra-fast massively parallel computers in the 1980s.

Superconductors offer promise for high-speed, large-capacity computers in the 1980s. Fundamental breakthroughs in superconducting elements have motivated investment by IBM into this technology. The present course of this development is directed toward large Earth-based computers. With the development of practical high-temperature superconductors, anticipated by 1990, the overhead of refrigerator systems will become much less significant and practical space-borne superconducting computers would also appear possible toward the end of this century.

F. PARTICIPANTS

Sincere appreciation is expressed to all who devoted their time and energy in the task of making these forecasts a worthwhile contribution in the Outlook for Space.

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G. INDEX OF MICROFILMED FORECASTS

No additional forecasts are available for Acquiring and Processing Inanimate Matter - Microstructures.

*From JPL, unless otherwise noted.

Section IV. ACQUIRING AND PROCESSING INANIMATE MATTER – MACROSTRUCTURES

R. A. Boundy

A. SCOPE

The word macrostructure is defined here as all the areas typically included under the disciplines of materials and structures. Specifically, the areas of metals, composites, polymers, and ceramics are included under the heading of materials technology, while the areas of advanced concept development, computer-aided analysis and design, vehicle dynamics, and vehicle structural integrity are included under the heading of structures technology. Also the area of space processing of materials is included as a separate category.

As with any undertaking of this magnitude, some overlap and some omissions occur. An example of overlap is the discussion herein of electronic ceramics, which straddles the boundary between the macrostructures and microstructures fields. The minor duplication is justified on the basis of the importance of the subject and the diverse backgrounds of the forecasters (ceramist versus solid-state physicist). An example of an omission is low-temperature effects on metals which is somewhat accommodated by the discussion of cryogens in the section on Storing Matter (Section VI below).

B. ORGANIZATION AND APPROACH

When the field of Acquiring and Processing Inanimate Matter-Macrostructures was defined, an attempt was made to consider all technologies within this field.

The principal drivers of structures and materials technology are the new and advanced vehicles being planned for the future. Once these vehicles are identified, the technology required to make them feasible and economically viable can be defined and predictions made based on the forecast of time needed to provide the required technology.

For the purpose of this forecast, the advanced vehicles were divided into three broad classes: launch and reentry vehicles, conventional spacecraft structures, and large erectable spacecraft structures. Contributors from the appropriate NASA Centers were then asked to identify and predict the technology accomplishments in those areas critical to each vehicle class. In some cases, the technology applied to more than one vehicle class. Consequently, it was felt more appropriate to make the forecasts on technology areas rather than vehicle classes. However, to relate technology forecasts to vehicle classes the matrix shown in Figure 5-2 was developed. This matrix not only indicates what technology is needed for each vehicle but gives an indication of its priority.

Forecasts were made for the materials technologies in areas of metals, composites, polymers, and ceramics. Structures technology areas forecasted were advanced concepts, computer-aided analysis and design, vehicle dynamics, and vehicle structural integrity. In addition, forecasts on space processing of materials are included.

TECHNOLOGY AREA	LAUNCH AND REENTRY VEHICLES	CONVENTIONAL SPACECRAFT STRUCTURES	LARGE ERECTABLE SPACECRAFT STRUCTURES
MATERIALS TECHNOLOGY			
METALS	M	M	L
COMPOSITES	H	M	H
POLYMERS	H	M	M
CERAMICS	H	L	L
STRUCTURES TECHNOLOGY			
ADVANCED CONCEPTS	H	L	H
COMPUTER-AIDED ANALYSIS AND DESIGN	H	L	H
VEHICLE DYNAMICS	H	H	H
VEHICLE STRUCTURAL INTEGRITY	H	H	H

PRIORITIES:

H • HIGH, M • MEDIUM, L • LOW

Figure 5-2. Materials and structures technologies required for future space vehicles

The objectives of the Contributors were to select parameters, to select forecast methods, and to agree on the content of the required forecast and on the schedule. A parameter is defined as a quantitative measure of a functional capability. In most of the following forecasts, the parameters are quantified and displayed as graphs of the particular function plotted against time, including the 1980-2000 time period of interest. In some forecasts, the Contributor believed that a qualitative projection was more appropriate. Therefore, some of the forecasts take the form of narrative projections and are found in the body of this section.

The general forecasting method used was exploratory, in which technology parameters are projected into the future starting from a base of

accumulated knowledge in relevant areas. Most of the specific forecasts that follow can be classified as trend extrapolation (continuation of the past). Where a field is mature (e.g., aluminum alloys), the trend is extrapolated with good confidence of "what will be", usually without a forecast of "what is possible". Where a field is immature (e.g., composites), the trend is extrapolated with reasonable confidence of "what will be," usually with a forecast of "what is possible." In most instances, the accompanying narrative gives the reasons for believing that "what is possible" may occur and states the additional requirements needed for making the "what is possible" forecast occur.

C. FORECASTS

The forecasts which follow are both qualitative and quantitative in nature. A graph or graphs are presented showing either a parameter projected against time or some other pertinent variable. A summary of the most pertinent advancements which have been forecasted and their payoffs for the period 1980-2000 are shown in Table 5-1.

Between 1975 and 1980 some improvements can be anticipated, as shown in the forecasts which follow. However, no significant breakthroughs or obstacles to progress are identified for this interval. Research budgets are currently low, and it is assumed this situation will continue until 1980. Some progress will be made in space processing, but large impact is not expected until the mid-1980s, when large lift capability into Earth orbit should be routine. In short, the 1980 baseline will not be significantly different than now.

1. Materials Technology

The major advances in materials technology for space vehicle applications are summarized in Table 5-1. These advances will be better realized by general support of all basic elements rather than by concentrated efforts devoted to only one material system or concept. The design criteria for components in present and future spacecraft are varied and require efficient use of many classes of materials for high reliability and high structural efficiency. Steady progress in basic research programs as well as appropriate applications programs is the key to future progress in this area.

A recurrent theme for the materials forecasts is the importance of processing and manufacturing technology. In many forecasts, the improvements in processing variables are the key to advances in the material technology. This is especially relevant for the areas of composites and ceramics.

Space processing will provide a manufacturing environment that can result in significant improvements of these variables. While it is very difficult at this time to quantify the role space processing will have on advances in metals technology, ceramics, composites, etc., the impact of such advances is inevitable and where possible has been factored in. The need to consider the processing of materials in attempts to project advances within the field is apparent when one considers that the observed properties are a direct result of the processing technique used.

a. Metals

The use of metallic alloys in spacecraft structures is a mature technology, drawing in part on the history of application of these materials in aircraft structures; thus, they are expected to be the predominant materials in most future spacecraft structures applications.

(1) Light Alloys, Titanium Alloys, and Stainless Steels. The light alloys (aluminum and magnesium) will continue to be the major materials for ambient temperature spacecraft structures and cryogenic tankage for launch and entry vehicles and space vehicles.

In view of the advanced state of their development, potential gains to be made in material properties for light alloys will be small. The predicted advancement in design stress/density and stiffness/density are shown in Forecasts FC 5-22 and FC 5-23.

The "B" curve in FC 5-22 indicates possible advances which can be made if high-strength titanium alloys or high-strength steels are substituted for aluminum alloys. High strength levels are currently feasible in steels and in solution-treated and aged titanium alloys, but the drawbacks of low toughness and relatively poor stress corrosion resistance must be overcome to fully utilize these strength levels in design.

As indicated by the "A" curve in FC 5-23, no significant increase in stifness/density is expected for aluminum, titanium, or high-strength steel. On the other hand, beryllium-aluminum alloys have stiffness/density ratios on the order of 3.5 times that of the other light alloys while beryllium is 6 times greater. The "B" curve in FC 5-23 reflects increasing use of Be-Al alloys and Be to achieve a fourfold increase in the stiffness/density ratio by the year 2000 in stiffness-critical members. This improvement requires processing developments to reduce cost, to realistically treat toxicity considerations, and to maximize toughness in these alloys.

At elevated temperatures in the vicinity of 315°C (600°F), the structural material which would be most likely specified is titanium alloy and for temperatures approaching 540°C (1000°F) stainless steels will be used. Similar to the light metals, only a 5 to 10 percent increase in design strength parameter is forecast for this class of alloys.

(2) Superalloys and Refractory Metals. Metals in this class are candidates for operation in hot structures, radiative thermal protection systems, and power generation components operating from 540°C (1000°F) to over 2200°C (4000°F). Included here are nickel and cobalt base alloys (such as R41, L605, H188), dispersion stabilized alloys (such as TDNi-Cr and TDNi-CrAlY), and alloys of columbium, molybdenum, tantalum, and tungsten. The latter require protective coatings for operation in oxidizing environments at temperatures above about 540°C (1000°F). Chromium alloys have received some development in the past and, while resistant to oxidation, have nitriding problems in air which further embrittle alloys of

Table 5-1. Forecast summary for materials and structures, 1980 -2000

Basic Elements	Expected Advancements	Payoff
Materials	**Metals**	
	Fourfold increase in stiffness/density with beryllium, beryllium-aluminum	Significantly lighter stiffness-controlled space structures
	Superalloys and refractory metals with 1200°C (2200°F) use temperature	Efficient space radiators and reusable metallic heat shields
	Composites	
	Fibrous-epoxy materials with long-term stability in space environment	Predictable, reusable material
	Fibrous-polyimide IPPQ or metal matrix materials for 315-540°C (600-1000°F) use temperature	Cost-effective, lightweight entry structures
	Polymers	
	Ultrahigh modulus polymer fibers	Inexpensive, tough, processable replacement for graphite
	Fire-resistant high-temperature polymers	Space vehicle safety
	Threefold increase in adhesive toughness, strength, and durability	Low-cost space structure
	Electro-optical polymeric memories	Exponential increase in information storage density
	Ceramics	
	Twofold increase in strength	Reusable entry insulation and engine structure
Structures	**Advanced Concepts**	
	Composite structures for launch/reentry/synchronous orbit vehicles	30% to 50% savings in structural weight
	Composite structures for thermal expansion control of wave reflectors, transmitters, or absorbers	Two orders-of-magnitude gain in passive thermal distortion control of antennas, reflectors
	Ultra-lightweight composite space panel structure	Stiffer, cost-effective space structures
	Large erectable space structures	Major breakthrough in antenna/reflector/solar array cost, performance for earth observation, power or space platform missions
	Thermal structures for advanced entry vehicles	25% weight reduction in advanced space transportation systems
	Computer-Aided Analysis/Design Methods	
	Automated vehicle design process	Faster, lower-cost vehicle design cycles
	Remote technical communications between government/contractor/subcontractor	More reliable, better-evaluated designs
	U.S. preeminence in design software systems	Large national/international market
	Vehicle Dynamics	
	Active controls on launch/reentry vehicles	50% gust load alleviation
	Payload dynamic response prediction and test capability	Simpler, cost-effective paylod qualification cycle
	Accurate definition of flight loads	Substantial yearly cost reduction
	Vehicle Structural Integrity	
	Capability to predict flaw growth rates and identify critical structural areas	Predict reusability and necessary refurbishment for spacecraft
	Advanced space tankage technology	Reliable, reusable tanks
	Advanced material and component nondestructive evaluation techniques	Quality control and more efficient use of structural test data
Space Processing	Order-of-magnitude improvement in the homogeneity of semiconducting materials	Breakthroughs in "chip" circuitry, laser, and infrared detector technologies
	Orders-of-magnitude improvement in purity of processing	Production of materials with unique mechanical or electrical properties
	Containerless contact-free processing and positioning using electromagnetic/acoustic fields	Ultrasmooth, pure, nonnucleated materials of controlled shapes

marginal ductility. Most common design criteria for superalloys and refractory metals put a premium on creep strength, resistance to embrittlement during service, and oxidation resistance in attempts to increase maximum use temperatures.

Superalloys and dispersion-stabilized alloy technology development is currently used primarily by the turbine engine community. Maximum use temperatures for space vehicle structural applications are projected to rise from about 980°C (1800°F) today to about 1200°C (2200°F) by the year 2000.

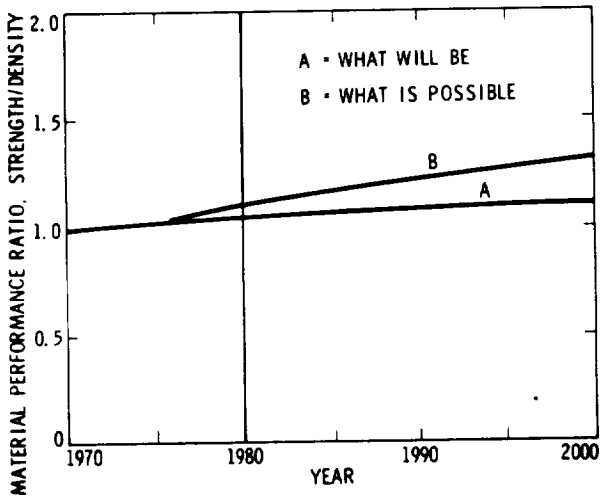
Refractory metal alloys with adequate strength for proposed space applications at very high temperatures have been available for more than a decade. For applications in thermal protection systems the performance and reliability of the oxidation-resistant coatings have been the primary concern. However, in ground simulation tests at maximum temperatures to 1320°C (2400°F), full-size, coated, columbium heat shields have demonstrated Space Shuttle reusability to be feasible for as many as 50 entry missions.

b. Composites

Utilization of fiber-reinforced composite materials in space structures will increase significantly during the remainder of this century. Operational feasibility of some spacecraft, launch and reentry vehicles contemplated for 1980-2000 will be enabled by the availability of materials which will permit lower structural mass fraction designs, will provide higher specific stiffness than conventional metallic alloys, and will provide the capability to build structures with zero (10^{-8} cm/cm °K) coefficients of thermal expansion. Raising the maximum use temperature for resin-matrix composites to 315-540°C (600-1000°F) and metal-matrix composites to perhaps as high as 1090°C (2000°F) will also broaden the types of structural applications. Major advancements in manufacturing technology, which will make composite structures economically competitive with conventional metals, will further stimulate interest in composites.

Major deterrents to widespread application of composite structural materials have been high costs and lack of knowledge on the long-term durability when subjected to moisture, thermal cycling, and ultraviolet exposure. Insufficient nondestructive test and inspection methods have also hindered their acceptance. These deterrents will be eliminated by comprehensive research and technology application programs in both aeronautics and space. Research and development during the remainder of this century is expected to focus on technology which will make composites economically competitive with metals and have equal or better reliability than metals. Commercial introduction of pitch-base graphite fibers, development of thin-gage fabrics, and development of standard materials specifications are expected to be major contributions to reduced costs. Baseline room-temperature mechanical properties, strength and stiffness, are not expected to change significantly. However, advancements which are expected include: epoxy-matrices with improved resistance to moisture degradation and micro-cracking; maximum use temperatures in the range of 315-540°C (600-1000°F) for resin-matrix composites and perhaps up to 1090°C (2000°F) for metal-matrix composites. State-of-the-art for polyimide-matrix composites will mature sufficiently in the next 5 years to permit applications to 315°C (600°F) or slightly higher for moderate exposure periods and 370°C (700°F) and even higher temperatures for short durations. Other resin matrices such as the polyphenyl quinoxaline (PPQ) family could contribute to this capability. Further refinements in aluminum-matrix composites could increase their maximum use temperature to 315°C (600°F) for moderate exposure periods and perhaps to 425°C (800°F) for short durations. Development of superalloy-matrix materials could increase the use temperature to the 1090°C (2000°F) range. Other materials developments which could influence the growth of applications are maturing of graphite/aluminum composites and aluminum-oxide fibers. New manufacturing and nondestructive inspection methods will also play a major role. Forecasts of Use Temperatures for composites in the temperature ranges 0 to 800°C and 800 to 1800°C are shown in FC 5-24 and FC 5-25, respectively.

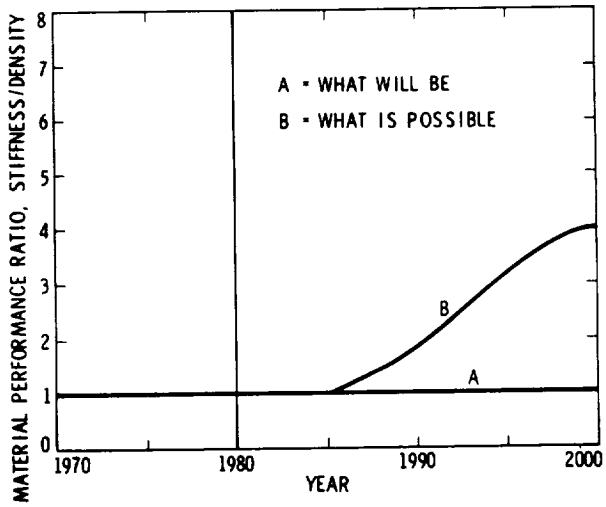
FC 5-22. Strength/Density of Light Alloys



DISCUSSION

Potential gains to be made in material properties for light alloys will be small in view of the advanced state of their development. Current spacecraft structures for cryogenic and ambient temperatures are fabricated primarily from 2000-, 6000-, and 7000-series aluminum alloys. Some use is also made of magnesium alloys and titanium alloys. The beryllium or beryllium-aluminum alloys may be considered where high stiffness requirements exists. For the foreseeable future, the light alloys will continue to be the major materials for ambient temperature spacecraft structures and cryogenic tankage for launch and entry vehicles and space vehicles. The B curve in this forecast indicates possible advances which can be made if high-strength titanium alloys or high-strength steels are substituted for aluminum alloys. High-strength levels are currently feasible in steels and in solution-treated and aged titanium alloys; but the drawbacks of low toughness and poor stress corrosion resistance must be overcome by substantial investment in materials and process development to utilize this strength level in design.

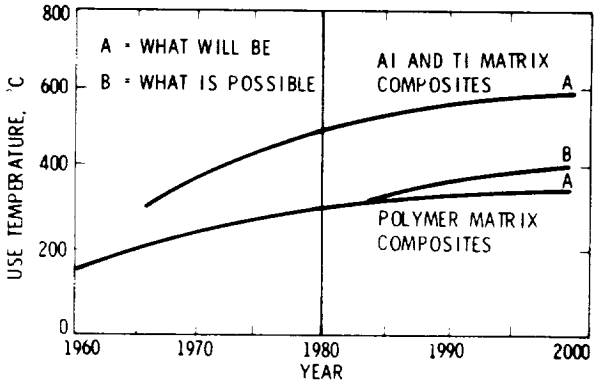
FC 5-23. Stiffness/Density of Light Alloys



DISCUSSION

No significant increase is expected for aluminum, titanium, or high-strength steel. Beryllium-aluminum alloys have stiffness/density ratios on the order of 3.5 times that of the other light alloys, while beryllium is 6 times greater. The B curve reflects increasing use of Be-Al alloys and Be to achieve a fourfold increase in the stiffness/weight ratio by the year 2000 in stiffness-critical members. The improvement requires processing developments to reduce cost, to treat toxicity considerations realistically, and to maximize toughness in these alloys. The possible gains to be made in this area rival those achievable with filamentary composites, while retaining the manufacturing and joining technology of metals.

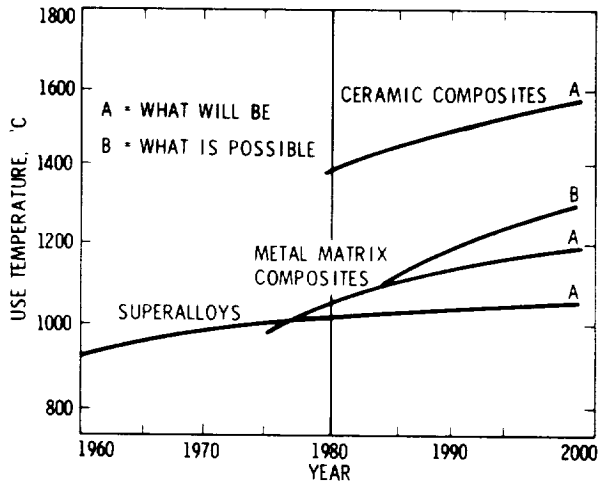
FC 5-24. Use Temperatures for Composites, 0-800° C Range



DISCUSSION

This set of curves, as well as the higher temperature set which follows, forecasts the upper temperature limit for high-performance components. The life expectancy for structural applications would be 30,000 hours, based on 1000-hour life tests at 138 MN/m^2. The limitation on use temperature for the composite materials is the polymer and the aluminum matrices. The titanium composite is also matrix limited but not by strength as much as ductility and oxidation protection. The fiber properties to achieve the increase shown are within current capability; the composite technology requires development. The complex combination of stress and temperature transients that can be encountered could restrict the temperature for some of the materials. For space applications, it is assumed that long-time, relatively constant conditions would be the norm. If transient conditions are to be imposed, thermal fatigue could cause reduction of allowable design limits.

FC 5-25. Use Temperatures for Composites, 800° C - 1800° C Range



DISCUSSION

These use temperature curves are based on 1000-hour tests at 138 MN/m^2. The metal matrix composites include directionally solidified eutectics and superalloy matrix composites reinforced with refractory wire, silicon carbide, or alumina filaments. The A curve represents the oxidizing condition limitation of upper temperature. The composites would have superalloy matrices. The B curve could be achieved if nonoxidizing environments were present, which space conditions may provide. The ceramic composite curve is based on improving the toughness or impact resistance of ceramics. The curve can represent what will be for stationary hardware and what is possible for rotating component applications. Graphite fibers in a suitable oxidation-protecting matrix will compete with ceramic composites at temperatures approaching 1650°C. An example of a current development is the carbon/carbon composite under consideration for the leading edge of the Space Shuttle wing. All the brittle fiber composites, including the ceramic matrix, the refractory metal matrix, and, to a lesser extent, the brittle fiber superalloy matrix composites are predicated on the development of fracture-tolerant designs. These are of current interest for ceramic development.

c. Polymers. Many macro and micro events can be characterized by a sigmoid or S-shaped curve. This is true of the development of a bacterial colony as well as material developments such as the discovery and introduction of high-density polyethylene. In a sigmoid behavior, there is a long period of induction followed by a rapid rise in the rate of occurrence which eventually slows and asymptotically approaches a limiting value.

In considering future projections of polymer properties, volume of sales, long-term applications, etc., one should first attempt to determine where on the S-curve the specific property is currently best situated. This is an extremely uncertain activity and is, of course, subject to even larger uncertainties due to unexpected major events in the future.

In speculating about the future properties and behavior of polymers, this forecast has tried to indicate: (1) the approximate past historical development of the specific property under discussion; (2) a semiquantitative indication of that property in 25 years; and (3) the ultimate value of the specific property under discussion.

There is a human tendency on the part of many designers to regard new classes of materials as substitutes or replacements for established classes of materials. Polymers are a case in point. When designers regard polymers (and polymer matrix composites) as another material class and not as a metal replacement, then space applications for polymers will very likely increase. The rate of that increase will depend on our ability to exploit the unique properties of polymeric materials to their fullest.

(1) Fibers. Great progress has been made since 1950 in the improvement in the properties of organic polymer fibers. In particular, the elastic modulus of organic fibers has increased from 3.5×10^3 (500,000 psi) in 1950 to over 1.4×10^5 MN/m^2 (20,000,000 psi) in 1970. Further increases in this property are likely to continue through this century. This progress is dependent on at least two major parameters: (1) the chemical structure of the repeat unit and (2) the sophisticated processing and orientation of highly crystalline fibers with controlled morphology. The ultimate in the modulus could approach that of the graphite fibers; e.g., 3.5×10^5 to 6×10^5 MN/m^2 (50 to 90 million psi) as shown in FC 5-26, the forecast graph for polymer modulus. Glass-like organic fibers such as Kevlar (PRD-49) will be useful for their high specific modulus as reinforcing materials with improved toughness and processing properties over those of the graphite or glass fibers. They will also have an improved compatibility at the interface with the resin matrix. The displacement of graphite or glass fibers by organic polymer fibers depends to some extent on improvements in interlaminar-fiber sheer strength and compressive strength.

(2) Films and Coatings. Polymer film specific strength (strength/unit mass or area) meets the requirements of very large space structures. In addition, these films reinforced with chopped Kevlar filaments or woven Kevlar will see broad application in future large space structures. However, for widespread use in space, their resistance to outgassing, to ultraviolet radiation and to high-energy particulate radiation found inside the Van Allen belts must be substantially improved.

These properties are especially important for thermal control coatings which require prolonged resistance to changes in optical properties. Metallized FEP Teflon and experimental coatings now being developed will satisfy the coating requirements for Earth orbital missions below the Van Allen belts through the year 2000. The only thermal control "coating" possessing relatively good stability to the high energy particulate and ultraviolet radiation in the Van Allen belts is the expensive and heavy silvered quartz mirror which is used currently on all synchronous orbit spacecraft. Since the degradation mechanisms for combined solar ultraviolet and particulate radiation on transparent polymeric films are not well defined, it is doubtful that polymers can be designed to be resistant to this environment prior to 1990 without substantial support. The same is true of coatings for future near-Sun missions, e.g., Venus lander and Mercury orbiter. These will require advanced thermal control coatings capable of 500°K operating temperature with low outgassing and resistance to high fluxes of ultraviolet and solar wind plasma radiation.

(3) High Temperature Polymers. As we approach the 500 to 700°C range, carbon-carbon bonds begin to rupture, and in the presence of oxygen further reactions begin to take place which lead to destruction of the useful properties of organic polymers. Even with a multiple bond structure in the backbone, as in ladder or step-ladder polymers, it is very doubtful that the long-term use of organic polymers will be improved much over current levels of 250-300°C for 20,000 hours. During the next few decades, more effort will be spent to develop and control the chemistry and improve the processability of those potentially outstanding classes of polymers already in existence.

In looking at currently available polymers, few if any commercially available polymers have been shown to meet these conditions successfully. Price and volume are again strong factors which could change the picture. Polyimides, polybenzimidazoles, and polyquinoxalines are the three most likely classes of polymers that will be in use 25 years from now for such high-temperature space applications as composite-matrix materials, thermally stable electrical insulation (particularly in and around radiation shields, as all of these polymers have excellent radiation stability), and fire-resistant fibers and coatings.

The increasing concern for human health and safety will stimulate the production and use, during the next 25 years, of fire-resistant polymers having minimum smoke and vapor generation. Such polymers will be obtained by changing the basic molecular structure to a more stable form and by adding chemicals which retard flame spread and smoke generation.

(4) Adhesives. Improvement in the properties of adhesives has been rapid since 1950. Lap shear strength has probably doubled and

could triple over current values during the next 25 years as shown in FC 5-27. In addition, it is theoretically possible to increase the index, α (toughness, strength, durability), by an order of magnitude over that obtainable in 1975. The Earth-side use of adhesives and sealants has been one of our more rapidly expanding markets, and this commercial success has motivated further research in certain sectors. The use of adhesives and sealants at elevated temperatures still remains a problem, but one which technically can be overcome by the year 2000 with appropriate support.

Maximum application of adhesive bonding to the joining of space structures could pay significant dividends in terms of weight reduction and, to a lesser degree, of assembly cost reduction. During the next decades, pressure-sensitive, smooth-curing adhesives will be developed with high levels of toughness not presently achievable without the use of undesirable volatile components. In certain applications, adhesives which have unique stability to ultraviolet and particulate radiation and high vacuum must be discovered and developed.

(5) Structural Foams. The large-scale use of structural polymer foams is just beginning to develop. It is estimated that over 10,000 tons of structural foams were used, in the world, in 1974; and it is projected that over 200,000 tons of structural polymer foams will be produced by 1980. With this large-scale development will come increased opportunities for these materials to be used in space in the next 25 years. Replacement of certain zinc and aluminum parts is one area in which polymer foams are showing growth. With increased use, marked improvements in processing are expected. Also, better control of properties are expected to extend current ability to produce foams with a designed spectrum of properties in a single unit, and with a tough outer skin integrally bonded to low-density cores. Current values of flexure strengths for acrylic foams are:

Density, kg/m^3 (lbm/ft^3)	Flex Strength, N/m^2 (psi)
30 (1.87)	8.8×10^4 (128)
50 (3.12)	18.6×10^4 (270)
70 (4.37)	29.4×10^4 (427)

Projections indicate foam strength to go up by two to four times for given densities.

(6) Electro-Optical Polymers. Polymers with active semiconductive and photoconductive properties are now just emerging as significant growth factors in the commercial markets. The present examples include doped semiconducting polymers, such as the polyvinylcarbazoles, now used in commercial electrostatic copiers as a competitive replacement for the selenium coating used on the original electrostatic copier. During the next 25 years, the largest computer and copier corporations will vigorously expand their current aggressive R&D programs to develop solid electro-optical polymers which can be used as recording blocks with no moving parts, these electro-optical polymers will have memory storage and resolution capacities equal or better than those existing in current tape recorders.

In macromolecular synthesis, long-chain polymers will be made which can store information in electrical, magnetic, or optical sites at discrete points in functional groups of atoms along the chain. Such memory sites are likely to see commercial production within the next 25 years. When developed, they will possess long-term stability and foster the exponential increase in information storage density which has been so successful in solid-state inorganic elements and compounds, e.g., Si, Ge, and GaAs.

Processing flexibility and ease of formation will permit unusual shapes and thicknesses which probably will result in as yet unrealized devices using new electro-optical polymers.

(7) Superconducting Polymers. Much speculation has been directed toward synthesis of the theoretically possible polymers with superconducting properties at room temperature. To date, these materials have not been made, and the several theories are in conflict with each other. As a far-out projection, it may be possible by the early part of the next century that these room-temperature superconducting polymers could be emerging as realities from the polymer laboratories. Their use as energy converters, memory devices, etc., boggles the imagination.

d. Ceramics. Ceramics are generally defined as nonmetallic, inorganic materials that are the result of man's processing, rather than natural occurrences. These materials find a wide spectrum of applications, generally involving their ability to provide unique combinations of properties. Ceramic materials considered here will be those employed for structural and electronic applications.

(1) Structural Ceramics. The need to consider the processing of ceramics, in attempts to project advances within the field, is apparent when one considers that the observed properties of ceramics (any material in reality) are a direct result of the processing technique used. All materials exhibit behavior based on past history. Consequently, new elements or new compounds of technological importance are unlikely; rather, those which have existed for many years will exhibit new properties, find new applications, or become available at lower cost as a result of improved processing techniques.

In contrast to the many properties of ceramic materials whose particular value can be related to processing, other properties stem primarily from the nature of interatomic forces. For example, the prediction of a high-strength filament with an elastic modulus greater than 10^6 MN/m^2 (150 million psi) (approximately that of diamond) is unacceptable, since the prediction of new, presently unknown, high-strength bonds has no basis. However, when a property value exists for known materials but is unavailable to be used, perhaps for reason of cost, then predictions involving

accessibility of known properties are reasonable. Thus, filaments having moduli approaching that of diamond are possible, perhaps even likely, depending upon the demand placed on the materials' developer and the resources allocated to him.

Structural ceramics are primarily used to satisfy unique combinations of property requirements, at least one of which is adequate strength. In most real applications, ceramic materials normally fail by crack propagation, which is generally related to preexisting flaws (often at the surface). This conclusion has been reached as a result of considerable research efforts through the past decade to evaluate the potential for producing ductile ceramics. In general, results have been negative; little real progress has been made toward general improvements in ductility. It is generally accepted that brittleness is an inherent property of ceramic materials and that significant increases in ductility will not be observed in the future. Consequently, improvements in mechanical strength to be expected should be based on improvements in the following factors, all consistent with brittle behavior: (1) processing, (2) surface preparation, (3) flaw detection, and (4) predictability of performance.

The brittle fracture of ceramics frequently involves the extension of preexisting surface flaws, and thus the surface is exceedingly important to mechanical behavior. The importance stems both from the high probability of damage to the exposed surface, along with the high probability of maximum stress levels occurring at the surface. However, it must be emphasized that methods of improved surface preparation, while general in concept, usually require specific technological development consistent with the materials, application, and environment at hand. Such development is frequently costly and difficult to justify.

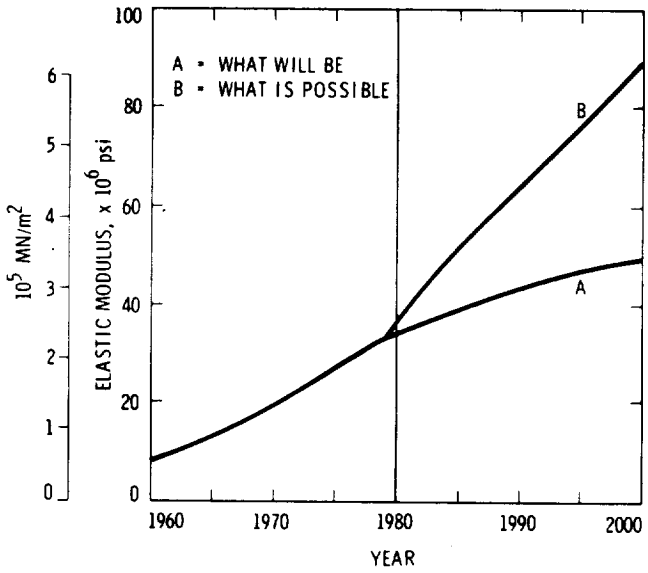
Concentrating then on polycrystalline ceramics for structural applications, which are normally produced by sintering powders under appropriate conditions, the projected improvements in strength at a high confidence level are large, based on slow but continuous improvement of such processing. This processing includes better control of microstructure, such as grain size, grain orientation, and pore structure through research and developments in sintering and related ceramic processing procedures. Major improvements have been made in recent years in the production of dense, homogeneous, structural ceramics by the control of purity and by the use of grain growth inhibiters and sintering aids. These developments have been the result of considerable fundamental research on sintering in ceramics and the technological demands for improved ceramic materials in such applications as high-intensity lamps, ceramic substrates, and gas turbine components. Continued activity as a result of continued technological demands can be projected to make available most any structural ceramic in dense and homogeneous forms. The graph in FC 5-28 shows the forecast for the strength of polycrystalline ceramics for the next 25 years.

(2) Electronic Ceramics. Within the time frame of this projection, great demands are anticipated to be placed on ceramic technology for new and better materials in the area of electronic ceramics. For example, information processing is anticipated to strive for greater speed, smaller size, wider range of environmental operation, and lower cost. Communications systems are anticipated to demand lower cost, higher information density, and greater reliability. In addition, many transducer applications will expand. The details of projected requirements for these and many other applications should be sought in the Outlook for Space main report. It is projected here only that demands for such materials will be great and highly specialized and that substantial developmental support will be forthcoming.

The size of crystals available for specific applications, in general, does not exhibit any fundamental limitations. It is anticipated that any crystal capable of being grown on a millimeter scale today can be made available upon demand with dimensions of a significant fraction of a meter. Major limitations are cost, energy, and time; and breakthroughs significantly reducing these limitations are not apparent. Control of the internal structure of crystals for electronic applications will probably represent the area of major improvement in the following decades.

In almost all cases, improvements in ceramic technology as a result of space research will rely on improved, or novel, processing. For example, optical and electronic crystals and glasses will be made available with compositions heretofore unobtainable because processing can occur in space without a supporting container. In other cases, unusual microstructures, such as homogeneous froths or foams or compositional variations in materials, will be available. Space research is anticipated to make important advances in the understanding and applications of nucleation and crystallization in ceramic technology. Important new products will undoubtedly become available through the elimination of heterogeneous nucleation from melt as a result of contact with a container. The ability to understand and use such crystallization techniques should greatly enhance the availability of directional solidified eutectics, single crystals of complex composition, and other complex crystallized structures of more than one constituent.

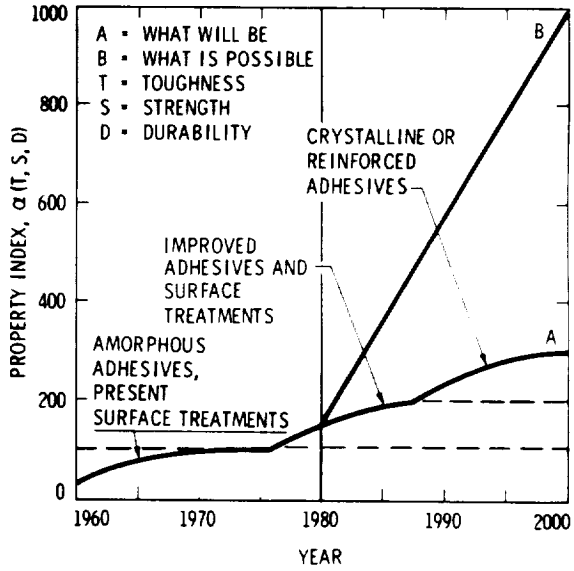
FC 5-26. Polymer Fiber Modulus



DISCUSSION

Great progress has been made since 1950 in the improvement in the properties of organic polymer fibers. In particular, the modulus of organic fibers has increased from 3.5×10^3 MN/m^2 (500,000 psi) in 1950 to over 1.4×10^5 MN/m^2 (20,000,000 psi) in 1970. Further increases in this property are likely to continue through this century. This progress is dependent on at least two major parameters: (1) the chemical structure of the repeat unit and (2) the sophisticated processing and orientation of highly crystalline fibers with controlled morphology. The ultimate in the modulus could approach that of the graphite fibers; e.g., 3.5×10^5 to 6×10^5 MN/m^2 (50 to 90 million psi). Glass-like organic fibers such as Kevlar (PRD-49) will be useful for their high specific modulus as reinforcing materials with improved toughness and processing properties over those of the graphite or glass fibers. The displacement of graphite or glass fibers in their respective applications by organic polymer fibers depends to some extent on improvements to certain auxiliary polymer fiber properties, including interlaminar fiber shear strength and compressive strength.

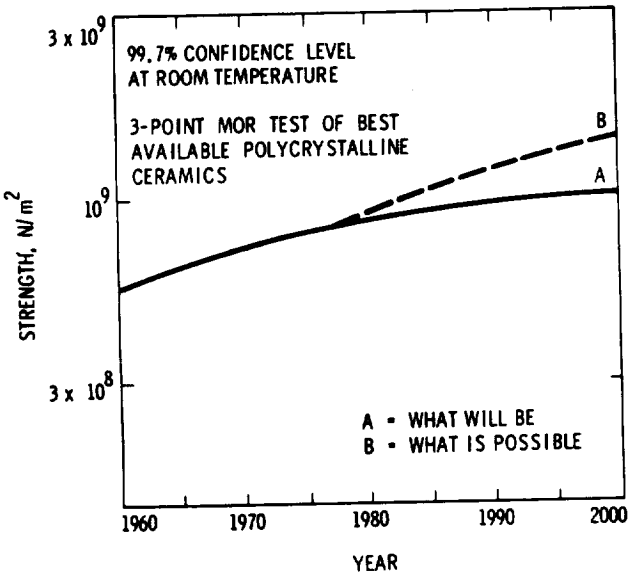
FC 5-27. Adhesive Advances



DISCUSSION

The property index, α, is used here as a figure of merit for adhesives, with a value of 100 for the year 1975 as a bench mark. The index consists of toughness (T), strength (S), and durability (D), which are representative of peel strength, lap shear strength, and long-term aging, respectively. The A curve shows a factor of three increase from 1975, based on expected achievement of presently conceived program goals with expected funding support. On the other hand, the B curve indicates what is possible (a factor of ten improvement in α) if new ideas are vigorously pursued based on a $30-$40M program over the next 25 years.

FC 5-28. Strength of Polycrystalline Ceramics



DISCUSSION

It is generally accepted that brittleness is an inherent property of ceramic materials and that significant increases in ductility will not be observed in the future. Consequently, improvements in mechanical strength to be expected should be based on improvements in the following factors, all consistent with brittle behavior: (1) processing, (2) surface preparation, (3) flaw detection, (4) predictability of performance. The projected improvements in strength at a high confidence level of polycrystalline ceramics are large, based on slow but continuous improvement of such processing. This processing includes better control of microstructure, such as grain size, grain orientation, and pore structure through research and developments in sintering and related ceramic processing procedures. Major improvements have been made in recent years in the production of dense, homogeneous, structural ceramics by the control of purity and by the use of grain growth inhibiters and sintering aids. Continued activity as a result of continued technological demands can be projected to make available most any structural ceramic in dense and homogeneous forms.

2. Structures Technology

a. Advanced Concepts. The advanced concepts to be discussed here include composites, large erectable space structures, and thermal reentry structures.

(1) Composites. Composite structural concepts are expected to play a major role in the development of weight-critical space systems. Structural weight reduction forecasts for space systems are shown in FC 5-29. For future launch vehicles, the emphasis on low system development costs may make secondary structures (control surfaces, struts, etc.) the only feasible structural application of composites. However, if future launch systems are desired for orbiting larger payloads, it is anticipated that the composite structures will prove to be cost-effective. For the present family of Space Shuttle systems, it is projected that a series of composite structural component retrofits will be made to the orbiter and tankage system to improve performance characteristics. Thermal structural concepts will be of great interest in reentry vehicles. Because of directional expansion characteristics, composite thermal structural design will be difficult; however, composite structural concepts conceived to alleviate vehicle thermal stress problems are likely to emerge.

For space vehicles, composite concepts will emerge in three areas: high energy vehicles; thermal expansion control; and minimum-gage, stiffness controlled designs. For high-energy vehicles such as space tugs, synchronous Earth satellites, and planetary spacecraft, premium prices will be paid for modest weight reductions to inject higher weight payloads, so that graphite composite structures will be cost-effective. Projected activity in synchronous orbit associated with communications and LANDSAT-type programs suggest a large demand for composite structures for weight savings. For thermal expansion control, unique composite concepts using thermal-expansion-compensating structural configurations, thermally inert laminate configurations, and clever mechanical joint designs will be employed. The potential for passive thermal expansion control is shown in FC 5-30, where an order-of-magnitude change in coefficient of expansion appears achievable. Low coefficient of expansion will permit precise control in wave reflecting transmitting or absorbing devices (e.g., solar reflectors, antennas or telescopes). For minimum gage, stiffness-controlled structure, composite structural concepts will offer new design dimensions to circumvent weight problems. A specific example of lightweight space panel structure being investigated at LaRC is illustrated in Fig. 5-3. Open, graphite/sandwich truss work

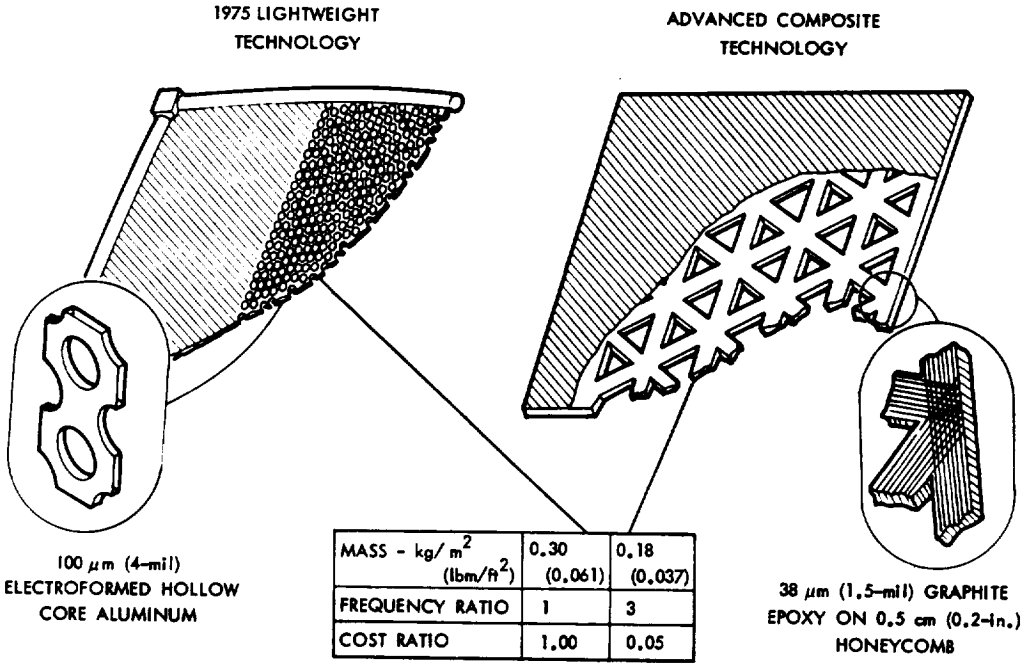


Figure 5-3. Example of advances in lightweight composite structures

is found to be significantly stiffer and less expensive than the lightest metal structure. Other more advanced concepts, such as load-path tailoring exploiting the variable elastic properties of laminates or innovative uses of curvature or spin-stabilization, could offer order of magnitude gains in structural efficiency. However, radically new concepts must overcome the handicap of long lead times.

(2) Large Erectable Space Structures. A novel structural concept, which will provide great potential for new space capability in the 1980-2000 time period, is large erectable space structures. In the early 1980's man and/or man-operated devices will be able to construct structures in space, orders of magnitude larger than possible today. Unlike launch and reentry vehicles and conventional spacecraft, where the technology is relatively mature, large erectable spacecraft provide a new dimension in structures where innovative and advanced concepts can produce gains measured in order of magnitude rather than percentages.

Deployable structures that can be launched in a packaged condition and expanded in space have been a necessary part of space flight since its conception. Most of the past applications of these structures fall into two broad categories: solar arrays and antennas. Currently, the largest solar cell array flown is the Skylab array which is 10 meters in length. The largest antenna in space is the ATS-6 which is 10 meters in diameter.

As indicated in a recent survey (Ref. 5-41), there are many possible space applications for large erectable structures in the future. As in the past, the structural requirements for the majority of applications are either large antennas or large relatively flat surfaces. A complete new technology needs to be developed for such structures so that they can be delivered into space, unpacked, assembled, and maintained with the required precision and orientation, shape, thermal stability, and rigidity. Some of these structures will be in the several kilometer size range, and in many cases their surfaces will have to be shape controlled to the centimeter or millimeter range. Examples of the need for such structures in the future catalog of space activities include very large microwave antennas, microwave reflectors, solar arrays, radiators, solar sails, and telescopes. In addition to structural integrity and shape control, the dynamic interactions involved in the pointing control of such structures are unprecedented.

One of the principal technology drivers will be the antenna. Large high-frequency antennas are needed for a variety of applications, including deep space communications, multibeam communication satellites, Earth and space observations, and power transmission to either Earth or other spacecraft. It is important to note that as the frequency requirement of an antenna increases, the requirement for accurately shaped surfaces increases proportionally. Thus, increasing the frequency requirement from 1 to 10 GHz necessitates an improvement in antenna configuration of one order of magnitude.

The forecast for erectable antenna structures is shown in FC 5-31. The major thrust will be both to increase the size of the antenna to approximately 100 meters and to develop the technology (both active and passive) to maintain surface geometry for high-frequency antenna capabilities. An antenna 100 meters in diameter capable of operating at a minimum frequency of 10 to 20 GHz is envisioned. This diameter antenna would provide the capability of performing the majority of the desired communications and Earth observation tasks. It would represent one order of magnitude increase over today's capability, thus permitting more reliable extrapolation to larger erectable structures. Finally, it is felt that this size represents the largest antenna structure that has a possibility of being packaged and transported by one Shuttle trip.

Less accurate antennas up to 1 km in diameter are possible. These very large structures would require multiple Shuttle launches or advanced launch vehicles capability as well as new concepts in structures and dynamics design and analysis. Such very large structures must be either assembled in space from modules (e.g., erectable 100-m units) or fabricated and assembled in space from elements (e.g., trusses, tubes, and fittings) transported to space.

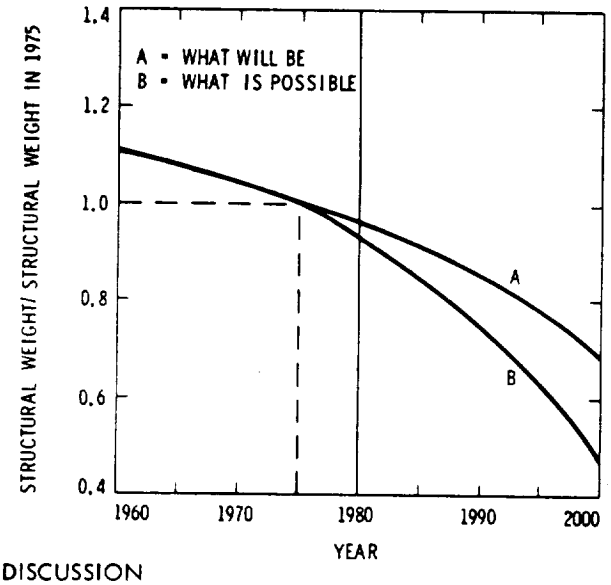
Very large planar structures such as solar array substrates require less accurate surfaces than most antennas. Sizes on the order of 10-50 square km are possible and indeed will be required if the solar power station becomes a reality. These extremely large structures would also be assembled in space either from erectable modules or from structural elements fabricated into modules in space.

To accomplish these predictions, major thrusts in several technology areas are necessary. Because of the requirements for larger structures that will inherently be flexible, the structure design will become stiffness-limited rather than strength-limited. There will be a need for unique structural configurations to improve stiffness characteristics.

New and advanced ultralight concepts will be developed that can be efficiently packaged into the Shuttle, erected in space, and accurately oriented to the desired direction. Using the most current technology available, the most optimistic projection of the packaged size of a 100-m antenna is that it would take 3 Shuttle flights to place it in orbit. The new concepts, along with newly developed packaging techniques, will permit an increase in packaging density of large structures by a factor of 3 or more.

Automatic deployment will be replaced by the efficient use of man and/or manned operated devices for assembly. This will eliminate the use of complex deployment devices and, hence, permit simplification of concept design. Modularity will be an important consideration in the final choice of concept design of these large structures. Not only is modularity important for ease of construction and erection but it also permits easy repairability, thus increasing service life.

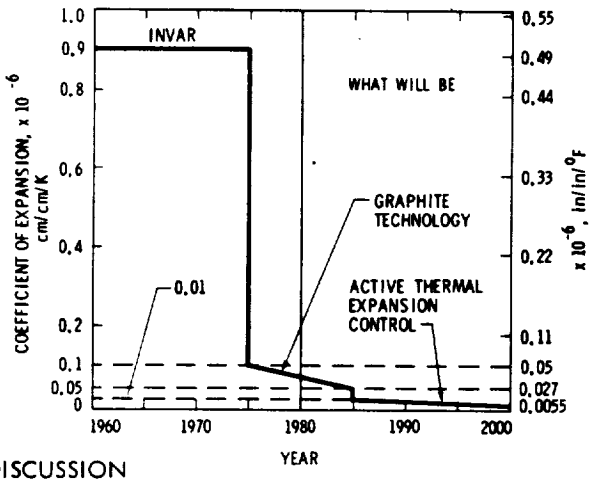
FC 5-29. Structural Weight Reduction for Space Systems



DISCUSSION

The A curve, showing a 30% reduction in structural weight by the year 2000, is based on the use of composites and structural concepts which will evolve naturally. The 50% reduction in structural weight shown in the B curve depends not only on the full utilization of the unique properties of composites, but also on development of structural concepts using new and different structural analysis and design techniques.

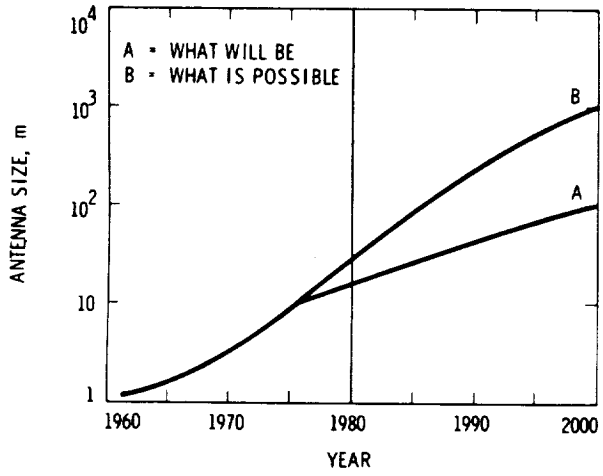
FC 5-30. Thermal Expansion Control Capability



DISCUSSION

For thermal expansion control, unique composite concepts using thermal-expansion-compensating structural configurations, thermally inert laminate configurations and clever mechanical joint designs will be employed. The potential for passive thermal expansion control is shown in the figure, where an order of magnitude change in coefficient of expansion appears achievable. Such control will permit precise control in wave reflecting, transmitting, or absorbing devices (e.g., solar reflectors, antennas, or telescopes). No differentiation is made between "what will be" and "what is possible" because the absolute values for coefficient of thermal expansion are very small numbers.

FC 5-31. Erectable Antenna Structures



DISCUSSION

The major thrust in large erectable antenna structures will be both to increase the size of the antenna to approximately 100 meters and to develop the technology (both active and passive) to maintain surface geometry for high-frequency antenna capabilities. An antenna 100 meters in diameter, capable of operating at a minimum frequency of 10 to 20 GHz, is envisioned. This diameter antenna would provide the capability of performing the majority of the desired communications and Earth observation tasks. It would represent one order of magnitude increase over today's capability, thus permitting more reliable extrapolation to larger erectable structures. Finally, it is felt that this size represents the largest antenna structure that has a possibility of being packaged and transported by one Shuttle trip. Antennas with less surface accuracy and diameters on the order of 1 km are possible, as shown in curve B. These very large structures would require multiple Shuttle or advanced launch vehicle capability and would be either assembled in space from modules (e.g., erectable 100-meter units) or fabricated and assembled in space from elements transported to space (e.g., trusses, tubes, and fittings).

The large erectable space structure will be appreciably stiffer for its size than today's structure, and new control concepts will be needed. The increase in structural size by one order of magnitude will create stiffness and control problems that must be solved. In conventional spacecraft, the control frequencies are designed about one order of magnitude below the frequency of the structure. The increase in size of the large erectable structure reduces the structural frequency to an extent that this criterion is difficult if not impossible to meet. Thus new control system concepts will be developed to permit control frequencies of the same order as structural frequencies (see FC 5-41).

A potentially useful structural concept for space applications in the future is the inflated structure. Although some limited applications have been made in the past (e.g., the Echo satellites), future applications may include large manned spacecraft as well as inflated cylindrical structural elements for assembly into space trusses.

The need for these new classes of space structures (very large, lightweight, and flexible) will introduce some new problems and will emphasize some old ones. Dynamic interactions between structures and attitude control systems may produce severe problems requiring new approaches for solution. Geometric non linearities associated with large deflections may become important in both the structural and attitude control analyses.

(3) Thermal Reentry Structures. As utilization of space becomes routine and "colonization" a viable goal, space transportation systems will become fully reusable, have longer life, lower operating cost, and greater operational flexibility than the current Shuttle system. There will be a 25% reduction in structural weight over current state-of-the-art technology. To achieve this goal new structural concepts will be developed and advanced materials used.

These new concepts will be developed to minimize the thermal load. Among the concepts considered will be Earth entry vehicles two to three times the size of the current Shuttle orbiter. These concepts will be configured to have very low planform loading during entry, thereby having surface radiation equilibrium temperatures well within the use temperatures of current superalloy materials. With reduced thermal loads, primary structure can become external surface and obviate the need for some, or all, of the thermal protection systems and their parasitic weight. Unique thermal/structural design techniques and optimization schemes, using both mechanical and thermal loads as design variables, will be used to identify the most efficient concepts which accommodate thermal growth without induced stresses. A case in point is the use of curved elements to form beaded panel construction. This type of construction has demonstrated a 25% reduction in weight over conventional concepts at ambient temperature. Presumably similar improved efficiency will be subsequently verified at elevated temperatures. Further weight reduction will be achieved through the use of advanced high temperature composite materials.

b. Computer-Aided Methods of Analysis and Design. Growth of the application of computers in aerospace vehicle analysis and design is characterized in FC 5-32. Application of computers during the past 20 years has revolutionized the task of structural analysis so that, today, analysts handle complete vehicles in considerable detail. However, the amount of data generated in computer analyses is so great as to make interpretation and communication among the various disciplines difficult and complex.

Emphasis in the future must be placed on exploitation of the computer in the integration, management, and communication aspects of the vehicle design process, rather than on technical calculation tasks alone. This emphasis will lead to dramatic growth in computer application from the preliminary structure design process (sizing and arranging) to the total vehicle design process (pure analysis). The acquisition of early sizing information will lead to much improved structural mass information early in the design process. This in turn can result in substantial reductions in gross takeoff mass and thereby cost of aerospace vehicles, if escalating effects of resizing the total vehicle can be exploited. Reduction in product cost can accrue by increasing the speed and accuracy of the design process and by delivering a higher quality design to manufacturing, thereby reducing the number of design changes during fabrication and, in turn, reducing expensive redesign, retooling, and rework activities.

However, experience indicates that as the cost per unit analysis decreases, the depth of analysis increases to effectively balance the ratio so that the design cost is not greatly affected. Only the sophistication of the design is increased. Forewarned is forearmed.

As computer-aided design technology becomes a reality for design of alternate vehicle configurations, it is anticipated that new methods of concept selection and engineering design development will occur. Future projections suggest that data bases for components will be stored and accessed by computer terminals heavily assisted by computer graphics. Management and generation of drawings will be automated and computer-aided manufacturing programs will be generated at the end of the final design cycle. Remote national and international communications between government technical people, industry contractors, and subcontractors will be feasible.

Although preliminary costs of developing such design systems appear large, recent computer development suggests that such systems will be cost-effective by the late 1980s for preliminary design. It is projected that design costs and major design errors will be minimized by providing far greater depth of design much earlier in the vehicle design cycle. It is possible that the government will revise the submission-selection process for advanced vehicle designs by requiring proposers to submit computer representations of proposed designs rather than drawings or design sketches. Improved techniques for analysis and computation will permit far more rational organization and evaluation of design efforts, will promote interdisciplinary design

communication, drastically reduce the dollar/manpower/time outlays required for design of new configurations, and help maximize the return from strength, vibration, and fatigue testing. It is forecasted that the U.S. will obtain a preeminence in this technology and that considerable technology spinoff will occur into other than the aerospace sector.

c. Vehicle Dynamics. Most of the launch vehicle and reentry vehicles projected to the year 2000 are not expected to have any unique structural dynamic design considerations which are not already being examined for the Shuttle system. For vehicles which are expected to reenter the Earth's atmosphere and have aircraft-like performance requirements, it is anticipated that the dynamic response of large masses of fluid, flying horizontally, will lead to advanced liquid baffling techniques. In addition, during launch and entry, it is likely that the maturity of aeronautical load alleviation techniques using active controls will find applications on advanced launch systems. The potential here is to reduce structural bending moments by up to 50% under severe gust loading conditions. For the large complex launch systems, it is also anticipated that advanced interdisciplinary design and test techniques for in-depth analyses of "POGO" (longitudinal engine-induced oscillation) stability will be feasible.

For space vehicles, three major technology thrusts appear likely. The first thrust is the reduction of space payload qualification costs. Techniques will be developed to define dynamic loads and deflections of payloads without recourse to complex reanalysis of the complete coupled payload-launch vehicle. These conservative design techniques will be used by a large family of low-cost payload developers, while the more complex (but probably lighter weight) payload qualification route will be reserved for larger weight-critical systems. A dynamic-acoustic simulation facility capable of providing a qualification "ride" to candidate shuttle payloads is also a likely technical achievement to help reduce costs for potential users.

A second thrust is more accurate definition of space payload flight loads. Imprecise knowledge of the payload-launch vehicle dynamic environment can cause wide variations in the specified qualification loading levels (expressed as the power spectral density). For example, the Apollo Service Module levels were initially unconservative whereas Mariner levels were an order of magnitude too high. The inaccuracies in such specifications lead to large costs associated with meeting artifically high qualification levels or large costs associated with redesign efforts to adjust unconservative designs. It is expected that simulation efforts using real-time data obtained on early vehicle flights will eliminate such large load uncertainties. It is estimated that total space system costs could be reduced by six million dollars per year assuming Shuttle launched mass-to-orbit reaches 1968 levels.

A third space vehicle dynamics technology thrust is the development of payload isolation techniques which will attenuate dynamic loads and possibly acoustic noise loads. These isolation techniques may be either active or passive and will benefit from emerging crash safety and active controls technology being pursued in aeronautics research.

d. Vehicle Structural Integrity. As in other disciplines (particularly electronics) space structures will have demanding requirements for reliability. The quality and level of structural analysis capability will be improved and substantiated by test. This advance will be particularly important for composite structures where unusual modes of failure occur, and where high local stresses must be accounted for to prohibit premature brittle failures.

For reusable space structures, technology to predict the life of critical structural components after extended space operation will be developed. The understanding of flaw behavior and slow crack growth in both metal and composite structures will provide meaningful methods of proof testing and life projection. On-board life monitoring systems will be employed for critical elements. Structural system analysis models will be developed in which successive failure or deterioration can be studied to determine appropriate failure times and monitoring points in which to refurbish reusable structure.

Because large space-tankage generally will be one of the most critical flight safety items, fracture studies in lightweight metal or composite tanks will be emphasized. Basic technology needs include development of elastic-plastic failure criteria to predict conditions under which leakage and fracture failures will occur; standardization of fracture/crack propagation test methods for tough thin gage materials; and enlargement of data banks. Criteria for rejection or acceptance of flight hardware specified for long-time operation will be reexamined carefully. Because of their potential efficiency as well as reliability, serious efforts to develop reliable composite tanks will continue. Improved fabrication techniques for forming and joining thin liners to penetration fittings will be developed, as well as refined design concepts to minimize local strain concentrations and use of higher modulus fibers to minimize liner cycling effects.

To enhance vehicle reliability, significant advances in the state of the art of nondestructive evaluation will be made. Improvements in flaw detection are expected to provide a major improvement in the reliability of high-strength materials. Flaws controlling fracture are frequently in the size range of 1 mm or less, and present technology has not been adequate to resolve them reliably. Techniques being evolved, employing interference analysis of shortwave-length energy waves, such as high-frequency acoustics and eventually X-rays, coupled with extensive computer analysis of the data generated, should permit reliable nondestructive testing (NDT) definition of structural materials. Such improvements are predicated on a steady, long-term commitment to NDT development. Field measurements techniques rather than readouts of data-at-a-point will be employed to check large components. Advanced inspection systems will be developed by exploiting candidate test techniques such as acoustic and pulsed holography, infrared thermography with image enhancement, acoustic emissions, microwave scanning, fiber optics combined with low-light-level TV, and neutron radiography. Dynamic test techniques

using more automated data reduction techniques, programmed multishaker controls, and variable random/sine/impulse forcing functions will provide considerably more information per unit of test time for large vehicles. General technology thrust in the structural test area will be to obtain more depth of data on strength, stiffness, and dynamic behavior at both micro and macro levels.

3. Space Processing

To utilize fully the space environment for processing of materials, the unique environment which is not available on Earth must be characterized. The major factors involved are the weightlessness and extremely high vacuum with an "infinite" pumping capacity. Processing materials in extreme high vacuum (10^{-14} torr) opens up the possibility of producing materials with impurity content several orders of magnitude lower than the purest materials presently obtainable.

The most obvious effect of the zero-g environment is manifested on a macroscale by the lack of need to support a liquid (or solid) object. Any relative motion in fluids due to differences in density is precluded. The characteristics of liquids and fluids are determined by their intermolecular forces. Gravity-induced convection due to thermal gradients imposed on the liquid is also eliminated.

The absence of buoyancy results in the stability of liquid-gas mixtures in spite of density differences. As a result, terrestrial processes which may be markedly improved by space processing include:

(1) Metal matrix and polymer matrix composites, including improved properties and, more uniquely, production of the object directly in the shape of the final product.
(2) Dispersion-stabilized alloys produced by casting and with very fine grain sizes.
(3) Production of metal and alloy foams.
(4) Extended solubility and new alloys from immiscible liquids.
(5) Controlled- or reduced-density materials as self-supported shapes and coatings.

Convection applies to the internal motion caused by the combined effects of gravity and density differences produced by thermal gradient. Gravity-induced convection is of substantial magnitude, so that in the absence of gravity-induced convection internal motion is reduced to a minimum. This internal motion is of prime concern in solidification processes for two reasons:

(1) Motion enhances nucleation and is therefore undesirable in all processes of crystallization control such as growth of single crystals or whiskers, directional solidification, or suppressed crystallization.
(2) Convective currents may induce imperfections during crystal growth, such as dislocations, and impair the properties of the end product.

The history of materials development specially for solid-state physics-oriented applications (semiconductors, superconductors, etc.) has taught us the highly sensitive dependence of physical properties on very small quantities of impurities and the associated impurity-imperfection pairs. New materials and industries have emerged in the past 20 years from the development of high-purity materials. In such an environment, we are combining one or more of the following: (1) extreme purification of a melt, (2) formation of deposits or crystals from the vapor phase without contamination, and (3) the high perfection in crystal growth processes.

a. Homogenized Electronic Materials. The electronic and optical properties of materials like germanium and silicon are well known. Significant improvements in the gross aspects of the homogeneity of semiconductors have been observed on Skylab (microstructural defects in germanium were reduced almost an order of magnitude), and more detailed experiments are required. The forecast for improvements in space processing homogeneity is shown in FC 5-33. The sensitivity of the magnetoresistance to inhomogeneities is well known, and a variety of tools is available to assess bulk property variations.

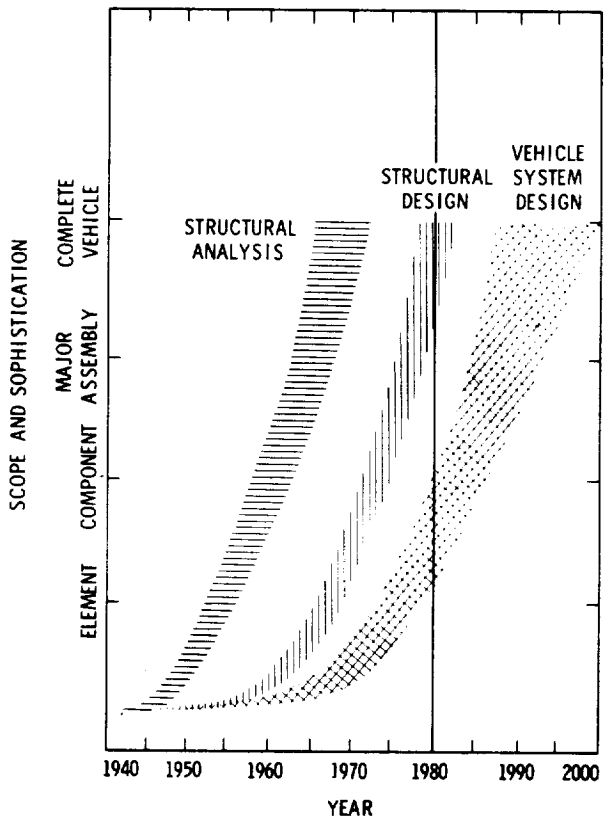
Integrated circuits could be significantly improved in reliability and reduced in size even below present miniaturized versions if the basic semiconducting "chip" were homogeneously doped with the proper impurity. Defects on a microscopic level, such as local concentrations or depletions of impurity atoms caused by gravity-induced convection at the solidification interface, cause inoperative elements of the circuit and usually discard of the entire chip. If alternate areas on the chip can be used, increased size is required. Similarly, repairs add cost and overall size increases.

As more materials become available, bond structure studies by cyclotron resonance may be enhanced because of improved homogeneity. Indeed, for small-band gaps materials like Hg-Cd-Te and Pb-Sn-Te, this technique of zero-g regrowth may be essential for obtaining the homogeneity required for far infrared detectors and lasers. The behavior of metals that are essentially free of micro-precipitates would also be of considerable interest.

There are now approximately fifteen locations in the United States where highly sophisticated materials are prepared. Much of our recent advance in communication, instrumentation, and computer technology has been based on improved semiconducting materials developed at these facilities. New standards which could be most useful for these facilities, could be created by space manufacture of these materials and such articles could serve as models for future manufacturing.

b. Purification. In the terrestrial environment, the processes of melting, zone refining, and evaporation followed by condensation from the vapor phase, singly or in sequence, are used to produce high-purity materials as single crystals or polycrystalline aggregates. The purity level of the material after processing is the resultant of the purifying and contaminating reactions it

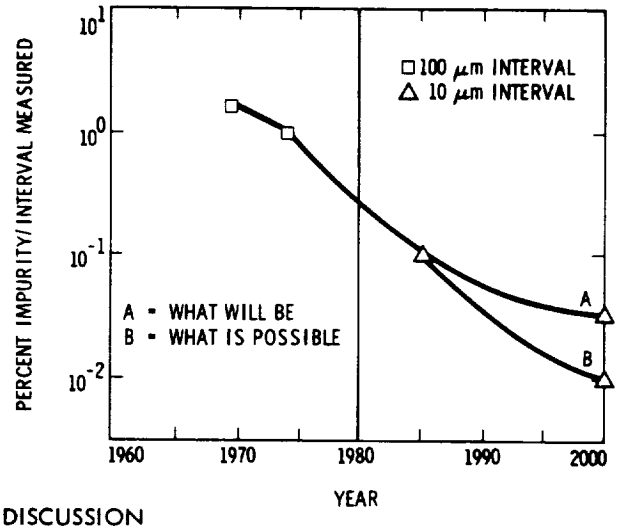
FC 5-32. Growth of Computer Aided Methods in Space Vehicle Design



DISCUSSION

The growth of automation in vehicle design, past and futur is shown above. It traces the automation of structural analysis from elements to complete vehicle capability, the emergence of automated structural design and its development to a mature technology, and the prospect of automated vehicle design growing rapidly from the embryonic systems now being used. The past 20 years brought about a revolution in structural analysis through computerization. From the vantage point of 1985 or 1990, we will see that a similar revolution will have occurred in vehicle design.

FC 5-33. Space Processing Homogeneity Improvement



DISCUSSION

Homogeneity refers to the uniform distribution of "impurity" atoms in semiconducting materials. Measurement of small quantities of impurity atoms over small spacial intervals is an important processing parameter. Significant improvements in the gross aspects of the homogeneity of semiconductors have been observed on Skylab (microstructural defects in germanium were reduced almost an order of magnitude), and more detailed experiments are required. Integrated circuits could be reduced significantly in size even below present miniaturized versions if the basic semiconducting "chip" were homogeneously doped with the proper impurity. Defects on a microscopic level, such as local concentrations or depletions of impurity atoms caused by gravity-induced convection at the solidification interface, cause inoperative elements of the circuit and usually discard of the entire chip. If alternate areas on the chip can be used, increased size is required. Similarly, repairs add cost and overall size increases. As more materials become available, bond structure studies by cyclotron resonance may be enhanced because of improved homogeneity. Indeed, for small-band gap materials like Hg-Cd-Te and Pb-Sn-Te, this technique of zero-g regrowth may be essential for obtaining the homogeneity required for far infrared detectors and lasers. The behavior of metals that are essentially free of micro-precipitates would also be of considerable interest.

undergoes. It is possible to go through the steps of purifying beryllium down to 10^{-2} ppb atomic, which is purity orders of magnitude higher than achieved to date. One can easily conjecture the production of the following:

(1) Large perfect diamonds and other crystals epitaxially grown on clean surface without contamination.
(2) Bulk materials of very high strength, approaching theoretical strength values since one can remove impurities and the associated impurity imperfection combinations to very low levels.
(3) Materials with very high corrosion resistance.
(4) Materials with unique electrical properties. For example, in very perfect high-purity conductors, can the superconducting transition temperature be raised by a significant amount?
(5) Materials with unique magnetic properties.
(6) Materials with greatly enhanced catalytic activity.

To accomplish these objectives in the near future, containerless processing and positioning techniques must be perfected. Electromagnetic and acoustic fields have been developed to the point where their usefulness has been clearly demonstrated. The next step is to control the shape and configuration of the "levitated" mass.

Due to surface tension, the natural shape of a nonspinning liquid specimen in a zero-g environment is a sphere. Of interest is the reverse of sphere formation, i.e., the deformation of the liquid sphere into a specific shape by means of noncontacting force fields such as electromagnetic or acoustic fields. The merits of contact-free forming are not only the absence of material contamination and nucleation sites but also the possibility of high surface smoothness. Nonspherical bodies of rotation can be produced by spinning the liquid specimen (inertial forces); but most contactless forming will require special shaping of the confining force field, e.g., a very intense short-wave-length standing acoustical wave to produce flat sheets or ribbons.

D. SUMMARY

The field of macrostructures encompasses the traditional disciplines of materials and structures. For these forecasts of technologies for the period 1980-2000, the specific elements addressed were (1) materials technology, which included metals, composites, polymers, and ceramics; (2) structures technology, which included advanced concepts, computer-aided analysis and design methods, vehicle dynamics, and vehicle structural integrity; and (3) space processing with emphasis on homogeneity and purity of materials.

Figure 5-2 is a matrix of technologies required for future space vehicles. It gives an overview of the relative importance of each discipline to achieving the technology in the areas of (1) launch and reentry, (2) conventional spacecraft structures, and (3) large erectable spacecraft structure.

The forecasts of advancements in materials and structures are summarized in Table 5-1. For materials these include (1) a fourfold increase in stiffness/density with beryllium or beryllium aluminum alloys; (2) superalloys and refractory metals with 1200°C (2200°F) use temperature; (3) composites with long-term stability in the space environment; (4) fibrous-polyimide or metal matrix composites for 315-540°C (600-1000°F) use; (5) ultra-high modulus polymer fibers, approaching 6.2×10^5 MN/m^2 (90 million psi); (6) fire-resistant high-temperature polymers; and (7) a twofold increase in strength of ceramics.

For structures, these advances include (1) composite structures with 30% to 50% weight savings; (2) composite structures with two orders of magnitude improvement in thermal distortion control; (3) major breakthroughs in large erectable space structures for antennas, reflectors, and solar arrays; (4) automated vehicle design processes; (5) U.S. preeminence in design software systems; (6) active controls on launch-reentry vehicles with 50% greater load alleviation; (7) improved payload dynamic response prediction and test capability; (8) capability to predict flaw growth rates and identify critical structural areas.

For space processing, these advances include (1) order of magnitude improvement in the homogeneity of semiconducting materials; (2) several orders of magnitude improvement in purity; (3) ultra-smooth, pure nonnucleated materials of controlled shapes; and (4) single crystals with dimensions a significant fraction of a meter.

A recurring theme from these forecasts is the importance of large erectable structures to implement the requirements of future space activities. These structures include large antennas of the order of 100 m in diameter with accurate surfaces and even larger planar structures. If collecting solar power in space and beaming it back to Earth is to become a reality, then extremely large structures on the order of 1 km in diameter for microwave antennas and 10-50 square km for solar array substrates will be required. These structures will be assembled in space either from modules such as erectable 100-m units or from structural elements such as trusses, tubes, and fittings.

Another recurring theme is the importance of processing, both on Earth and in space, to the realization of many of the advances projected. Another is the role of composites, both polymer and metal matrix, to achieving significant gains in efficient use of materials in structural applications.

The technology for processing materials and fabricating complex structures in Earth orbit will be a reality in the 1980-2000 time frame. Furthermore, by the year 2000, the basic technology in this field to accomplish many of the requirements for the very large structures needed for orbiting space colonies will be available.

It is assumed that a more likely area of space colonization is the Moon. The basic technologies represented in this section will be sufficiently mature to support various Lunar operations. These include mineral recovery, oxygen extraction, base construction from imported and naturally occurring materials, and construction of a Lunar observatory. The limitation to accomplishing these goals is the national/international willingness to commit to such an effort.

E. PARTICIPANTS

Special thanks go to E. Kruszewski as a contributor and for coordinating the major contributions made by the Langley Research Center to this section. Thanks are also due to the several organizations and individuals who made constructive critiques of early drafts, including I. Hedrick, RTAC Committee on Materials and Structures; H. Siegel, RTAC Committee on Materials and Structures; and P.G. Ackerman, AIAA Technical Committee on Space Systems.

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F. INDEX OF MICROFILMED FORECASTS

The following forecasts, concerning the acquisition and processing of inanimate matter - macrostructures, are available at the Jet Propulsion Laboratory. This information may be retrieved by calling Mr. George Mitchell at (213) 354-5090 and giving the document number (1060-42) and the volume number (Vol. V) followed by the correct page reference numbers as listed below:

	Title	Page No. (1060-42), Vol. V)
1.	Ceramics	5-55 - 5-72
2.	Metals and Composites	5-73 - 5-81
3.	Polymers	5-82 - 5-88
4.	Structures	5-89 - 5-93
5.	Space Processing	5-94 - 5-99

*From JPL, unless otherwise noted.

Section V. TRANSFERRING MATTER

K. M. Dawson and N. R. Haynes

A. SCOPE

The Transferring of Matter field involves the ability to translate the center of mass of an object from one location to another and to maintain stability and orientation control about this center of mass. Of primary concern is the accuracy with which this translation and orientation control can be accomplished. The energy required to move the object from one location to another or maintain stability is addressed in the Management of Energy part of this report (Part Four). The broadest scope of the Transferring of Matter field would include moving any matter from one point of the universe to any other point and controlling the orientation of matter during the transfer. From a practical, space-activity-oriented point-of-view, the scope of the field has been reduced to include only the movement of space vehicles in our solar system, through atmospheres and on planetary surfaces. This reduction of scope is not felt to be unduly restrictive for the 1980 to 2000 period.

B. BACKGROUND

In providing this translation, stability and orientation control for space vehicles, a large number of relatively independent technologies are required. These include sensors (gyros, optical trackers and scanners, accelerometers, ground station receivers and antennas, etc.), actuators (momentum wheels, thrusters, magnetic torquers, etc.), processing electronics (both on-board and ground computers for analysis and control), target body statistics (target ephemeridies, size, shape, etc.), and such operational considerations as round-trip light time. All of these technologies come together with numerous analytical tools to provide an overall capability for translation, stability, and orientation control. The conventional titles used for these spacecraft-related capabilities are Guidance, Navigation, Stabilization, and Control.

In selecting primary parameters that would be projected in this study, it was concluded that the numerous technology items described above would not provide the most useful information for mission designers. The most useful primary parameters were, in fact, the overall functional-element-level capabilities that result when the independent technology items are combined. Mission designers need to know how accurately a space vehicle can be delivered, how accurately an instrument can be pointed, or how well the location of a roving vehicle can be determined, etc. They are generally not interested in how accurately a gyro or star tracker can be built. It was with this in mind that the Translation of Matter Committee approached the selection of primary parameters.

It should be noted that in developing these primary parameters some target-related statistics have been incorporated into the results. Thus, some projections are "target dependent" and the Transferring of Matter capabilities at one target are not necessarily the same as at another target. This is not expected to be a problem, since these target-dependent parameters are clearly identified in the forecasts.

C. ORGANIZATION AND APPROACH

1. Committee Organization

A Transferring of Matter Committee was established which consisted of representatives from JPL and five NASA Centers: Ames, Goddard, Johnson, Langley, and Marshall. Each committee member was selected on the basis of his unique skills and background in some element of Transferring of Matter. The range of expertise covered all anticipated mission classes during the 1980 to 2000 period.

The purpose of the committee was to:

(1) Select the primary parameters that were to be projected.

(2) Aid in generating the forecasts. (Committee members either generated the forecasts themselves or acted as contacts with specialists in their organizations who performed the forecasts.)

(3) Review the final forecasts for accuracy, consistency, and completeness.

2. Parameter Selection

In selecting primary parameters, the committee reviewed the broad general mission types that NASA could undertake. These included flybys, atmospheric probes, landers, orbiters, rendezvous, planetary rovers, and space stations for various bodies in the solar system. As mentioned earlier, classes of missions outside the solar system were not considered since those were felt to be extremely unlikely in the 1980-2000 time period. From these classes of missions, primary parameters related to transferring of matter were generated.

The specific primary parameters that were developed are described and discussed below in the forecasts (subsection D). In selecting these parameters numerous discussions were held both within the committee and with outside consultants. Although other parameter choices were possible, the ones projected were felt to provide the major pieces of data needed by mission designers in studying future project candidates.

3. Forecasting Techniques

In general, a form of trend extrapolation was used in developing the forecasts. If specific examples of current technology and/or demonstrated past capability were available, these were used as starting data points. If certain technology innovations were known to be moving toward application, these were also shown in the projections at appropriate times. And, if certain physical laws were ultimately limiting the improvement of the parameters, these were to be included by the forecaster. Beyond these guidelines, the forecasters were directed to use their best judgments, based on their knowledge and experience in the field.

D. FORECASTS

1. Background, Present Status, and Forecast of 1980 Improvement

The technologies related to transferring matter (i.e., guidance, navigation, stabilization, and control) are relatively mature and in most cases have been well developed. Space vehicles have been accurately delivered to Mercury, Venus, Mars, Jupiter, and the Moon. Landings have been accomplished on the Moon and Mars and atmospheric probes sent into Venus. Both manned and unmanned roving vehicles have gone to the Moon. In addition, sophisticated manned and unmanned Earth orbiting stations have been established. By 1980, Saturn will have been reached and at least one more payload will have been set down on Mars.

The net result of these past and projected achievements is a significant transferring of matter capability.

By 1980, transferring of matter technology will permit:

(1) The flyby of any object in the Solar System with sufficient accuracy to provide reasonably useful scientific data.

(2) Landing stationary vehicles on the Moon, Venus, Mars (including Phobos and Deimos), and Mercury, and landing roving vehicles on the Moon and Mars.

(3) Delivering atmospheric entry probes into Venus, Jupiter, Saturn, Uranus, and appropriate satellites of Jupiter and Saturn.

(4) Orbiting any planet.

(5) Returning samples from the Moon, Mars, and Mercury.

(6) Controlling and stabilizing large, manned and unmanned, stations in Earth orbit.

(7) Flying "drag-free" spacecraft that compensate for non-gravitational forces.

This is not to imply that significant engineering challenges do not exist, or that technical capabilities are adequate to achieve great enough scientific returns to justify the costs for some of the missions, but it means that, starting in 1980, the nation could decide to perform missions in some form with the knowledge that guidance, navigation, stabilization, and control capabilities would be adequate. The continuing research and development in these areas is expected to improve technology and reduce costs so that more missions become cost-effective.

2. Selected Forecasts

The forecasts (shown on the following pages) that emerged from the parameter selection process are listed below:

(1) Delivery Accuracy for Flyby Targets in the Solar System.

(2) Location Accuracy of Planetary Orbiters.

(3) Entry and Landing Accuracy for Atmospheric Landers and Probes and Communication Time for Outer Planet Probes.

(4) Vehicle Rendezvous/Docking with Man-made Craft.

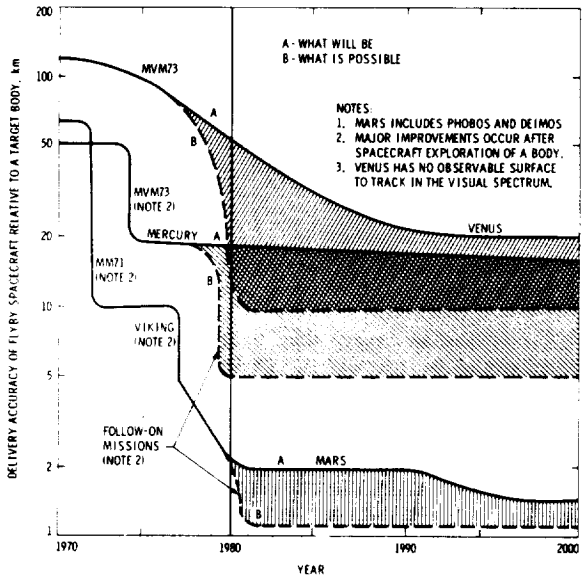
(5) Planetary Roving Vehicle Mobility and Navigation.

(6) Spacecraft Stabilization and Control System.

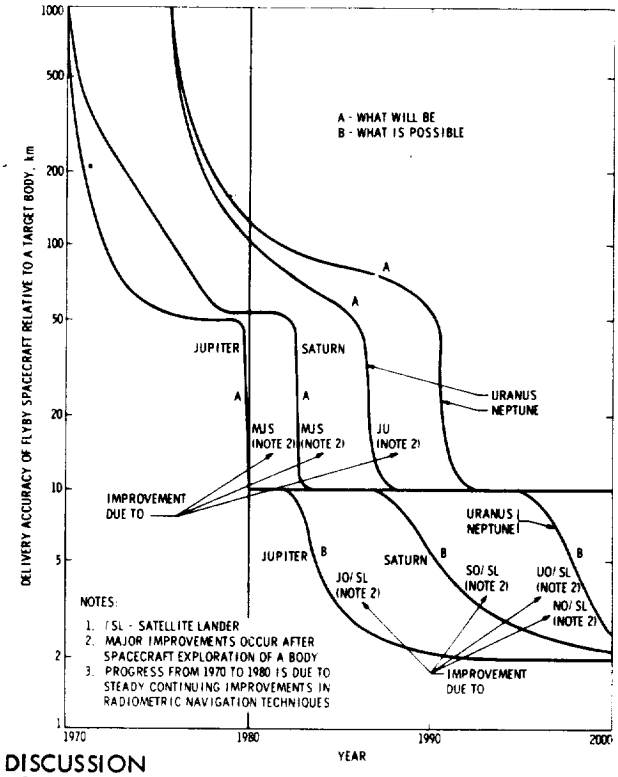
(7) Large, Flexible, Structures in Space.

FC 5-34. Delivery Accuracy for Flyby Targets in the Solar System*
(Radio Plus Optical Data)

a. Terrestrial Planets



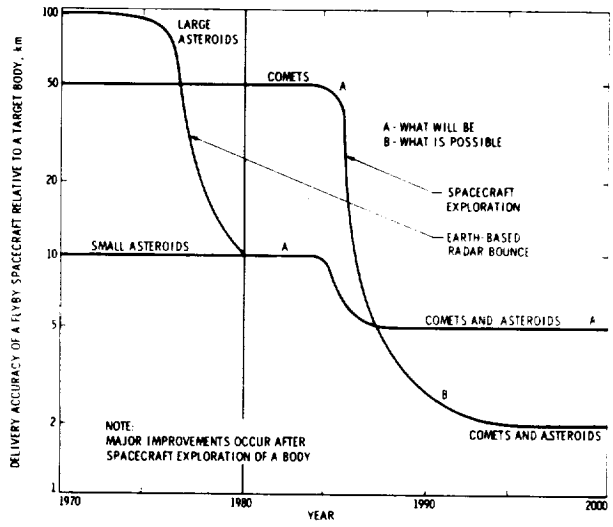
b. Outer Planets and Major Satellites



DISCUSSION

Delivery performance of radiometric data is limited by declination viewing angles. It is forecast that, in about 1980, as the interferometric-like data types come into widespread use, this limitation will disappear and an accuracy of approximately 50 km per AU will be possible for anywhere within the inner-planet system and 75 km per AU for the outer planets. These accuracies would be limited by errors in the planetary ephemerides.

c. Comets and Asteroids



From 1980 to 2000 it will be possible to put those same planetary ephemerides on an Extragalactic Radio Source (EGRS) coordinate system. This can be done by interferometrically tracking, first the spacecraft and then an EGRS, when that spacecraft is very near or even on the target planet, with a technique called Differential Very Long Baseline Interferometry (ΔVLBI). Once the planet ephemerides are referred to the EGRS system, subsequent flights can be flown from one to two orders of magnitude more accurately than will be possible by 1980. The critical factor for the availability of this increased capability for a given planet is when the first flyby with ΔVLBI of that planet is completed.

Optical data will control the combined radiometric plus optical data accuracy; therefore, errors limiting the optical data will limit the combined data accuracy. Initially, images of the target body limb will be processed to determine the direction to the center of the target body when maps of the surface are not available. When using limb fitting techniques, the controlling optical error is center finding which is expressed as a percentage of the body diameter and will range from 1% for the terrestrial planets up to 10% for small asteroids and satellites.

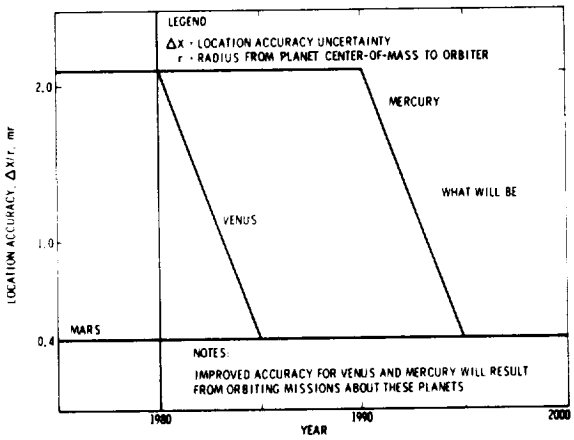
Center-finding errors can be significantly reduced when a map of a significant portion of the target body surface is available. Optical sensors can track surface features whose positions are known relative to the target body center. Surface maps will be obtained either after the first flyby mission or from Earth-based radar mapping for larger asteroids and satellites out to Saturn. These maps should have positional accuracies of better than 10 km.

This forecast assumes the use of Earth-based radiometric data supplemented initially by on-board optical data, and later by Earth-based Quasi Very-Long-Baseline Interferometry (QVLBI) as well as on-board pulsar navigation.

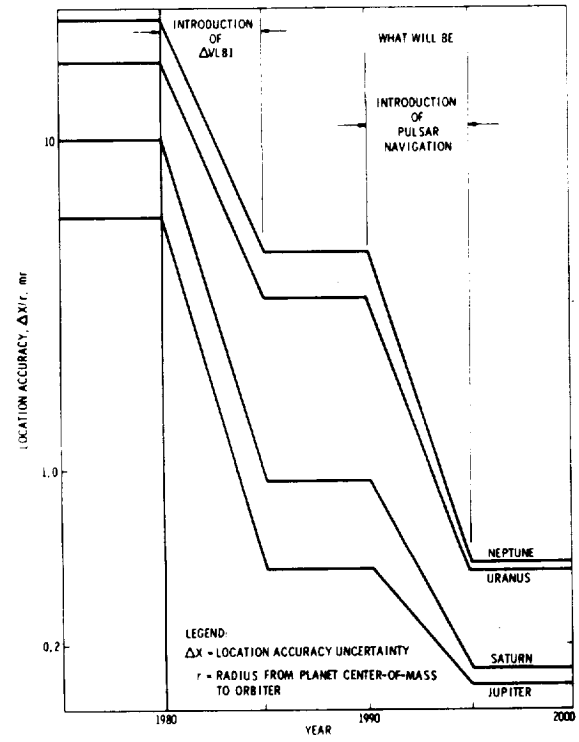
*Delivery accuracy is the accuracy relative to the target center of mass.

FC 5-35. Location Accuracy of Planetary Orbiters

a. Inner Planet Orbiter (Planet Viewing Orbit)



b. Outer Planet Orbiter (Planet Viewing Orbit)

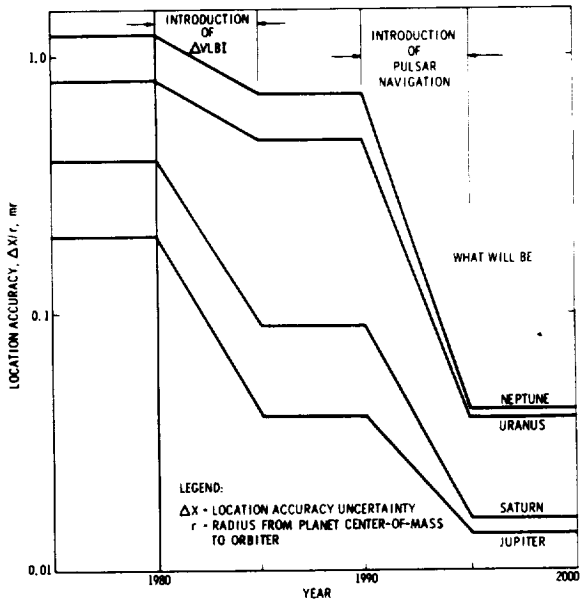


DISCUSSION

Planetary orbiters are used as remote-sensing platforms to view the surface of a planet or its natural satellites, and as a launching platform from which to enter the planet's atmosphere or land on its surface. The location of the satellite in its orbit must be accurately known and controlled to ensure precision alignment of sensing instruments and proper de-orbit aiming of probes and landers.

The parameter ΔX is the component of spacecraft planetocentric position error which is perpendicular to the instantaneous planetocentric vector. This component of the error completely dominates the radial component.

c. Satellite Tour Orbits



If the planetocentric location of the satellite is denoted in spherical coordinates by r (radius), α (right ascension) and δ (declination), the parameter uncertainty is:

$$\Delta X = \left[r^2\left(\cos^2\delta\,\Delta\alpha^2 + \Delta\delta^2\right)\right]^{1/2}$$

The forecast assumes the use of Earth-based radiometric data along with ΔVLBI and pulsar navigation in the early 1980s and early 1990s, respectively.

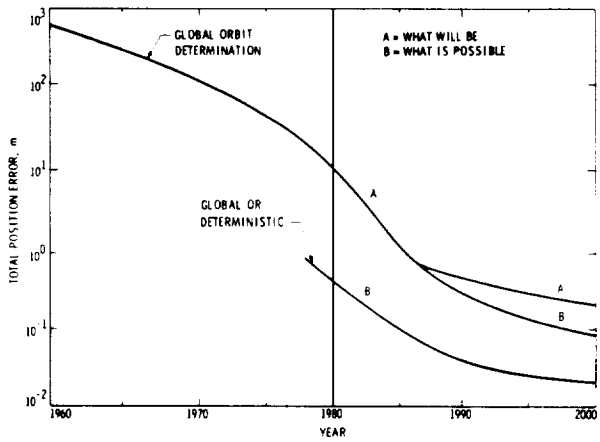
Two types of planetary orbits are considered in the parameter forecast: Planet viewing orbits, which are assumed to have a periapsis radius less than twice the planet radius, R, and an apoapsis radius less than 10R, and natural satellite tour orbits, which are assumed to have a periapsis radius less than 5R and an apoapsis radius less than 100R.

Only planet viewing orbits are considered for the inner planets Mars, Venus and Mercury. For these planets, the accuracy of the forecast parameter is limited primarily by the effects of the gravity field modelling uncertainties on the orbit determination process. At present Venus and Mercury are uncharted planets and thus are more difficult to navigate around than Mars.

For outer planet orbiting stations in planet viewing orbits, earth based radio accuracies are limited by the small angular rotation rate of the earth-planet line-of-sight which limits the viewing parallax. However, when ΔVLBI becomes available, the uncertainty in the forecast parameter is reduced significantly. Pulsar tracking can offer even further improved accuracies, with the location of a planet viewing Jupiter orbiting station possibly determined to within 30 km.

The location of outer planet orbiting stations in satellite viewing orbits is more accurately determined than for planet viewing orbits, since the longer orbital period allows for increased earth-planet viewing parallax. The 1975 uncertainty of a satellite tour Jupiter orbiter, for instance, is within 50 km at periapsis. ΔVLBI can yield an improvement to within 10 km, and pulsar tracking may reduce periapsis location uncertainties to within 3 km.

FC 5-36. Location Accuracy of Earth Orbiters



DISCUSSION

The projected parameter is the total position error in inertial space of an Earth-orbiting satellite. High accuracy in orbit position knowledge is required to support future Earth observation experiments (e.g., ultra-high-resolution ground scanners) and related operations such as orbit control and maintenance.

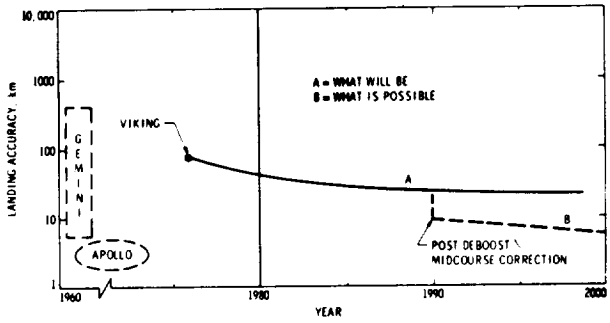
The forecast assumes the use of two types of orbit determination (O.D.) technology: global or statistical orbit determination and local or deterministic orbit determination. Global O.D. is the computation of the state vector from measurement in which no single measurement uniquely determines the complete state. It is the current system. In local or deterministic O.D., the position is determined using short arcs of multi-station data in which the state is uniquely determined by the measurements. It is a possible system of the future.

The results of the global orbit determination assume an order-of-magnitude improvement by the mid-80s in the Earth gravity model, the global tracking station locations, and in atmospheric density models.

The "what will be" curve is based on global orbit determination while the "what is possible" are based either global or deterministic.

FC 5-37. Entry and Landing Accuracy Atmospheric Landers and Probes and Communication Time for Outer Planet Probes

a. Landing Accuracy for Planetary Missions

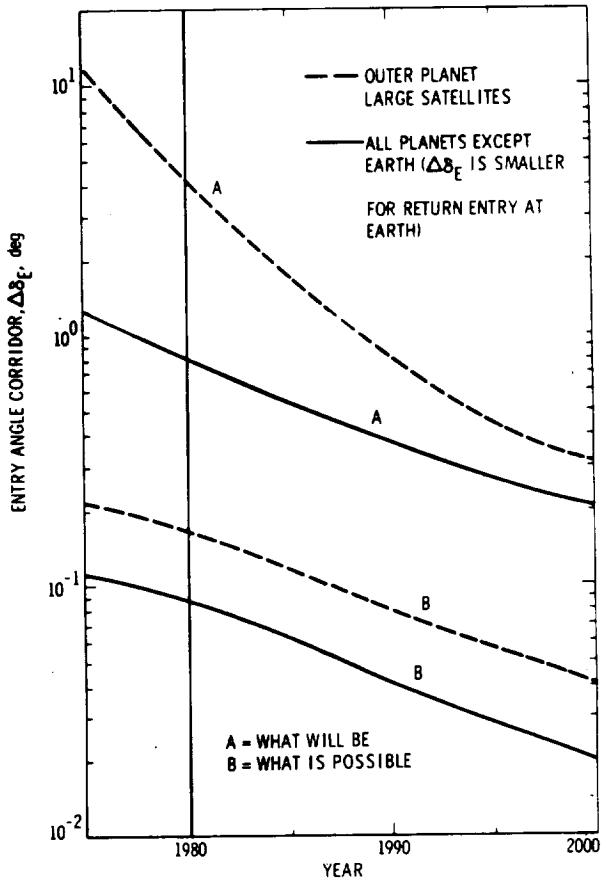


DISCUSSION

The forecast parameter is the accuracy with which a survivable lander can be landed on the surface of a planet. Because the surface is undefined for the outer planets, the forecast is for Venus and Mars. The landing accuracy is defined as the error in km in landing at a pre-defined planetocentric feature or location.

The forecast assumes the current Viking capability and extends it to include, in the future, the ability of the lander to determine the actual separation maneuver errors from the bus and to adaptively maneuver to null these errors during descent.

b. Entry Corridor Control for Planetary Entry



NOTES:
1. Assume entry angle = 15°
2. "What will be" assumes radio and optical, probe deflection
3. "What is possible" assumes best delivery from satellite orbit
4. For other values of δ_E

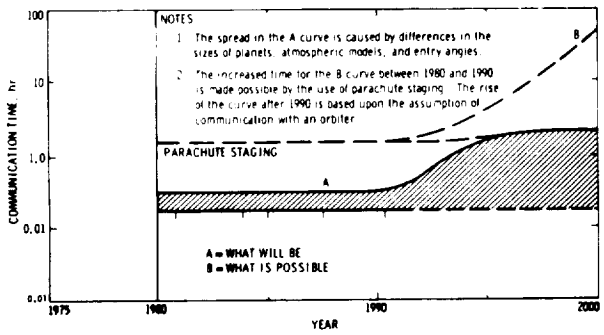
"What will be," $\Delta\delta_E \sim 0.26\ \Delta\delta_E$ cosecant δ_E (all δ_E)

"What is possible," $\Delta\delta_E \sim 0.7\ \Delta\delta_E$ cosecant $3\delta_E$ ($\delta_E < 45°$)

DISCUSSION

For any probe or lander mission through a planetary atmosphere, the most important parameter in determining the probe or lander design and mission profile is the entry angle. Entry angle control is critically important in assuring both the survival of the lander and accomplishing the mission. The forecast parameter is the accuracy with which the entry angle can be controlled. It is dependent on delivery mode (release from orbit, bus deflection, or probe deflection), location accuracy of the bus at the time of release, and execution errors in the release maneuver. The improvements with time are the result of the improved knowledge of the bus location at release due to QVLBI and pulsar navigation techniques, and of a reduction in the errors in executing the release maneuver.

c. Probe Communication Time for Outer Planet Entry Probes



DISCUSSION

For the outer planet missions, the mission profiles through this century will probably be primarily a bus fly-by with a direct entry probe. In this profile the probe will communicate to Earth through a relay link with the fly-by bus. The most important parameter affecting science data return is the time available during atmospheric descent for the probe to communicate with the fly-by bus as it goes past the planet. The forecast parameter is the time in hours available for communication. This parameter is determined by the atmosphere of the planet, the entry angle control available, the fly-by altitude and its control, and the probe aerodynamic configuration.

FC 5-38. Vehicle Rendezvous/Docking with Man-Made Craft

a. Cooperative Docking

DISCUSSION

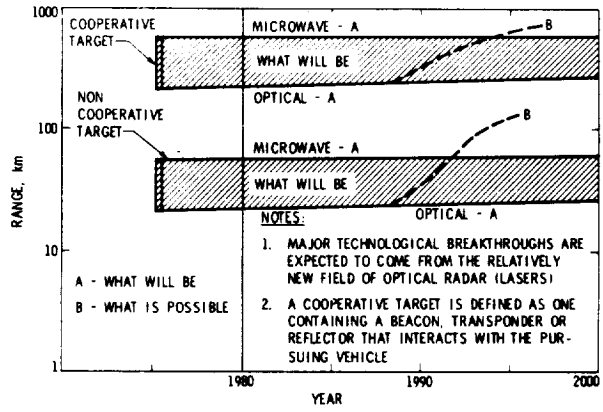
Manual and automatic docking (physical contact and latch) with a cooperative craft is state-of-the-art. The U.S. space program has employed a manual mode while the U.S.S.R. has demonstrated an automatic capability using rf systems.

b. Noncooperative Docking

DISCUSSION

This category of docking is defined as the physical contact and latch with a target that has not been designed to accommodate docking or is exhibiting anomalous behavior (e.g., tumbling). This class of problems is related to the field of teleoperation and robotics and does not lend itself to generalization. Each instance of noncooperative docking may require the development of special devices and methods.

c. Ranging Capability for Rendezvous Operations



DISCUSSION

Forecast: The forecast of on-board sensor range for both cooperative and noncooperative targets is shown. The projection is based primarily on the capabilities of the rendezvous sensor. As used here, a noncooperative target is defined as one which does not actively interact with the primary vehicle, which contains a radar-type sensor; and a cooperative target is defined as one which does interact with the pursuing vehicle and contains a beacon, transponder, or a reflector. For reasonable on-board power level and system size and weight, current performance of cooperative target sensors is 200–600 km. Noncooperative (skin track) sensor range is 20–70 km. The upper and lower bounds are representative of microwave and optical radars, respectively.

The "What will be" forecast is based on: optical radar will become competitive with microwave radar in future programs as a result of laster technology advances. Improvements in microwave systems will be in reducing the size and weight.

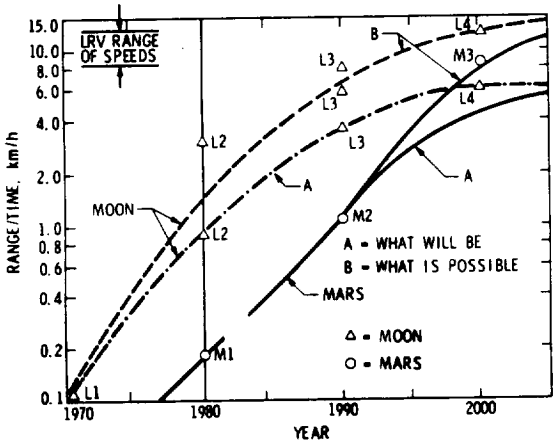
The "What is possible" forecast is speculation that a technological breakthrough is possible that will increase range capability by an order of magnitude over current levels.

Basis for the Forecast: Rendezvous can be accomplished with two different types of sensor systems and combinations thereof. The simplest sensor is an optical star tracker capable of tracking a sunlit rendezvous target (noncooperative) or a beacon (cooperative). Angle-only data are obtained and processed with information on chaser and target ephemerides and sensor error models to perform the navigation function. The second type of sensor is radar, which provides direct measurement of range/range rate, and and appropriate angles. The optical radar, or laser, is a relatively new field of endeavor, and major strides are expected in the area of lasing efficiency. Also, because of the newness of the technology and the support it is receiving from defense and industrial establishments, it can be speculated that a technological breakthrough will occur. Finally, the laser is more adaptable to multifunction utilization such as a combined rendezvous tracking and spacecraft docking sensor. This type of dual-mode system has appeared in baseline descriptions of several advanced spacecraft programs such as the Space Station and Space Tug.

Gallium arsenide (GaAs), yttrium-aluminum-garnet (YAG), and CO_2 lasers are currently the principal contenders for manned spacecraft automatic rendezvous and docking systems. Efficiencies of these devices are on the order of 10 percent or less and require power levels of 25 to 150 W to achieve rendezvous ranges of 200 km for cooperative targets and 20 km for noncooperative targets.

FC 5-39. Planetary Roving Vehicle Mobility and Navigation

a. Roving Vehicle Mobility (Range/Time)



NOTES:

1. PROJECTIONS ARE FOR UNMANNED MISSIONS
2. RANGE/TIME DOES NOT INCLUDE STOPS TO ACQUIRE SCIENCE DATA
3. DATA POINTS: (See text)
   - L1 RUSSIAN LUNOKHOD
   - L2 RESULTS OF THEORETICAL STUDIES AND SIMULATIONS
   - L3 UPPPER TWO POINTS BASED ON AVAILABILITY OF HAZARD AVOIDANCE SENSOR TECHNOLOGY. LOWER POINT BASED ON PROJECTED TECHNOLOGY AVAILABLE WITH CURRENT BUDGETS
   - L4 BASED ON THE AVAILABILITY OF SOPHISTICATED ARTIFICIAL INTELLIGENCE
   - M1 RECENT VIKING PROGRAM STUDY RESULTS
   - M2 BASED ON AVAILABILITY OF HAZARD AVOIDANCE SENSOR TECHNOLOGY
   - M3 BASED ON THE AVAILABILITY OF SOPHISTICATED ARTIFICIAL INTELLIGENCE

DISCUSSION

This parameter is the range capability per unit time for unmanned Lunar and Mars vehicles. Apollo 15, 16 and 17 carried Lunar roving vehicles which had range traverses of 25 to 35 km at average speeds of 10 km/hr. One conclusion of the program was that existing technology was more than sufficient to satisfy science requirements. Consequently it is not necessary to forecast capability of manned roving vehicles.

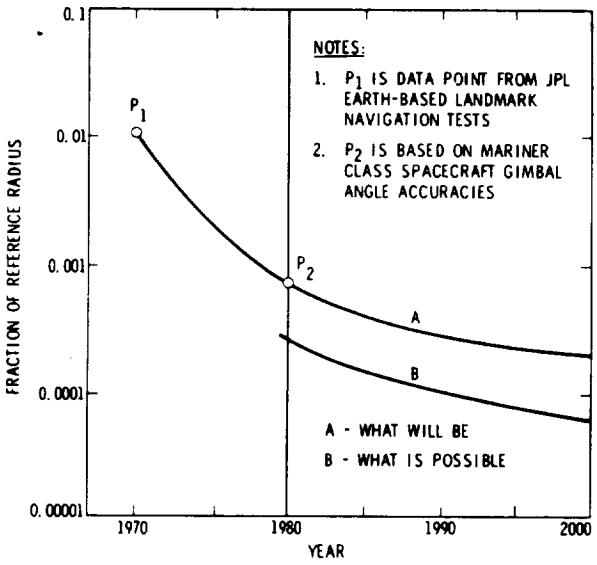
Forecast: This forecast shows the projected capability exclusive of stops to acquire science data. Note that the projections do not directly consider any risk factors. That is, no effort was made to determine the probability of mission success for the higher speeds. Therefore, when missions are planned, risk might very well dictate a lower speed than is considered possible by the technology status.

Basis of the Forecast: On the upper left of the forecast (a. Roving Vehicle Mobility) is shown the range of speeds for the Apollo LRV missions. The point L1 (Ref. 5-46) is the Russian Lunokhod with an average of about 100 m/h when operating. There are two L2 points. The upper point (Refs. 5-47 and 5-48) is the predicted theoretical capability from a number of studies. The lower point (Ref. 5-49) represents forecasts of a number of experts at MSFC who have done simulations with an instrumented vehicle in Arizona. There are three L3 points. The two upper points represent a range which the consensus of experts feel the hazard avoidance sensor technology could bring, whereas the lower point represents the most likely capability in 1990. This is based on the perfecting of sensors such as the laser radar to produce good information with resolution in the order of 30 cm at 30 m. There are two L4 points. These points assume a development of artificial intelligence technology using the charge couple semiconductor (CCD) sensor and computer memory techniques. Most experts feel that by the year 2000 the capability could optimistically approach that of the manned rover. The lower point is given as a more likely capability if funding is not sufficient to achieve the "What is Possible" forecast. CCD technology will probably develop rapidly in the sensor and memory areas because of the application to commercial television; however, the software application to autonomous rovers will probably be slow in development unless a definite mission is projected.

The Mars curve has only three points, but the basic thoughts given about the Lunar points at the same time are applicable. The Mars curve will be lower than the Lunar curve to begin with because of the semi-autonomy of vehicles, i.e., decision making on Earth. However, as the technology is developed to produce complete autonomy in the 2000 era, the curve should again approach the capability of a manned system. That is why the curve has a higher slope than the Lunar from 1990 to 2000. The point M1 comes from a recent study by the Viking program (Refs. 5-50 and 5-51) and represents the present thinking of experts at Martin Marietta Co., MSFC, and JPL.

FC 5-39. Planetary Roving Vehicle Mobility and Navigation (contd)

b. Roving Vehicle Location Accuracy



DISCUSSION

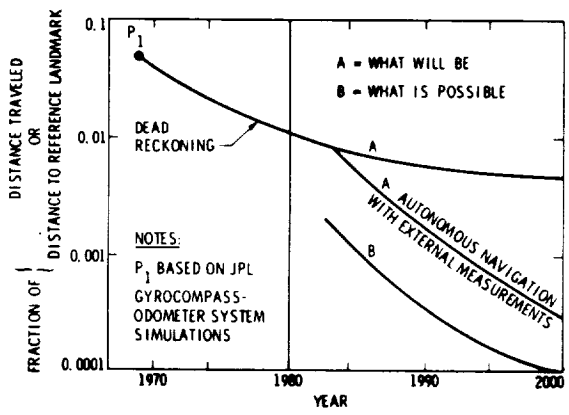
Forecast: This parameter represents the accuracy of locating a roving vehicle on the surface of a body (planet or satellite) with respect to either a body coordinate system (e.g., longitude and latitude) or landmarks on the surface. The units of this parameter are fraction of reference radius (defined below).

For location in body coordinates, the reference radius is the body radius and the parameter units are equivalent to radians of longitude and latitude. Location relative to landmarks has a reference radius which is a mean distance to landmarks; e.g., locating the vehicle with respect to mountain peaks 1 km away with a parameter value of 0.01 represents a 10-m error.

Basis for the Forecast: The forecast is based on the projected capability to make optical measurements of directions to distant references; e.g., Sun, stars, mountain peaks, etc. Thus, the accuracy is determined by angle measurement accuracy and data processing capability. The extrapolation to 2000 shows improvements primarily based on improved mathematical estimations and the capability of handling increased volumes of data.

The improvements shown by the "what is possible" curve represent increased effort and complexity in modeling and calibration.

c. Roving Vehicle Traverse Accuracy (Navigation)



DISCUSSION

Forecast: This parameter represents the accuracy by which a roving vehicle can measure or control its own motion across the surface of a body, either in absolute distance or relative to a map. The units of this parameter are fractions of distance traveled or of mean distance to reference landmarks. In mission design, the absolute distance accuracy relates to the required update interval, requiring Earth-based data processing, for a roving vehicle without autonomous, landmark-relative navigation.

Basis for the Forecast: It is assumed that the early roving vehicle has available for navigation only heading and distance traveled; e.g., a gyrocompass and odometer. This provides a dead reckoning type of navigation. Improvements in this system would be better heading measurements; multiple odometers to compensate, somewhat, for wheel slip; inertial measurements (accelerometers) to augment odometers; inclination (tilt) measurements, etc. These are all basically vehicle-internal measurements. The next stage of improvement would be to add measurements of external references; e.g., landmarks, for autonomous map-relative navigation and/or celestial sensors for body coordinate navigation. These external measurements may already exist on the roving vehicle for transmission to an Earth-based navigation data processing system.

The "what is possible" curve reflects the results of additional resources available for earlier completion of scene analysis (extracting environment information from sensor signals) and landmark navigation capability.

FC 5-40. Spacecraft Stabilization and Control System

DISCUSSION

Five parameters are pertinent to spacecraft stabilization and control:

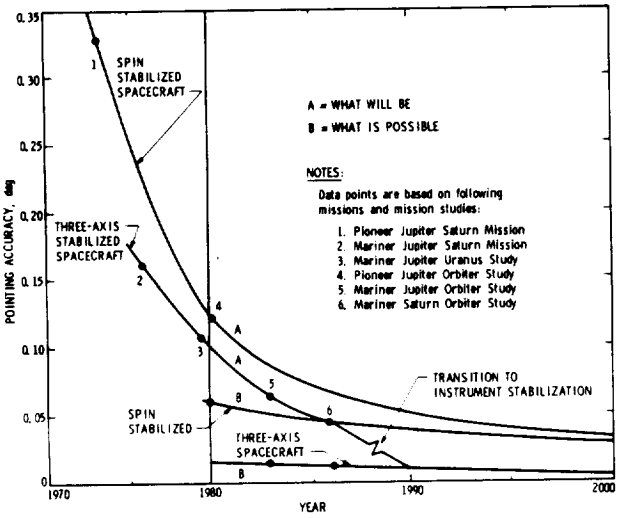
(1) Pointing Control Accuracy* and Jitter.**
(2) Motion Rate Settling Time.***
(3) Pointing Knowledge Accuracy.****
(4) Control System Weight.
(5) Control System Power.

The first and third of these are of most general interest and will be discussed here (items 2, 4, and 5 are discussed in the microfilm version -- see G below).

In projecting the primary parameters, three separate mission-related classes were examined: manned Earth orbiters, unmanned Earth orbiters, and unmanned interplanetary vehicles. Each of these classes depends on specialized technologies that have developed as a result of meeting peculiar mission and user requirements. To provide mission designers with maximum visibility and understanding, the classes and associated technologies have been kept separate.

a. Pointing Control Accuracy and Jitter

(1) Unmanned Interplanetary Vehicle Pointing Control Accuracy



Forecast: The projections for both the three-axis and spin-stabilized spacecraft are shown above. The approach that has been taken in defining pointing control accuracy is to reference the pointing ability to a base vehicle (defined as the navigation body) upon which the instrument being pointed is rigidly mounted. Thus, the pointing accuracy is, with one exception described below, a body-fixed line of sight in inertial space. The exception (see above graph) is based on the development of simple ways to accurately stabilize and point the instrument itself with respect to the vehicle.

Note that if a flight project were willing to pay the high cost of launching Earth-orbital spacecraft technology now in existence, for an interplanetary mission, the pointing accuracy could be increased by one to two orders of magnitude. (See the following forecast: Unmanned Earth Orbiting Vehicle Pointing Control Accuracy/Jitter).

Basis for the Forecast: The forecast is based on a number of future mission studies and expected hardware improvements in gyros, reaction wheels, star sensors, and especially on-board computer capability. In particular, in the 1980 to 1985 period, expected hardware developments are rather solid. The ones having the most influence will be the development of:

(1) Digital, gas-bearing, dry tuned rotor, inertial reference units.
(2) Precision magnetic-bearing reaction wheels.
(3) Advanced digital and hybrid computers for onboard control.
(4) Charge coupled device star sensors.

In the 1985 to 1990 period, the following major developments are expected, and used for the predictions:

(1) An instrument platform will be controlled independently using the vehicle only as a base body.
(2) Direct torquer drives will be used for actuators.
(3) The tuned rotor inertial reference unit will be used on the instrument platform. High accuracy (low drift) will be available, with celestial sensor updates for low-frequency drifts.

Beyond 1990, it is assumed that improvements will continue in all the above areas. It is likely that unexpected breakthroughs in technology will take place.

Two major advancements in control theory are expected to improve pointing accuracy. First is the progressive application of modern control theory for on-board control made possible by computer developments using LSI technology. The second is the improvement of modeling and analysis techniques to predict the interaction of vehicle structure with control. These predicted improvements are incorporated as follows:

* Ability to point a reference vehicle vector with respect to a desired direction.
** The limit cycle about the actual achieved pointing direction.
*** The time it takes for a transient disturbance to settle out below a maximum allowable angular rate.
**** The a posteriori knowledge of where a vehicle reference vector was pointed.

FC 5-40. Spacecraft Stabilization and Control System (contd)

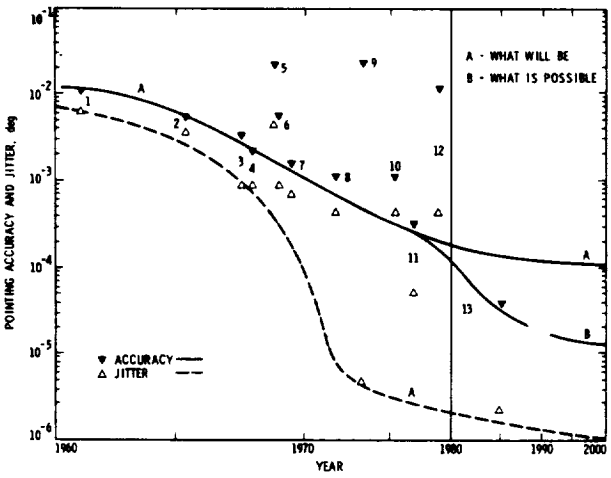
(1) Modern Control Theory: From 1977 to 1985, state estimation and filtering will be used to obtain better sensor, and hence, attitude information. The filters will progressively incorporate the deterministic knowledge of structural interaction from improved modeling techniques. From 1985 to 1995, adaptive control will be developed from primitive beginnings to sophisticated control.

Unknown preflight disturbances from the vehicle or environment will be automatically assessed and reduced. Beyond 1995, the predictions are gross extrapolations.

(2) Nonrigid Vehicle Modeling Techniques:

Flexible structure interaction with control is a major problem. The accuracy with which it can be predicted is directly applicable to the development of state estimators noted above. This prediction accuracy will improve due to better analytical methods. Even more important, vehicles being flown in the future, which are quite flexible, will provide empirical data to improve the theory.

(2) Unmanned Earth Orbiting Vehicle Pointing Control Accuracy and Jitter (Inertial Pointing Control System)

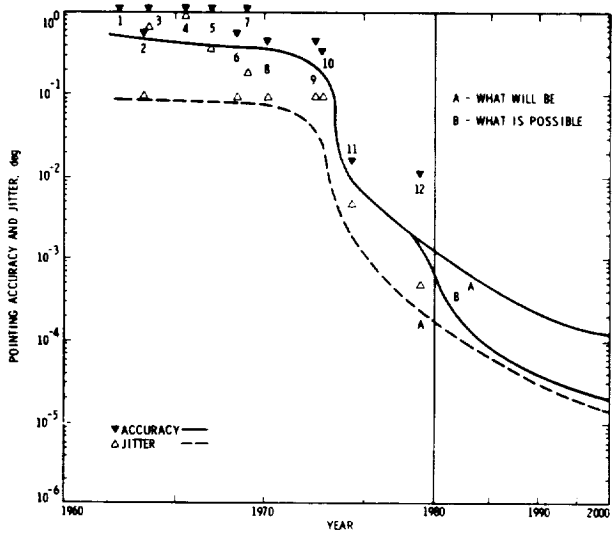


NOTES:

Data points are based on the following missions:

1. OSO-I (Orbiting Solar Observatory)
2. OSO-II
3. OSO-III
4. OSO-IV
5. OAO-A2 (Orbiting Astronomical Observatory)
6. OSO-V
7. OSO-VI
8. OSO-VII
9. OAO-C
10. OSO-J (Eye)
11. IUE (International Ultraviolet Explorer)
12. SMM (Solar Maximum Mission)
13. LST Large Space Telescope

(3) Unmanned Earth Orbiting Vehicle Pointing Control Accuracy and Jitter (Earth Pointing Control System)



NOTES:

Data points are based on the following missions:

1. OGO II (Orbiting Geophysical Observatory)
2. Nimbus II
3. OGO III
4. OGO IV
5. OGO V
6. Nimbus III
7. OGO VI
8. Nimbus IV
9. ERTS-B (Earth Resources Technology Satellite)
10. Nimbus V
11. ATS-VI (Advanced Technology Satellite)
12. EOS (Earth Observation Satellite)

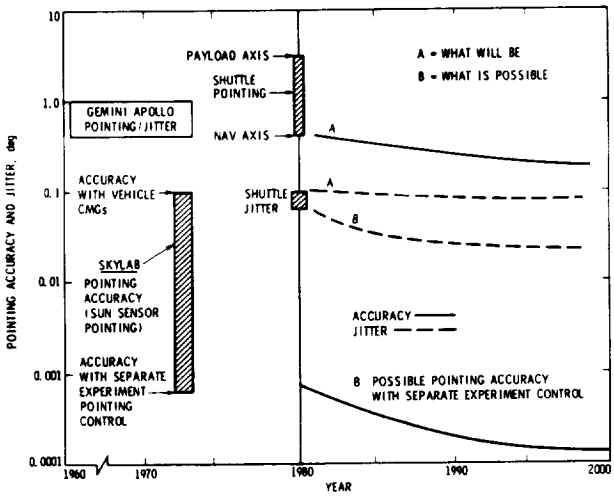
Forecast: For unmanned Earth orbiters, two general types of pointing accuracy are of interest: Inertial Pointing and Earth Pointing. The difference between the two is that the Earth Pointing systems are limited by the accuracy of Earth sensors or by the ability to convert from inertial reference to Earth reference and by the accuracy of the ephemeris data. With the improvement of onboard digital computers, the performance of Earth Pointing systems will approach Inertial Pointing systems in the 1990s. The above plots (Inertial Pointing and Earth Pointing) show accuracy and jitter of the Inertial Pointing and Earth Pointing axes. The performance is limited primarily by the accuracy and noise of the attitude sensor.

The accuracy of inertial pointing systems has improved over the past decade from about 0.01° to 0.001° and this can be expected to improve to about 0.0001° by the year 2000. The limiting accuracy will be due primarily to the structural and thermal stability of the satellite. The jitter is roughly two orders of magnitude better than the accuracy.

The present accuracy of Earth pointing systems is about 0.1° with a jitter of about 0.01°. A significant improvement can be noted in the 1973-75 time frame. This is due primarily to the availability of gyro inertial reference systems and on-board digital computers to convert from inertial to Earth referenced coordinate systems.

FC 5-40. Spacecraft Stabilization and Control System (contd)

(4) Manned Vehicle Pointing Control Accuracy and Jitter



Forecast: The above graph is a combined plot of pointing accuracy and jitter. Historically, Gemini and Apollo are located between 0.5° and 1.0° (accuracy and jitter) as typical values for manned transport systems. Skylab control capability was 0.1° (pitch and yaw) utilizing control moment gyros (CMGs) and was improved to 0.0007° by employing a precise experiment control system. The 0.0007° control level could be maintained for fifteen minutes.

The Space Shuttle is shown with a pointing accuracy of 0.5° for the navigation axis. Thermal distortion of the structure degrades this to one to three degrees at the payload bay axis. The "What will be" forecast is that pointing accuracy will be improved from 0.5° to 0.25° as a result of star tracker technological improvements. Jitter levels for manned spacecraft will remain at the 0.1° level. The "What is possible" forecast for rigid-body jitter shows a level of 0.05° obtainable by 1985 and presumes spacecraft control by high-performance CMGs.

b. Pointing Knowledge Accuracy

Pointing knowledge, the after-the-fact determination of the direction of an instrument pointing vector, is often of interest to experimenters and data users. Since pointing knowledge can be derived from numerous data sources other than control sensors, it is somewhat difficult to give a specific projection about future accuracy. The data sources that are available for determining pointing knowledge are completely dependent on vehicle design configuration and external environment data sources (such as reference stars, etc.). It is possible, though, to make some general statements about pointing knowledge and provide some bounds on the parameter.

As a rule of thumb, over the 1980 to 2000 period, pointing knowledge will be two times better than control accuracy, as projected in these forecasts (FC 5-40). While one might expect control to come closer to knowledge as time progresses, the assumption here is that other, noncontrol-related information will improve knowledge.

FC 5-41. Large Flexible Structures in Space

a. Control of Large Lunar-Based Radio Antennas and Optical Telescopes

DISCUSSION

It is quite possible that between 1980 and 2000, it will be desirable to build large two-degree-of-freedom antennas and telescopes to operate on the Moon. Much of the control-system-related technology developed for Earth-based stations will also apply to these. In general, Earth-based control system accuracies and functional capabilities would be adequate if the system could be made to operate in the Lunar vacuum and temperature environment. Although the reduced gravity may make some control jobs easier, in general, the lubrication and protection of large bearings, structural integrity over wide temperature ranges, and the effects of space radiation on coatings of all surfaces will create many problems. Although numerous engineering problems exist, the basic control system technologies will exist between 1980 and 2000 to put large articulated antennas and optical telescopes on the Moon.

b. Control of Large Space-Based Solar Arrays and Radio Antennas

DISCUSSION

It has been proposed that Earth-orbiting solar arrays with a size magnitude on the order of square kilometers could be used to generate power to be transmitted to Earth via microwave links. In addition, there has been a general interest in using and accurately controlling large antennas to improve telecommunication performance and to beam large amounts of rf energy to Earth, as part of a space power station. These two proposals present obvious control problems: keeping the arrays Sun-oriented and the antennas pointed at stations on the Earth.

In general, the major concern is with structural interactions between the antennas or solar arrays and the control elements (sensors and actuators). Although no complete functional systems have been developed for solving these problems, one cannot rule out the feasibility of successful system designs in the time frame being considered.

It is projected that by 1980, large arrays on the order of a thousand square meters can be controlled to acceptable accuracies.

By 1990, areas of a few tens of thousands and by the year 2000, areas of hundreds of thousands of square meters should be controllable.

For larger parabolic antennas with pointing accuracies somewhat more stringent than for the solar arrays, areas of a few hundred square meters can be pointed accurately by 1980, up to ten thousand square meters by 1990, and tens of thousands by the year 2000.

These "what will be" forecasts are based on current technology development efforts. A concentrated program focussed on improving the technologies involved could produce improvements of one or two orders of magnitude in these numbers.

E. SUMMARY

Transferring of matter technologies are currently well developed and will continue to improve during the 1980 to 2000 time period. During the last twenty years of this century technology will be available to: delivery payloads to any point in the solar system with considerable accuracy; land on and traverse the surfaces of Mars and the Moon; point vehicle payloads with high precision; and stabilize and point large spacecraft structures. Some specific capabilities will include the following:

(1) With the advent and use of such techniques as ΔVLBI, on-board optical measurements, and pulsar navigation in addition to Earth-based radio, the accuracy in delivering spacecraft to the planets on flyby missions should increase from the current 50-100 km for the inner planets and 100-1000 km for the outer planets to 2-20 km for the inner planets and 2-10 km for the outer planets, and their major satellites.

(2) The accuracy in the knowledge of the position of an orbiter about another planet should ultimately approach a few kilometers in periapsis altitude using the same techniques mentioned above. For Earth satellites this accuracy should approach 2-20 cm with the expected improvements in station locations, gravity field characterization, and atmospheric modeling.

(3) For lander and probe missions, landing accuracies at the inner planets should approach 10-30 km, and entry corridor control should approach 0.2° at all planets. Communication time for outer planet entry probes to the flyby bus will improve from the current times of roughly 20-30 minutes to a few hours, for staged or floater probes.

(4) With the development of more sophisticated "artificial intelligence" for unmanned roving vehicles, traverse speeds will increase from the 0.1 km/h for 1970 technology to as much as 10 km/h by the end of the century.

(5) The ability to accurately point spacecraft instruments will improve from 0.1 degree to 0.005 degrees for interplanetary spacecraft and from 0.001 degrees to 0.0001 for Earth orbiters using sophisticated state-of-the-art sensors and actuators.

(6) The ability to properly stabilize and control large solar arrays and similar structures will increase from a thousand square meters in 1980 to hundreds of thousands of square meters by 2000. This will result from improved structural dynamics modeling techniques and greater on-board computer capability with new sensor and actuator capabilities.

The transferring of matter technologies that are expected to make the greatest progress during the 1980 to 2000 period are related to roving vehicles and the control and pointing of very large spacecraft structures

F. PARTICIPANTS

Sincere appreciation is extended to the individuals who devoted their time and expertise toward the task at hand and the several organizations that conducted constructive critiques of the early drafts.

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The critiques and comments of the following individuals during the review process added greatly to our confidence in the validity of the material and were greatly appreciated:

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G. The following forecasts, concerning the transferring of matter, are available at the Jet Propulsion Laboratory. This information may be retrieved by calling Mr. George Mitchell at (213) 354-5090 and giving the document number (1060-42) and volume number (Vol. V) followed by the correct page reference numbers as listed below:

	Title	Page No. (1060-42, Vol. V)
1.	Delivery Accuracy for Flyby Targets in the Solar System (D. W. Curkendall and T. C. Duxbury	5-110 - 5-115
2.	Delivery Accuracy for Planetary and Earth-Orbiting Spacecraft (J. F. Jordan and F. E. Velez)	5-115 - 5-126
3.	Entry Corridor and Touchdown Dispersions for Probes and Landers (C. E. Kohlhase and R. C. Kennedy)	5-127 - 5-128
4.	Atmospheric Flight Mechanics (R. C. Kennedy).	5-128 - 5-134
5.	Vehicle Rendezvous/ Docking with Man-Made Craft (R. C. Kennedy).	5-135 - 5-137
6.	Planetary Roving Vehicle Mobility Control and Navigation (C. S. Jones, H. K. Bouvier, and W. G. Breckenridge).	5-138 - 5-146
7.	Spacecraft Stabilization and Control System Parameters (H. K. Bouvier, H. C. Hoffman, and R. C. Kennedy)	5-146 - 5-163
8.	Large Flexible Structures in Space (H. K. Bouvier).	5-164 - 5-165

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Section VI. STORING MATTER

D. W. Lewis

A. SCOPE

This field of technology deals with the extra-terrestrial storage of a great variety of things. Storing matter or storage has been viewed as the containment, protection, preservation, or maintenance-of-state of any mission-related item. This comprehensive "animal, vegetable, or mineral" scope expands to include all types of life support systems, and the mechanization of the environmental control and protective systems for all space vehicles and stations. To address so vast a subject, restrictive criteria were adopted to focus on the more important subjects.

These criteria were twofold. First, the study was directed toward applications where technology development needed additional effort rather than examining all subjects within the existing technology. Second, consideration of technology needed for missions which are unlikely in the time period of the study was avoided. This, however, did not exclude the preparatory work that would be required for missions a few years beyond 2000.

Five areas were identified in the Storing of Matter field which were judged to significantly restrict potential space activities during the subject time period. Figure 5-4 is a summary reconstruction of the logic which led to the identification of these key areas. The following discussion will refer to this figure and briefly explain how the various branches of it were viewed.

The storing of animate matter was considered apart from the storing of inanimate matter because of the historical separation of the manned from the unmanned technology in NASA activities to date. This division of work has fostered differences in terminology, grouping of engineering disciplines, and design emphasis. The experience of the personnel, their reports, and their intuitions exist in this format and it would have unnecessarily expanded the effort to have organized it otherwise.

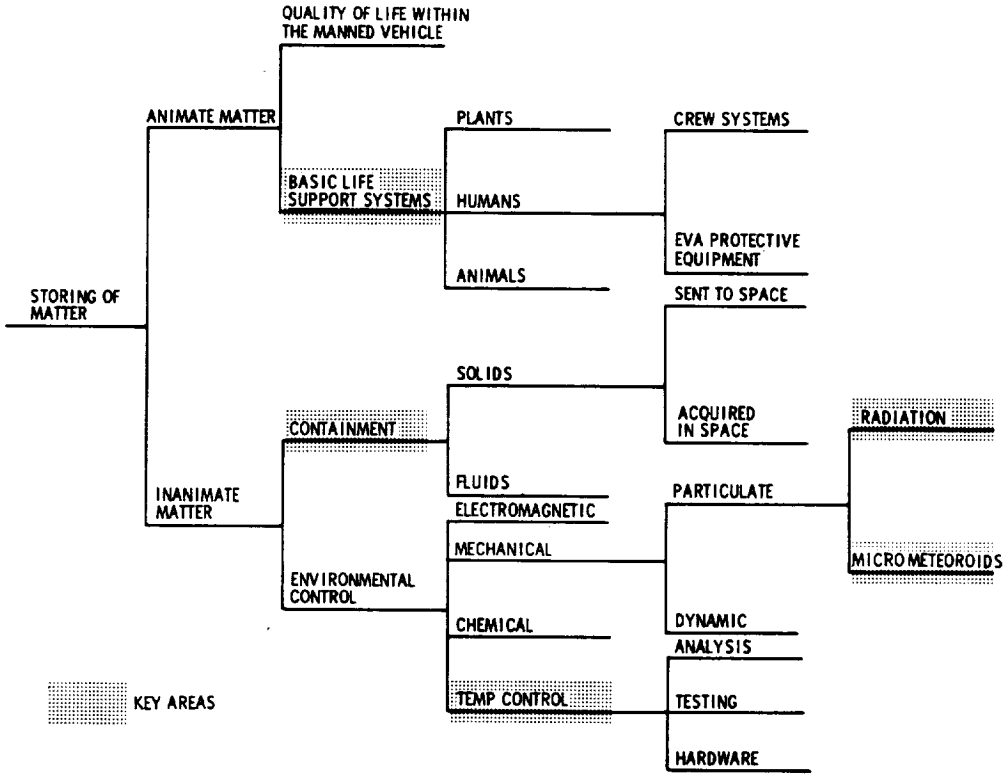


Figure 5-4. Logic leading to identification of key areas in storing of matter

The provision for the basic life support systems was identified as the major area for study emphasis. The quality of life in the manned system is important, particularly for extended missions, and may become more important when the basic life support capabilities are achieved. Life support systems for experimental animals and plants were viewed with less concern than the human life support systems. For, as mission durations increase, the achievement of sufficiently reliable human life support systems becomes the predominant problem. This less demanding for unmanned missions. The growing of plants to produce food is discussed in Part Five, Section II of this report.

The key areas which were identified for inanimate matter were also interrelated to the operations of life support systems. The study focussed on the containment of stored matter and the provision for an acceptable environmental control. A history of space experience exists for most of the inanimate disciplines, permitting the design of systems which are compatible with dynamic environments, electromagnetic fields, and the chemical properties of materials.

The protective systems for meteoroids and radiation, using current estimates of these environments, may have a significant design constraint for certain of the 1980-2000 missions. Therefore, these areas were noted for further investigation.

Containment of matter was also considered important because fluids will be stored in every type of mission and solids will be the most likely form of the mission payloads. Atomic waste concentrates may be sent into space and samples from planets and space laboratories may be acquired in space.

Temperature control within the spacecraft was another important area considered. It could have been included in the field of Transferring Energy (thermal); however, temperature control has become so integrated into the design of all space equipment it was treated here.

To summarize, the five key limiting areas selected for special attention are:

(1) Life support systems (primarily the regenerative processes to reduce storables).
(2) Containment of pressurized fluids (particularly gases for long durations) and of solids (with emphasis on reliable storage of dangerous nuclear or biological material).
(3) Meteoroid protection (or micrometeoroid shielding).
(4) Radiation protection (particularly for unmanned spacecraft near Jupiter or Saturn and for manned operations during solar flares).
(5) Temperature control (with emphasis on the development of devices which extend control capabilities beyond that possible using thermophysical properties of materials alone).

B. ORGANIZATION AND APPROACH

As a result of discussions with various recognized leaders in this field, the Coordinator of the Storing of Matter field identified the five key areas listed above. A committee meeting to focus particular attention on the life support areas was held and the Coordinator met individually and in small groups with the experts in the other areas.

Subsequent to these meetings, contributions were submitted for each of the five key areas for further identification of technical limitations or key developments possible for the 1980-2000 period. These contributions were summary in nature and gave background, current technology, and predictions in each area. These contributions have been further summarized by the Coordinator in the following subsections of this Part. Of the five areas treated in more detail, only two appear to have important technical limitations which may still be unresolved in the 1980-2000 time period. These are the life support area and the temperature control area. These two areas were selected for the forecasts given in this part of the report. Missions planned in this time period should recognize these limitations.

C. FORECASTS

1. Background, Present Status, and Forecast of 1980 Improvement

a. Life Support Systems. Manned mission durations for more than a few man-months will require major advances in life support systems because the mass and volume of stored expendables becomes impractical. For example, about 5×10^3 kg of expendables would be required per man-year (e.g., 4 men for 3 months) for a life support system having no regenerative cycles. As shown in Fig. 5-5, regenerative cycles for air revitalization and water-waste subsystem will be needed to send men to Mars, establish colonies on the Moon, or extend (e.g., 6 months) Earth orbiter missions. The extraterrestrial production of any significant amount of food by artificial means remains a difficult problem. Nevertheless, food production is required for the considerable reduction of expendables. Growing food plants may well be the best solution.

The lead time for integrating these regenerative cycles into a specific mission is of the order of 5 to 10 years, because of their interactions with other spacecraft systems. This is also true for supporting items such as EVA (extra-vehicular activity) suits, cabin temperature and humidity control, fire control, and contamination control. For example, air revitalization subsystems make large demands on the power system and some may lose their advantage if the power system itself uses expendables.

Few new concepts are being proposed and developed. Most of the subsystems undergoing development are the result of mid-1960 thinking. Quantum improvements in the mid-1980s or 1990s are not expected unless the search for these new concepts is intensified.

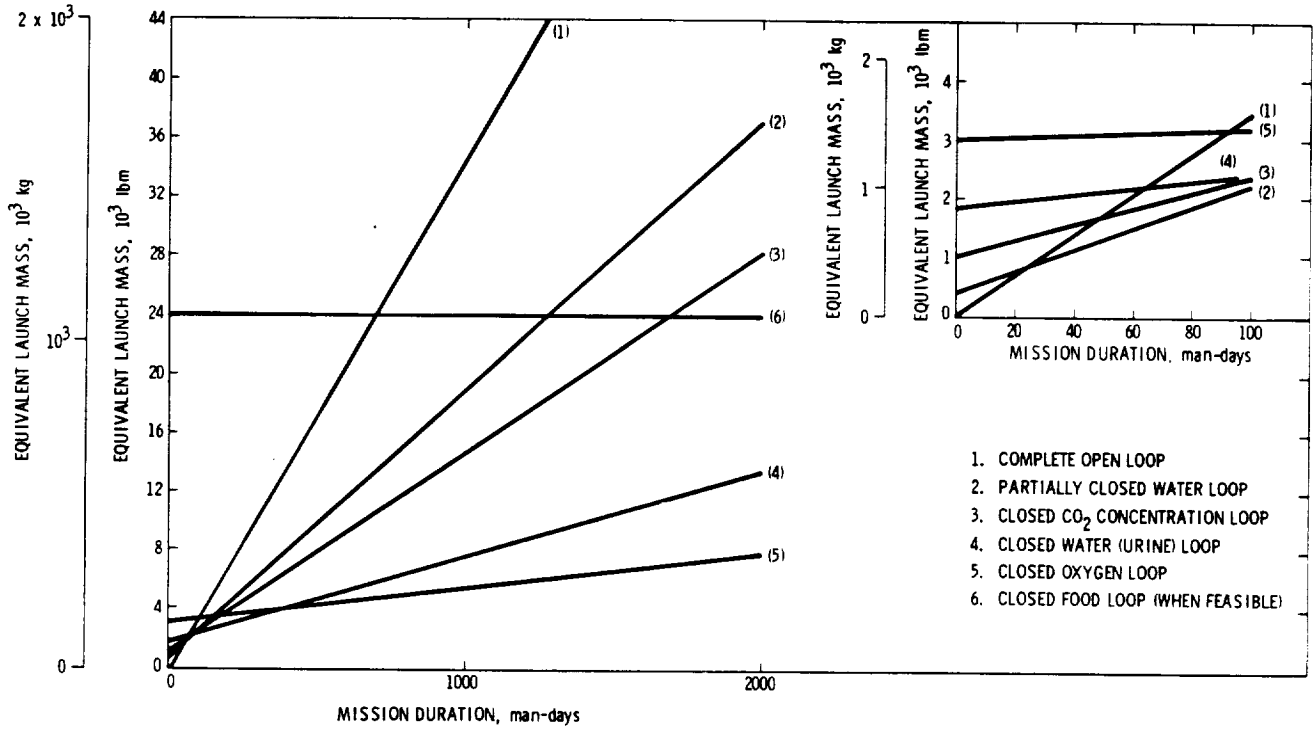


Fig. 5-5. Launch weight versus mission duration for various life support loop closures

(1) Air Revitalization. Methods are under development for oxygen regeneration and carbon dioxide (CO_2) concentration for use in the early 1980s. Oxygen reclamation is by the electrolysis of water and becomes an advantage over the storage of oxygen for mission durations in excess of approximately seven man-months. Curently, there is no question as to feasibility, and development is progressing on designs for ease in maintenance, improved efficiency, and long-term reliability. This oxygen supply technique is presently one of the larger power consumers of the regenerative life support process and efficiency improvements are needed. The high electrical power requirements are primarily due to electrode performance (an art) and the theoretical limitation. Significant power reductions are uncertain.

The vast majority of the development work accomplished in the reduction of CO_2 has been utilizing chemical and electrochemical processes. Some research has been performed to attempt to establish a process which would convert CO_2 directly to oxygen using either leafy plants or algae; however, no attempt has been made to take the difficult and costly step to integrate a system into a space vehicle environment.

There are three CO_2 reduction processes which are advanced enough to be considered viable candidates for advanced missions. The first process, the Sabatier system, is a low-temperature hydrogenation process which is exothermic enough to sustain the reaction at approximately 590°K (600°F). A byproduct, methane, must be stored, utilized by other spacecraft subsystems, or dumped. Insufficient hydrogen (H_2) is produced to complete the conversion of all CO_2. Therefore, additional H_2 must be stored if maximum conversion of CO_2 is desired. The development status of the Sabatier process is good and it is best suited for crews of less than 15 people with resupply periods on 6- to 9-month intervals.

For deep space missions or a Lunar station, the Bosch process is more appropriate. It requires a compressor to pump reactant gases through a catalyst bed and to maintain flow through a condenser/separator where product water vapor is condensed. This system requires the addition of heat (not necessarily electrical) and deposits carbon on a catalyst bed. Power requirements are about 56 to 70 watts per person compared to 2 to 5 watts of control power required for the Sabatier process. The development status of the Bosch

system is advanced and, as currently designed, is suited for populations of fewer than 20 people.

The third CO_2 reduction system to be considered as a viable candidate for the 1980-2000 period is the solid electrolyte system. It converts CO_2 directly to carbon and oxygen. CO_2 is removed from the cabin air by a concentration system and is pumped into the CO_2 electrolysis cell which operates at 1250°K and produces oxygen and CO. The CO is broken down to CO_2 and carbon over an iron catalyst. The CO_2 is then recycled to the electrolysis cell for further reduction. The objective of this development is to perform in one operation, both CO_2 reduction and O_2 generation for long-term space missions where complete closure of the oxygen loop is required.

Synthetic photochemical reduction of CO_2 to O_2 is now being investigated. It may prove to be a useful technique, but at present it is not as far advanced as the methods described above.

(2) Contamination Sensing and Control, Water, and Waste Management. Space systems to date have employed a measure of control over unavoidable contamination by trace elements in the spacecraft atmospheres. These measures involve exclusion of material, equipment isolation, absorption using charcoal or absorption of soluble substances on the condensate in humidity control devices. The results of numerous studies performed in anticipation of a space station indicated that these methods would be inadequate for longer missions, larger crews, and the anticipated greater variety of equipment. Upgrading these capabilities will probably be accomplished by the use of catalytic oxidizers and/or regenerable charcoal systems. For missions longer than approximately 4 months and crew sizes greater than about 10 people, these systems would be necessary. It will require several more years to fully develop the catalytic oxidizers and regenerable charcoal concepts for flight. Additional efforts will be required to understand maximum allowable concentrations, and to estimate generation rates.

Water and waste reclamation in the 1980s is expected to use the same techniques already in use. Water is recycled using either molecular filtration or phase change techniques. Solid waste management amounts to high-temperature destruction of metabolic wastes and/or spacecraft general trash to yield some useful gases and ash, to inactivate micro-organisms, and to reduce the remaining volume which requires storage. It may be possible that water and waste management subsystems will be coupled with food synthesis techniques by the year 2000, although this is a difficult challenge. At present, cattle manure is being converted to cattle feed by a process involving fermentation. At the very least this demonstrates that waste conversion is possible, although the speequally suitable for humans.

(3) Food Production. As mission durations increase for manned space flights and regenerative technology is utilized for air revitalization, water reclamation, and waste management, the mass penalty associated with carrying stored food becomes predominant. Many conceptual food regeneration systems have been investigated. These include algae, hydrogen fixing bacteria (Hydrogenomonas euthropha), duckweed, chemical synthesis (glycerol, fructose, alcohol), synthesis of proteins, and stabilized enzyme carbohydrate synthesis systems.

For dietary reasons, unicellular biological or chemical synthesis food systems will not alone be able to close the food/waste cycle. Although processed cellular mass has been successfully fed to animals, all human feeding studies to date have demonstrated that conventional processing of the harvested cellular mass is insufficient because the test subjects get sick (gastrointestinal). More complex biological systems and selected animal strains which approach a complex closed ecosystem are discussed in Section II, C of this Part.

It has been determined that 30 percent of a crew's diet might be composed of physiochemical synthesis of regenerated organic compounds or nutrients. These studies have shown that chemical food regeneration systems (when developed) would become competitive with stored food systems for manned spacecraft missions in the 4,000 to 10,000 man-day range. Biological food production does not become competitive with stored food/physiochemical systems until about 10,000 man-days. Development programs for biological production of food may or may not be successful, because of complexity and sensitivity to unknowns.

(4) EVA Portable Life Support Equipment. The EVA capability developed for the Apollo lunar landing program included an EVA pressure suit at 0.25 atm (3.7 psia) and a portable life support system to provide thermal control, carbon dioxide control, trace contaminant control, humidity control, pressurization, and communications. Earlier EVA purssure suits were also 0.25 atm (3.7 psia), but used an umbilical life support system to provide air revitalization, pressurization, and thermal control. The Space Shuttle design calls for a 1 atm (14.7 psia) mixed gas atmosphere instead of the previous 0.34 atm (5.0 psia) atmosphere used on Mercury, Gemini, and Apollo. The change in pressure and gas mixture for the Space Schuttle will eventually lead to the development of a pressure suit of 0.54 atm (8.0 psia) for EVA which will probably be standard for all space and Lunar missions. EVA suits for Mars surface exploration would be quite different, particularly in the thermal control subsystems. Mass reduction would also be of greater importance.

The total expendable mass associated with a one-man, 8-hour EVA using the Apollo suit is about 9 kg. Most of this mass is carried in a water sublimator/heat exchanger for thermal control (7.7 kg) and in a LiOH canister for CO_2 control (1.7 kg). Because EVA requirements are expected to increase, studies are underway to reduce the mass of expendables, especially for thermal control and CO_2 removal.

The development of a new, higher-pressure, EVA suit has been initiated and the development of this suit should be available for extended capability in the early 1980s.

b. Containment. This section describes the physical containment of fluid and solid matter. The limiting factor for storage of fluids is that for high-pressure gases. Four primary parameters

exist for physical containment; permeation, leakage, fracture, and the effect of temperature. Permeation or movement of gaseous atoms through a solid by diffusion is for most purposes very small for metals (10^{-32} SPU*) but is greater for welds (10^{-10} to 10^{-12} SPU) and polymeric materials (10^{-6} SPU). For composite structures used as pressure vessels metal liners are used to reduce gas loss.

Leakage is the flow of fluids through microscopic voids in materials. Three problems exist in designing against leakage; leak rate measurement, detection of leaks, and the sealing of openings against leaks. Smaller containers (less than 1 m in diameter) are about 2 or 3 orders of magnitude easier to prevent from leaking. For larger containers the smallest detectable leak is about 10^{-5} cm^3/s.

Fracture of a container can result in either gross leakage or explosion of the contents into space. For monolithic metals, a unified fracture design criterion currently exists; for composite materials, it is expected within the next ten years. Pressure vessels can be designed to preclude failure by cleavage of the atomic bonds, yielding and crack propagation. Leakage or puncturing of the pressure vessel shells by micrometeoroids is the most likely means by which significant amounts of the contents can be lost. Enclosures for life support systems lose a significant amount of gas via overboard gas discharge and via air locks for EVA experiments.

The containment of solid matter is well within existing technology. Proper attention must be given to the selection of materials, seals, and the thermal and dynamic environments. There are, however, two significant areas which pertain to the 1980-2000 space planning. They are the containment of concentrated atomic waste material for launch from Earth to a safe orbit for disposal, and the containment of biological material secured or processed in space which is to be returned safely to Earth.

Techniques have been developed for nuclear materials used in spacecraft power systems. These designs have been demonstrated to remain intact and sealed after impact on hard rock at terminal velocities. Although nuclear waste may be potentially more dangerous, no technical limitations are expected.

Biological containment is more difficult if the organisms must remain viable. Studies of a Mars surface sample return mission conclude that remote insertion, sealing, and return of a viable sample can be accomplished with current technology. They also point out that the containers can survive direct entry with failed decelerator systems. The quarantine requirements for a sample return would be strict and an automatic sterilization of the sample in the event of a mission failure might be required. Return of biological products processed in Earth orbit should also be within existing capabilities.

*Standard Permeability Unit (SPU)=standard milliliters of gas at 0°C and one atmosphere pressure per cm^2 of exposed area per cm thickness per second under a pressure gradient of one cm of mercury.

Although it is not a space containment problem, it is estimated that the design and management of the Earth- or Earth-orbit-based receiving laboratory for a Martian sample would be expensive and require an estimated 10 years to bring to an acceptable operational status.

c. Radiation Protection. Space radiation hazards consist primarily of protons (or possibly neutrons) emanating from the Sun during large solar flares, protons and electrons trapped in the Earth's natural radiation belts, and cosmic radiation. For spacecraft with trajectories near Jupiter or Saturn, additional strong trapped radiation fields are encountered. During space flights, secondary radiations are produced by interaction of these particles with spacecraft materials.

Manned missions in Earth orbit or near the Moon are primarily concerned with the radiation from solar flares. There are two types of flares which have been observed. One is a very high peak of radiation lasting for a few hours. The other is not as severe but lasts for a few days. Techniques are being developed to provide some warning of severe peaks and advanced warning of about 40 minutes is generally possible. For short missions of the order of a few weeks, the chance of exposure to a flare or the dosage resulting from one or two exposures is not critical; but for longer flights of the order of months, the exposure could be excessive.

Space stations and Lunar bases will require shielding which has a fairly simple relationship to mass. The use of Lunar soil, or on-board water as shielding material, or the provision of protected enclosures into which the crew can retreat in case of a flare should preclude overexposure at the expense of spacecraft mass. One meter of Lunar soil covers or 0.3 to 0.6 m thickness of polyethelene is considered adequate shielding from solar flares.

For planetary missions near Jupiter and Saturn, hardened semiconductor electronics can be used. The exposure levels where electronics becomes sensitive to radiation are 5 to 10 orders of magnitude higher than for humans. By proper design techniques, the level where difficulties occur can be raised another 1 or 2 orders of magnitude (10^5 rads to 10^6 or 10^7 rads).

It is expected that radiation shielding by interposed matter will continue through the balance of this century. The only alternative considered, that of deflecting charged particles by generating magnetic fields, appears to be impractical. It is reasonable to expect a better understanding of the solar flare phenomenon in 1980. At one time, it was believed that solar flares followed an 11-year activity cycle but now it appears that they are more random. These phenomena should be better understood as data are accumulated.

d. Micrometeoroid Protection. While space is a relatively safe place to store matter, it does have its peculiar dangers. One of these is the collision with particles either there by nature or placed there as the results of explosions, overboard dumps from space vehicles or from some of the earlier space experiments. There is

growing concern over debris in orbits around the Earth from man-made sources. Particles in orbit around the Earth as well as natural particles orbiting the Moon and the planets, do not impact upon spacecraft at high enough relative speeds for "bumper type" shields to be effective. Space vehicles operating near the Earth or Moon (e.g., the Apollo) have used a design criterion for structural shields to be four times as thick as the calculated penetration depth of an impacting particle. The mass and velocity of the particles, as well as their probability of impact, are calculated on the basis of micrometeoroid models formulated from a variety of data sources.

The meteors which appear in the atmosphere surrounding the Earth have been the subject of study for several years. These studies have been refined by radar studies of the ionized trails formed by meteors passing through the atmosphere, and by measurements made by Earth-orbiting satellites and space probes. As a result of these studies and measurements, theoretical estimates have been made which postulate a flux of meteoroids throughout the solar system. These theories are usually discussed in terms of an isotropic distribution of meteoroids, although it is generally accepted that meteoroid streams exist in which the concentration of particles is greater than predicted by the flux theories. The models also describe speeds, directionality, mass, and physical characteristics of the particles.

These models are very difficult to formulate and even more difficult to trust. Although opinions vary, it is generally believed that the models are conservative. Very little data are available and much of it is unreliable. Anomalies on interplanetary flights (e.g., Mariner 7) usually have conflicting explanations, one of which is particle impact. To date ZOND II is the only spacecraft believed to have been lost due to a meteoroid impact but this cannot be verified.

The theory and performance of hypervelocity shield designs are not in good agreement, and shields like the ones developed for the Mariner 9 spacecraft were designed empirically and evaluated experimentally. These shields protect against particles smaller than approximately 1×10^{-6} grams. Probability calculations are usually made using environmental studies and estimates of shielding performance, and in practice, any risk estimate resulting from these calculations has been judged acceptable, in the sense that such calculations place few if any constraints on spacecraft design.

Relatively low numbers have been calculated for probability of penetration into vital spacecraft areas. For example, the Mariner 9 spacecraft had about one chance in a thousand for a penetration of its fuel tanks; the Viking '75 Orbiter because of its larger size and longer flight time has a little less than one chance in a hundred for the same fate. The reasons why such low numbers are "acceptable" are (1) the models and associated techniques are not considered trustworthy, and (2) it is assumed that we have never experienced flight problems due to meteoroid impact. During the next 25 years, this viewpoint may change because higher reliability numbers will be desired for manned flights or for flights returning from Mars with potentially viable samples. A change of emphasis would also occur if one or two spacecraft were lost clearly due to micrometeoroids. Without these forcing functions, however, it is expected that the current minimal effort of tabulating relevant flight data and modifying the models will continue.

Should serious work in this area be reinitiated, the development of more effective shields and the investigation of the environment with well designed flight experiments would take precedence. However, there are a number of spacecraft design approaches which may be as effective. Modular design of tankage and redundant design of equipment will be effective in reducing the vulnerable area.

e. Temperature Control. The heat exchange loops associated with crew and personal life support systems have been included in the Life Support System considerations. More generally, the purpose of the temperature control activity is to create a heat energy balance between a spacecraft or station and its environment which results in component temperatures which are within safe operating ranges. The major elements of the discipline are hardware technology, analytical ability, and test capability. Hardware technology includes both materials and devices. The status of these elements determines the ability to support future missions.

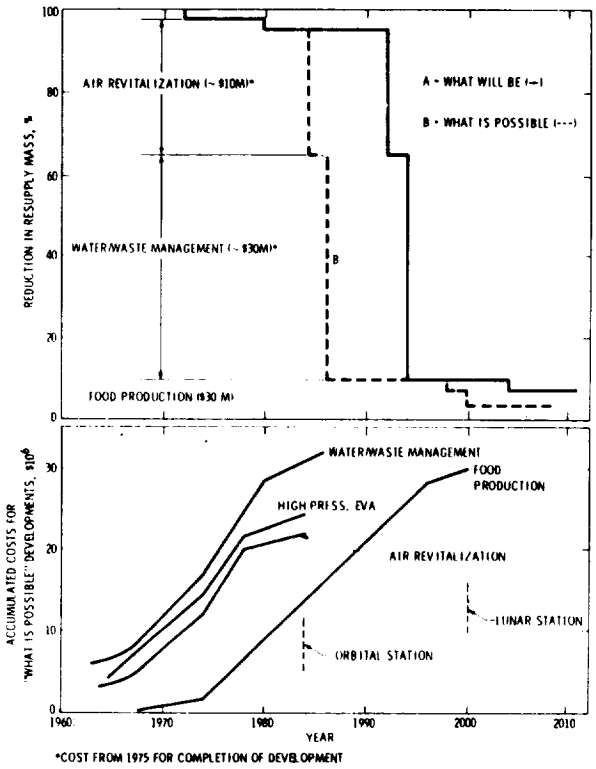
Materials or, more correctly, the thermophysical properties of materials have been developed to an extent that it would appear unreasonable to expect major advances in this area. The same is true for software for carrying out sophisticated analysis. Some improvements in computer techniques should be expected but the theoretical ability to model problems is beginning to be the limiting factor. Testing capability is also well developed, except for tests where system temperatures approach that of liquid nitrogen. Liquid helium facilities exist but they are small. The development of larger facilities of high quality could be accomplished within the framework of a project, should the need arise.

Because of differing special needs, a variety of devices are being developed and introduced which, in effect, extend the limitations of material thermophysics properties. There is an area where a serious shortcoming exists; it is expected that mechanical or thermoelectric refrigeration will be needed and currently there are no devices which are of flight-acceptable quality which could support missions longer than about 6 months. The most probable need will be in support of superconducting electronics operating a few degrees above absolute zero. The key obstacle to the development of these devices is funding support and the key obstacle to their use is power consumption for they are inefficient.

2. Selected Forecasts

The three areas, life support systems, containment and protection systems, and temperature control systems, selected for forecasting here, are forecasted on the following page.

FC 5-42. Life Support Systems



DISCUSSION

In the 1980s there will be:

(1) Oxygen reclamation and CO_2 control by electrolysis of waste water.
(2) Carbon dioxide reduction by both Sabatier and Bosch processes.
(3) EVA suits with 0.54 atm pressure and reduced mass.
(4) Water reclamation using phase change and filtration methods and waste incineration.
(5) Food supplements by physiochemical processes possible.

In the 1990s there will be:

(1) Oxygen reclamation from carbon dioxide using solid electrolysis techniques or synthetic photos synthesis.
(2) The possibility of food supplements from hydroponic or Lunar farms.

In the 1990s there will not be:

Food synthesis from solid waste.

FC 5-43 Containment and Protection Systems

DISCUSSION

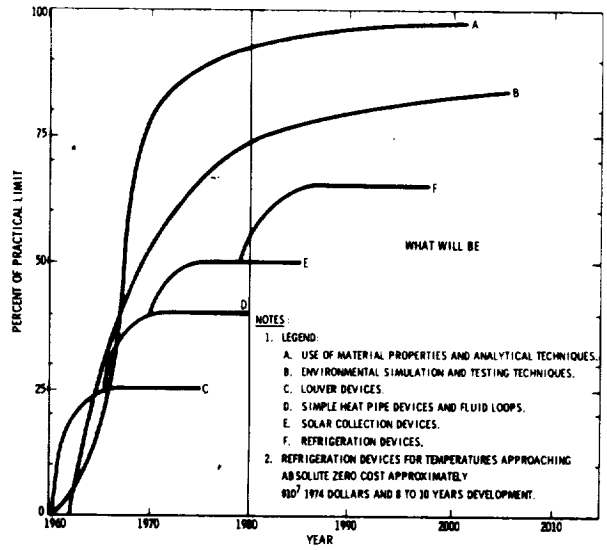
In 1980-2000 there will be:

(1) Unified failure criteria for composite materials similar to those now existing for monolithic metals.
(2) Gas storage using solid oxides and hydrides.
(3) Increased design constraints imposed by micrometeoroid considerations (i.e., modular construction, solid-gas storage, etc.).
(4) Reliable containment of dangerous solids such as nuclear waste or biological samples.
(5) Minor improvements in meteoroid and radiation models and shielding.

In the 1980-2000 there will not be:

(1) Effective protection from impacts by low-speed space particles (natural or man-made).
(2) Electromagnetic or electrostatic shielding from radiation.
(3) Detection and avoidance systems for meteoroids.

FC 5-44. Temerature Control



DISCUSSION

In 1980-2000 there will be:

(1) More use of project-peculiar temperature control devices.
(2) A low-temperature refrigeration system for superconducting devices.
(3) Larger facilities with heatsink temperature below that of liquid nitrogen if needed.

In 1980-2000 there will not be:

(1) Significant improvements in the thermophysical properties of materials and insulations.
(2) Significant advances in the ability to generate thermal models for analysis.

D. SUMMARY

The Storing-of-Matter field was surveyed for those technologies which would require advancement to support space activities anticipated in the 1980 to 2000 period. The field was defined to include the containment, protection, environmental control, and maintenance-of-state of all kinds of living and inanimate matter. Important areas were identified and an assessment made regarding current technology and the practical extension of it where this was possible and needed.

Five key areas were identified for discussion in this report. They were the Life Support Systems for manned space vehicles, Containment of fluids and solids, the environmental Protection from Radiation and Micrometeoroids, and Temperature Control of spacecrafts and stations. The regeneration cycles for air revitalization, water and food, and the development of devices for temperature control were identified as the most likely areas to limit our capabilities in this century.

It was concluded, in general, that the current technology could be used for future missions except in specific areas where expendables were used. Extrapolations in these areas resulted in impractical volume and mass requirements for the longer missions and larger crews expected. Hence, the development of regenerative cycles are necessary. Unfortunately, these cycles are much more complex than the existing open systems requiring development lead times of 5 to 10 years and funds averaging about 10 million 1974 dollars for each cycle brought to flight status. A great advantage is realized from developing some life support cycles over others, and it would seem sensible to concentrate initial work in these areas: water and waste management and air revitalization.

More efficient use of available resources would be possible if early project goals were selected. The development of options or the redesign of systems for each step toward larger crews or longer missions is unnecessarily expensive. The schedule of these developments can also be better coordinated with a common goal in order to avoid having a single system limiting the overall capability.

Finally, the eventual selection of reliability goals can affect development costs greatly. Some of the reliability goals set for the Mars surface sample return studies, for example, are two or three orders of magnitude higher than typical of current technology. In view of this, the definition of a project philosophy which is consistent with capabilities and resources is important.

E. PARTICIPANTS

The Coordinator expresses his appreciation to those, listed below, who so willingly and enthusiastically shared their experience by contributing to this study. Their inputs are maintained on microfilm (see F below). Appreciation is also extended to those others who through their many conversations helped focus the activity to the important areas treated in this part of the report.

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F. INDEX OF MICROFILMED FORECASTS

The following forecasts, concerning the storing of matter, are available at the Jet Propulsion Laboratory. This information may be retrieved by calling Mr. George Mitchell at (213) 354-5090 and giving the document number (1060-42) and volume number (Vol. V) followed by the current page reference numbers. These particular forecasts are categorized by subjects and forecasters; and they are organized by subjects and forecasters; and they are organized by the letters and numbers as follows:

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*From JPL, unless otherwise noted.

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A FORECAST OF SPACE TECHNOLOGY

Part Six. BASIC SCIENTIFIC RESOURCES FOR TECHNOLOGICAL ADVANCEMENT

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Prepared by a Task Group
consisting of participants from

Jet Propulsion Laboratory

under the direction of

Outlook for Space Working Group V

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Section I. INTRODUCTION

A. SCOPE

This Part, Basic Scientific Resources for Technological Advancement, has two major purposes:

(1) To identify relevant areas of science that will require funding in order to assure the realization of the technology forecasts presented in this report.

(2) To predict a few probable elements of the scientific/technological milieu of 1980-2000 for use as an aid to thinking in the context of future decades.

The effort was begun with the additional goal of "identifying new and forthcoming scientific discoveries which would have major impact on the technology of the coming decades." This goal was found not to be feasible, although the forecasting literature contains numerous anecdotes of this type. One problem is that the borderline between science and technology is ill-defined and ultimately arbitrary. (We will not attempt to define it here except implicitly, by example.) "Scientific" advances that have immediate technological impact tend to look more "technological" than scientific.

B. BACKGROUND

Out of the large literature concerning the interaction of science and technology, several other insights were found particularly appropriate to the study:

(1) Science and technology (during this century, at least) reciprocally support the advance of each other. The popular image of science opening new doors for technology is only half of the picture.

(2) Particularly relevant is Harvey Brooks' observation (Ref. 6-1) that science more often serves to provide an environment in which technological ideas can be exploited, than it serves as the origin of technological ideas. This observation is supported by arguments presented in the National Academy of Sciences Study, Physics in Perspective (Ref. 6-2), which explores the entire subject in some depth. The observation is also consistent with the findings of the Department of Defense study, "Project Hindsight" (Ref. 6-3), which identified very few scientific discoveries as directly related key milestones in the development (over a 20-year period) of various military systems studied. Most of the relevant science had been developed 30 and 40 years prior to the systems developments. If this is valid in general, the scientific discoveries of the past two decades will be the primary basis for most new technology during the next quarter-century.

(3) Some fields of science, even the more esoteric ones, promote the advancement of technology by virtue of their needs for extraordinary instrumentation or other experimental apparatus. Astronomy and high energy physics have been important technology drivers in this sense, and space science epitomizes the process.

(4) Much of the retrospective value of earlier forecasts lies in the analysis of where they went wrong. The unforeseen events which cause their stepwise obsolescence are not all technical. An instructive instance is Gabor's 1970 prediction (Ref. 6-4) that, at the present state of the art, oil shale would become a profitable source only when the price of oil is increased by a factor of 3 -- an event "not likely to be reached by the end of the century."

The contributors to this Part consisted of active research scientists covering several fields of physical science. The group's approach was guided by the two major purposes stated above, insights from the literature such as those just quoted, and an attempt to project the scientific and technological scene one or two decades hence.

Section II. SCIENTIFIC FIELDS RELEVANT TO SPACE TECHNOLOGY

Figures 6-1 through 6-4 are matrices which, in the judgment of the contributors, display the fields of science deemed relevant to support technological advances for the devices or systems forecast in Parts Three, Four, and Five. The titles of the technologies are somewhat abbreviated on the matrices, and reference to the forecasts themselves may be necessary in order to learn all that was forecast under a given title. In some instances, the technologies listed are combinations of two or more of those forecast, as reflected by a more general title.

Because the technologies selected for forecasting are a sample from space technology as a whole, the applicability of the matrices is correspondingly limited. However, most important technological areas appear to have been included in the forecast.

The science categories were drawn mainly from the American Institute of Physics Abstract categories and the Chemical Abstract categories. A few additional entries such as information theory, behavioral science, and computer science were added.

There is no straightforward way to derive implications of structure within the matrices, and the reader is cautioned not to treat them as mathematical matrices.

In particular, normative forecasting techniques in which numerical values are assigned to elements of science-technology matrices and conclusions drawn from the summation of these, are not applicable to subject matter as broad as is presented here. We have thus avoided numerical expressions of "impact" in the matrices.

The following general observations can be made. Scientific disciplines of most widespread applicability to NASA technologies appear to be largely those that concern the electromagnetic properties of solids. Right now, these areas are identified with many of the most significant device developments predicted for the period 1980-2000. The blank elements (little or no science impact on the technology) occur predominantly in the natural sciences. For instance, astrophysics, planetology and exobiology are not well represented. Their role as technology drivers was not considered in deriving these matrices. Some sciences are widely applicable because of their general utility (e.g., applied mathematics).

The expectation of significant advances based on device-oriented sciences is reinforced by the worldwide high level of support for research and development in these sciences.

As noted earlier, many of the technologies depend on a large number of scientific disciplines for support. This suggests that a very broadly based research and technology program will be required in order to assure that the advances projected in these forecasts do in fact occur. NASA's investment in some areas may be a small fraction of the total global investment. However, to have meaningful access to the other work in that field, it is important for the Space Agency to be represented by research in each area. We believe that the present space technology forecast, coupled with interaction matrices of the type presented here (but more precise and detailed), can provide a tool for developing a well-founded long-range research and technology support plan to meet NASA's needs.

Providing the extra emphasis to move from a "what will be" to a "what is possible" curve will generally involve an increased investment of resources across all of the sciences supporting a given technology.

In many respects, the matrices should be considered as raw data to serve as points of departure for detailed analysis of the importance of various disciplines (for given applications), or for assessing expectations that certain ones will provide the keys to given technological advances. An example of the kind of analysis necessary for well-founded assessment of the promise of various applied research activities in one limited area is the 344-page National Materials Advisory Board report, "Materials for Radiation Detection" (Ref. 6-5).

In some instances (e.g., certain aspects of remote sensing) advances in fundamental technique may contribute as importantly to increased capability as advances in hardware technology. Efforts toward these ends should thus receive a proportionate measure of R&D support.

"Physics in Perspective" (Ref. 6-2) offers an alternative presentation of the areas of technology advance which the major fields of physics research are expected to support. The document identifies areas or examples of (1) spin-off (straightforward application of present knowledge), (2) extrapolations (possible new inventions), and (3) technologies for which the needs of the science serve as a stimulator or driver.

The generality of the relationships denoted by the matrix elements in Figs. 6-1 through 6-4 leaves much to the imagination. While little is to be gained by tracing the science-technology connections in detail, there appears to be some

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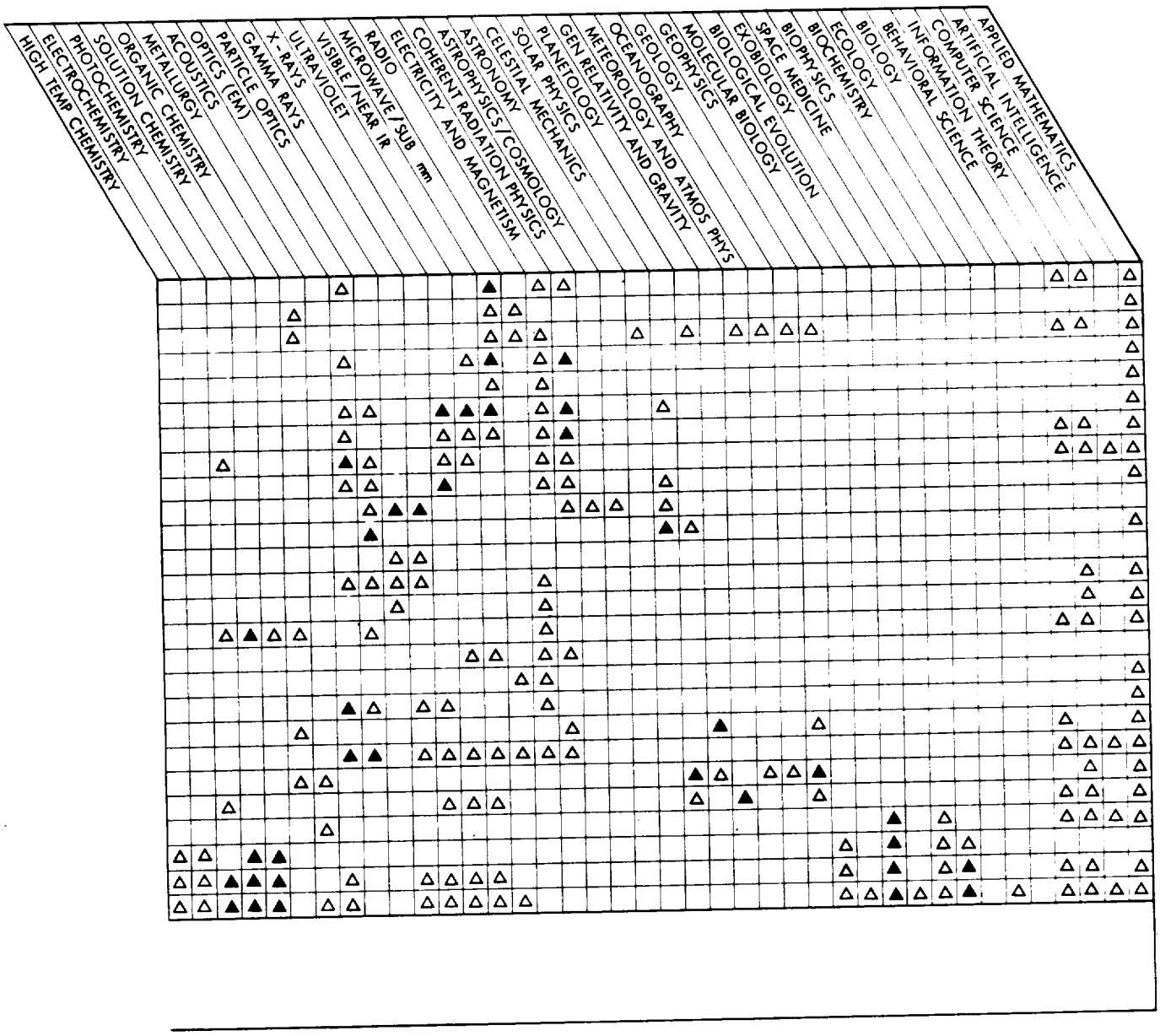
LEGEND

- ☐ LITTLE OR NO IMPACT
- △ IMPACT
- ▲ SIGNIFICANT IMPACT
- * PRESENT AREAS OF EMPHASIS WITHIN NASA

	METROLOGY	THERMODYNAMICS	THEORETICAL MECHANICS	FIELD THEORY	ELEMENTARY PARTICLES	COSMIC RAYS	NUCLEAR PHYSICS	ATOMIC PHYSICS	MOLECULAR PHYSICS	MACROMOLECULES/POLYMERS	FLUID PHYSICS	PLASMA PHYSICS	SUPERFLUIDS	THERMODYN PHASE PHENOMENA	LOW TEMPERATURE PHYSICS	STRUCTURE OF SOLIDS	LATTICE DYNAMICS	TRANSPORT PHENOMENA	SUPERCONDUCTIVITY	MAGNETIC PHENOMENA	OPTICAL PROPERTIES	RADIATION EFFECTS	SURFACES AND INTERFACES	THIN FILMS AND MEMBRANES	COLLOIDS	RHEOLOGY	CATALYSIS	REACTION KINETICS
* 3-2. MICROWAVE RADIOMETER (SPECTRAL) AND (IMAGING)							△	△								△			△	△	△		△	△			▲	△
* 3-3. RADIO TELESCOPE	▲			△			△						△			△			△				△					
* 3-4. RADAR IMAGING / SOUNDING				△			△						△			△			△	△			△				△	
* 3-6. IR REMOTE SENSING INSTRUMENTS				△	△		△						△					△	△	△	△		△	△	△		△	△
E. JOSEPHSON EFFECT IR DETECTOR					▲						△		△						△			△	△				△	△
* 3-8. MULTISPECTRAL IMAGING SYSTEM				△	△						△		△			△		△	△	△	△		△	△	△		△	△
3-7. ACTIVE LASER ABSORPTION SPECTROMETER					△						△		△		△	△			△	△	△	△	△		△		△	△
* 3-9. SOLID STATE CAMERAS											△		△		△	△			△	△	△	△	△	△	△	△	△	
E. ULTRAVIOLET INSTRUMENTS					△						△		△			△									△		△	△
* 3-11. X-RAY AND GAMMA RAY TELESCOPE / SPECTROMETER					△					△	△					△			△	△	△	△			△	△	△	△
E. SPACE PLASMA INSTRUMENTS			△							△	△					▲				△		△				△	△	
* 3-15. SOLID STATE PARTICLE DETECTORS									△	▲	▲								△	△	△	△			△	▲	△	△
3-16. PARTICLE POSITION SENSING DEVICES									▲	▲	▲				△			△	△							△	△	△
3-17. 10 TO 10^5 GeV ENERGY DETECTOR									▲	▲	▲				△			△	△							△	△	△
3-18. MASS SPECTROMETER / GAS CHROMATOGRAPH				△	△					△	△	△	△					△	△		△	△	△			▲	△	
E. THERMAL ANALYSIS INSTRUMENTS				▲														▲			△							
3-19. NUCLEAR MAGNETIC RESONANCE					△					△	△	△							△			△	△					
3-21. SURFACE MICRO-ANALYSIS INSTRUMENT					△						△	△														▲		
3-22. GRAVITY GRADIOMETER/GRAVITY WAVE DETECTOR	▲			△	△														△	△	△		▲	△		△	△	
E. MICROSCOPES (OPTICAL AND ELECTRON)	△			△																				△		△		
E. PASSIVE SEISMOMETER			△	△														△	△	△	△	△				△		
E. AEROSOL - PHOTOMETER			△	△								△	△		△			△		△	△	△			▲		▲		△
3-25. LIFE DETECTION PROCESSORS			△											△	△			△						△	△	△	△	△	
3-25. LIFE DETECTION CHEMICAL SEPARATORS			△										△	△	△			▲								△	△	△	△	△
3-25. LIFE DETECTION CHEMICAL DETECTORS			△																					△	△		△	△	△
3-25. LIFE DETECTION ACTIVITY DETECTORS			△																					△	△		△	△	△

NOTE: THE NUMBERS AND LETTERS PRECEDING INSTRUMENTATION DESCRIPTIONS ABOVE ARE EITHER FORECAST NUMBERS OR SUBSECTION DESIGNATORS OF PART THREE, SECTION II.

Figure 6-1. Effect of



science on technology: instrumentation

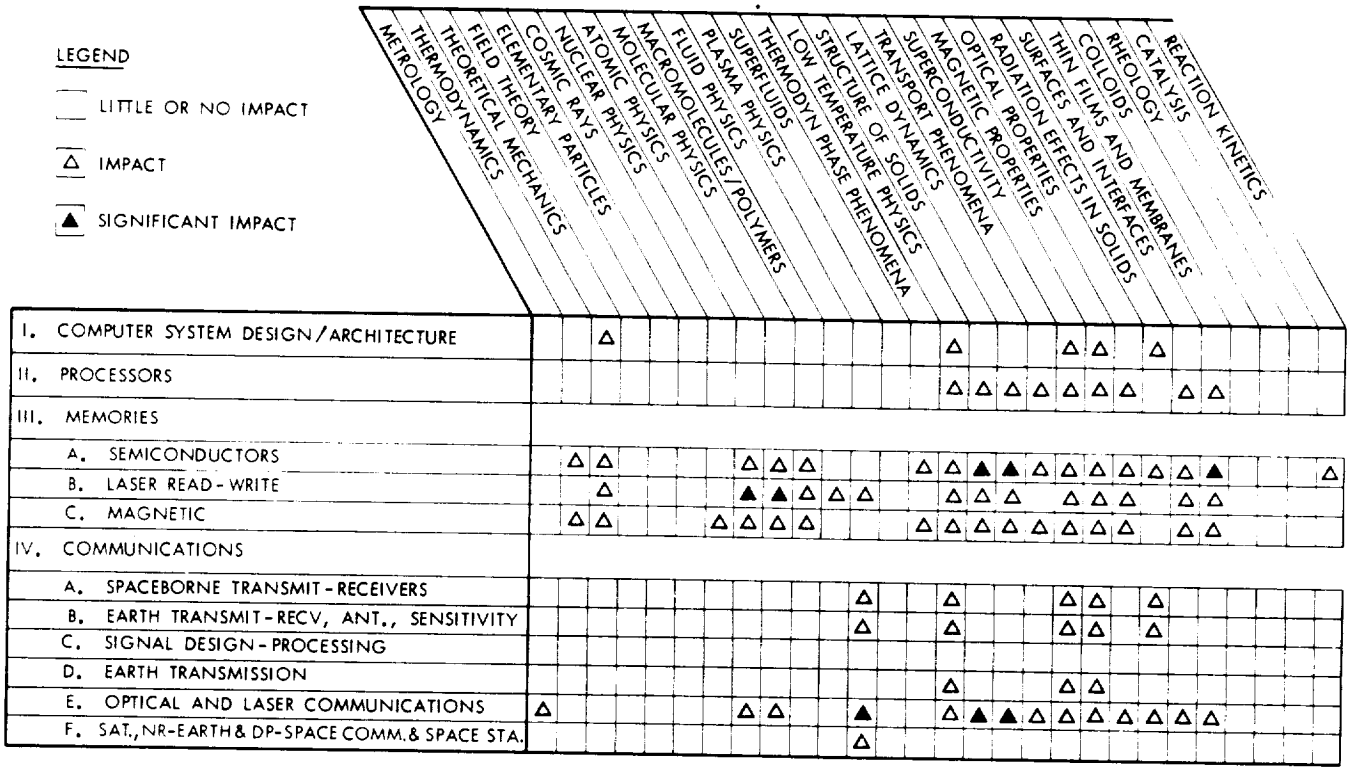
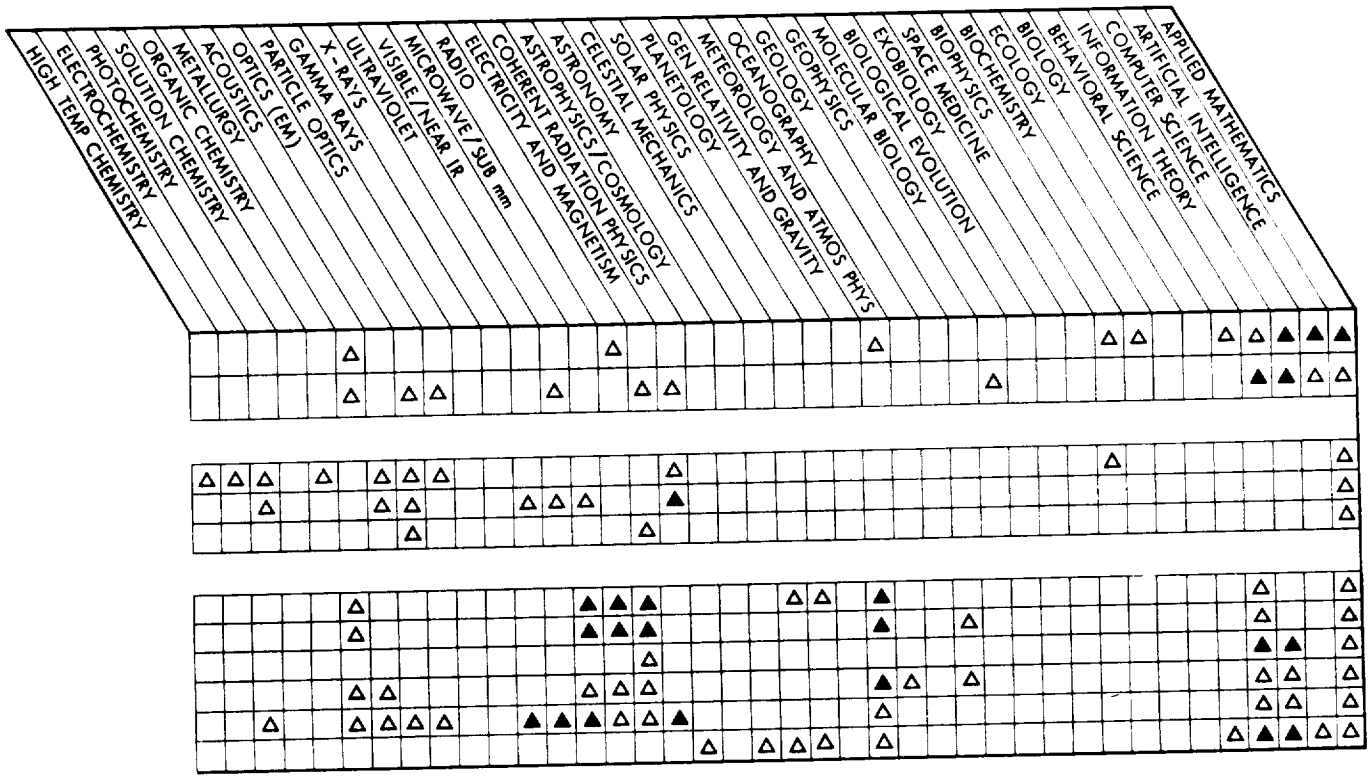


Figure 6-2. Effect of science on technology:



information processing, storing, and communication

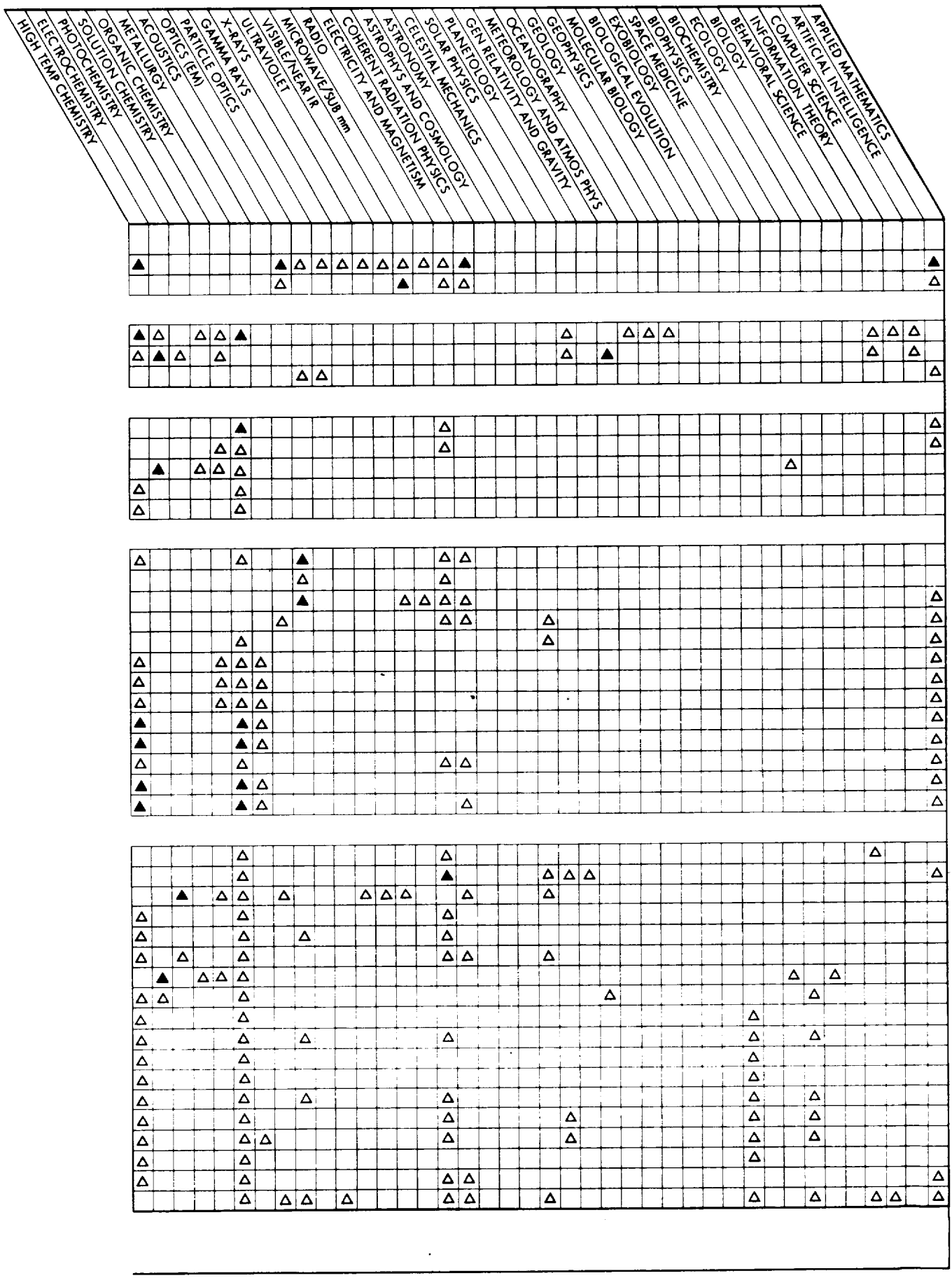
LEGEND

- ☐ LITTLE OR NO IMPACT
- △ IMPACT
- ▲ SIGNIFICANT IMPACT
- * PRESENT AREAS OF EMPHASIS WITHIN NASA.

		METROLOGY	THERMODYNAMICS	THEORETICAL MECHANICS	FIELD THEORY	ELEMENTARY PARTICLES	COSMIC RAYS	NUCLEAR PHYSICS	ATOMIC PHYSICS	MOLECULAR PHYSICS	MACROMOLECULAR PHYSICS	FLUID PHYSICS	PLASMA PHYSICS	SUPERFLUIDS	THERMODYN PHASE PHENOMENA	LOW TEMPERATURE PHYSICS	STRUCTURE OF SOLIDS	LATTICE DYNAMICS	TRANSPORT PHENOMENA	SUPERCONDUCTIVITY	MAGNETIC PROPERTIES	OPTICAL PROPERTIES	RADIATION EFFECTS IN SOLIDS	SURFACES AND INTERFACES	THIN FILMS AND MEMBRANES	COLLOIDS	RHEOLOGY	CATALYSIS	REACTION KINETICS
ENERGY TRANSMISSION																												
* 1.1	LASER BEAM GENERATOR												△	▲	▲		△	▲	△								▲			
* 1.2	MICROWAVE BEAM GENERATOR													▲	▲			△							△	△					
ENERGY COLLECTION AND PROCESSING																														
2.2	PLANETARY SURFACE MATERIAL																							△	△	△	△	△	△	△	▲	△
2.3	PLANTETARY ATMOSPHERIC MATERIAL													△	△		△			△	△			△				△	△	△	△	▲
2.4	ANTIMATTER								△	▲	△	△						△		△					△	△		△				
ENERGY STORAGE																														
* 3.1	FLYWHEELS																		△	△	▲	△		△	△		△				
3.2	SUPERCONDUCTORS			△	△								△	△			△	△	△	△	△	△		▲	△				△		
* 3.3/4	BATTERIES			▲									△	△	△				△			△					△	△	△		△	△
* 3.5	STABLE CHEMICALS			▲									△	△					△	△		△	△								△	▲
* 3.6	METASTABLE CHEMICALS			▲									△	△					△	△		△	△								△	▲
MECHANICAL ENERGY (PROPULSION) FROM																														
* 4.1.1	ELECTRON BOMB. ELECTROSTATIC THRUSTER			△									△	△			▲		△			△	△	△			△					△
4.1.2	COLLOID ELECTROSTATIC THRUSTER			△												△	△					△	△	△			△		▲			
4.1.3	ELECTROMAGNETIC ACCELERATOR							△			△		△	△	△		▲			△			△	▲	▲							
4.2.1	ELECTROMAG/BEAMED E. THERM ROCKET			▲	△											△	▲						△	△	△	▲		△				
4.2.2	ELECTROMAG/SOLAR SAILS				△																					▲		△	△			
* 4.3.1	CHEMICAL ROCKET/LIQUID			▲	△								△	△	△	△	△		△		△							△		△	△	△	△
* 4.3.2	CHEMICAL ROCKET/SOLID			▲	△								△	△	△	△	△		△		△							△		△	△	△	△
4.3.4	CHEMICAL ROCKET/METASTABLE			▲	△								△	△		△	△		△	△	△							△		△	△	▲	△
4.4.1	NUCL FISSION ROCKET/SOLID CORE			△	△						△	△	△		▲	△			△	△	△						△	▲				△
4.4.2	NUCL FISSION ROCKET / DUST BED			△	△						△	△	△		▲	△			△	△	△						△	▲				△
* 4.4.3	NUCL FIS'N ROCKET/ LIGHT BULB/GAS CORE			▲							▲	△	△		△	▲			△		△		△				△	△				△
4.5.1	NUCL FUSION/DIRECT HEAT ROCKET			△	△						△	△	△		▲	△			△	△	△						△	▲				△
4.5.2	NUCL FUSION/MICROEXPLOSIONS			△	△						△	△	△		▲	△			△	△	△						△	▲				
ENERGY CONVERSION TO ELECTRICAL FROM																														
* 5.1	ELECTRICAL (POWER CONDITIONING)														△				△				△	△		△	△					
5.2	MAGNETIC (TAPPING AMBIENT FIELDS)				△				△							△				△				△		△					
* 5.3.1	ELECTROMAG/PHOTOVOTAIC CELL			△										△	△	△				△	△	△	△	△		▲	△	▲	▲			
5.3.2	ELECTROMAG/THERMOELECTRIC			△										△	△					▲	▲	▲				▲	△					
5.3.3	ELECTROMAG/THERMIONIC			△										△	△					▲	▲	▲				▲	△					
5.3.4	ELECTROMAG/DYNAMIC CYCLES			△										△	△		△			△						▲	△					
* 5.4.1	CHEMICAL/FUEL CELLS			△										△	△		△			△								△				
* 5.4.2	CHEMICAL/DYNAMIC CYCLES			△										△	△		△			△								△	△	△		△	△
* 5.5.1	RADIOISOTOPE/THERMOELECTRIC			▲			△				▲	△							△	△	△	△					△	△			△	△
5.5.2	RADIOISOTOPE/THERMIONIC			▲		△	△				▲	△					▲		△	△	△						△	△				
* 5.5.3	RADIOISOTOPE/DYNAMIC CYCLES			▲							▲	△			△	△		△	△	△	△						△	△			△	
5.6.1	NUCL FISSION/THERMOELECTRIC			▲			△				▲	△							△	△	△	△					△	△				
* 5.6.2	NUCL FISSION/THERMIONIC			▲		△	△				▲	△					▲		△	△	△						△	△			△	
5.6.3	NUCL FISSION/LIQ METAL MHD			▲							▲	△				▲	△		△	△	△		△				△	△			△	
5.6.4	NUCL FISSION / MAGNETOGAS DYNAMICS			▲							▲	△				▲	△		△	△	△		△				△	△				△
5.6.5	NUCL FISSION/DYNAMIC CYCLES			▲							▲	△				△	△	△	△	△	△						△	△			△	△
5.6.6	NUCL FISSION/GAS-FLU. CO REAC-CONV			▲							▲	△	△			△	▲		△		△		△				△	△				△
5.7	NUCLEAR FUSION			△	△						△			△	▲	▲		△	△	△	△	△	△	△	△	△	△	△			△	

NOTE: THE NUMBERS PRECEDING THE ITEMS LISTED ABOVE ARE DEVICE CODE NUMBERS AS SHOWN IN PART FOUR.

Figure 6-3. Effect of



science on technology: energy

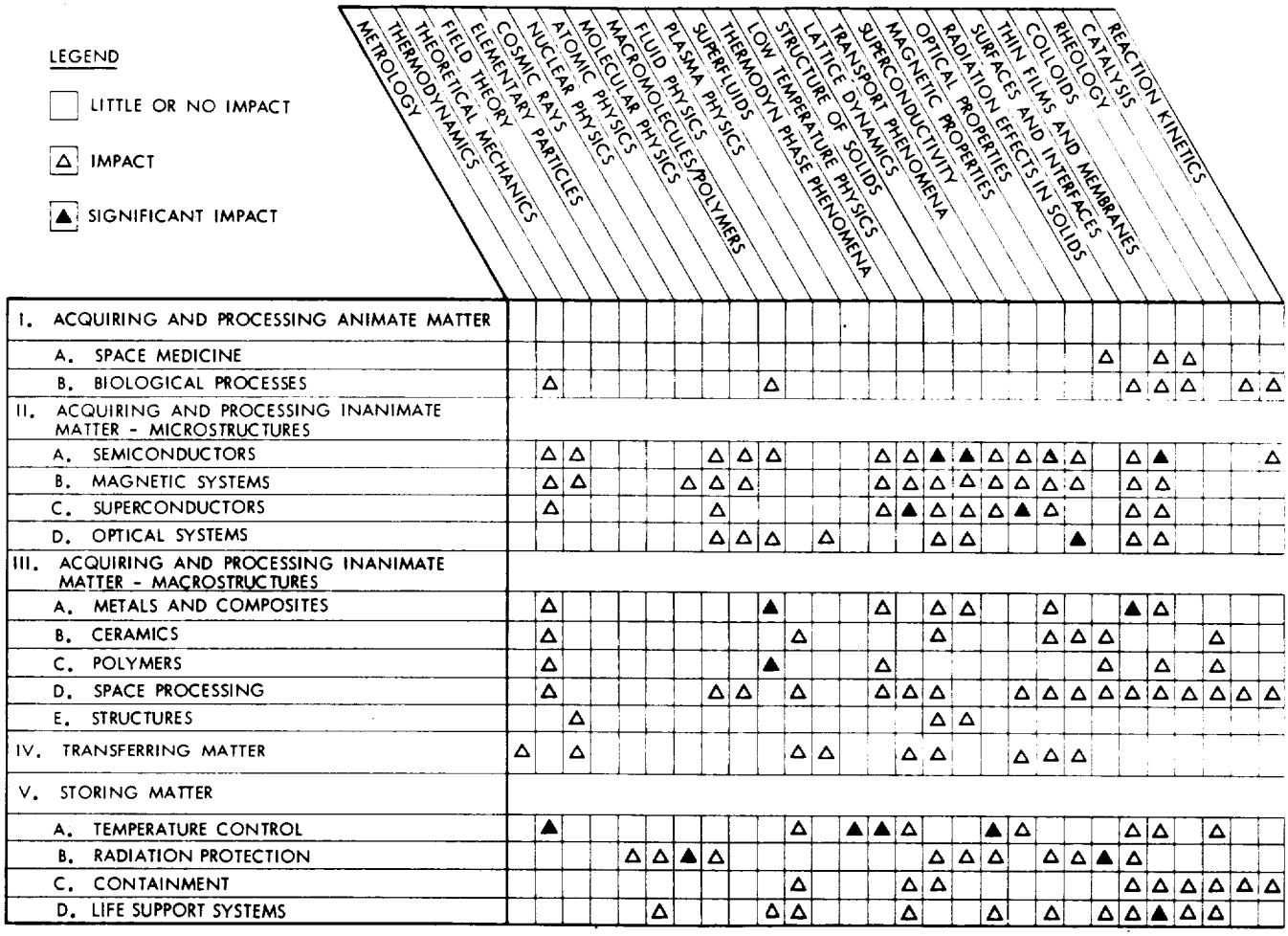
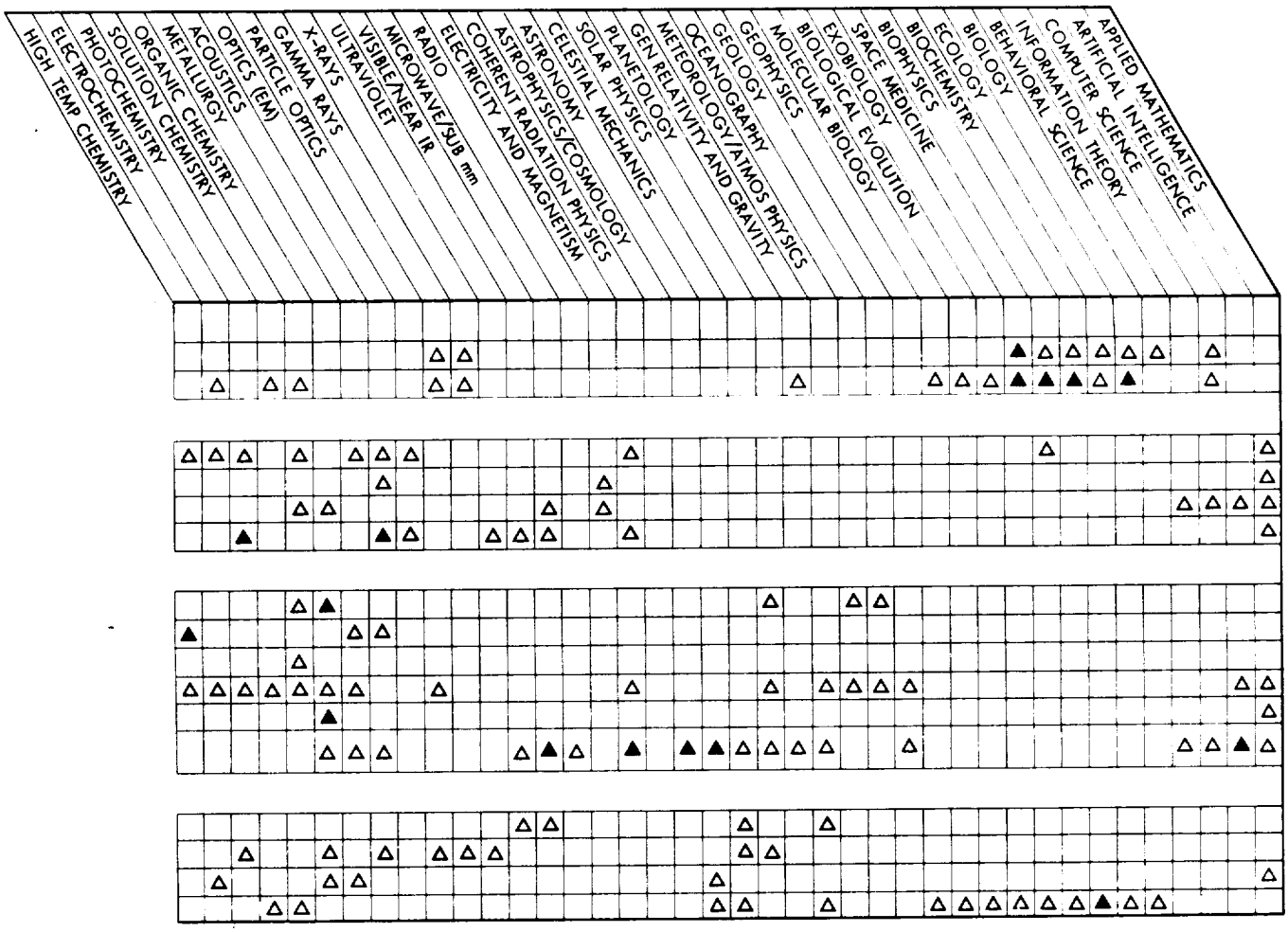


Figure 6-4. Effect of



science on technology: matter

value in giving a more tangible indication of their nature and how they might be traced.

For forecasts which project mainly extensions of parameters of given components or materials, the scientific connections are fairly obvious. For forecasts that deal with entire systems, consideration of several conceptual system models is usually required for identifying relevant scientific fields. There is an intermediate class of forecasts characterized by an implied need for new inventions. It is often productive of ideas of scientific relevance to think about explicit inventions that could bring about the new technology.

Examples of such inventions are tabulated below. These are inventions that might serve one or more of the technologies forecast, and whose accomplishment is likely to require advances at a fundamental scientific level. The associations with either forecasts or sciences are not spelled out.

The following table categorizes the inventions according to a judgment of the relative plausibility with which a qualitative conceptual design can be specified. The inventions are not selected or ordered on the basis of their programmatic importance, and more than one set of equal relevance surely exists.

Some inventions to advance space technology

Conceptually Advanced	Speculative
Large, erectable, space structures	Imaging gamma ray telescope
Sensors for the IR-microwave frequency gap	Certain lightweight instruments for space (e.g., electron microscope, geochemical age-dating system)
Gravity wave detectors	Gamma ray laser
IR spatial interferometer	High-speed information input/output devices for human/machine interface
Venus- and Jupiter-atmosphere burning fuels	Modes of communication with non-human beings
Electromagnetic propulsion systems	Storable metastable chemicals as energy sources
Laser power generators and converters for power beaming	Lightweight fusion power sources for space
Gas-core fission reactor	Antimatter (neutral atoms) production and storage
Fusion reactors (any weight)	Lightweight helium liquefier for space
	High-temperature superconductors (e.g., T>30 K)
	Counters to physiological deterioration in space environment
	Food synthesis from primitive organic substances

We have considered identifying some of the limitations which fundamental physical laws place on technological advances, but aside from obvious ones such as perpetual motion or acceleration beyond the speed of light, we have been unable to characterize these limitations with much confidence. An argument by F. B. Estabrook supports our belief that anti-gravity devices cannot be realized.

> "Any assessment of the possibility of antigravity principles or devices being discovered in the next 25 years must rest on one's judgment of the present status of gravity experiments and theory.
>
> Present-day relativistic gravitation theory is embodied in Einstein's famous General Relativity, or in a small family of related relativistic formulations. Verification of several detailed predictions of this theory has come in the last decade, from the precision celestial mechanics of the space program. At the same time, discovery of new classes of celestial objects, such as pulsars, has been seen to accord with other predictions of this remarkable theory. Penetrating and convincing recent theoretical developments have shown the theory to be a deeply causal field theory of a sort not too different from other successful relativistic theories for electromagnetism, neutrinos, etc. The conclusion drawn by all serious experts in this field is that the gravitational interaction of systems is essentially long range (this conclusion of course is also built into the classical Newtonian theory of gravity, an excellent approximation on any terrestrial scale), and further that the source of any gravity field is the essentially positive energy mc^2. It follows that gravitation is unshieldable, and always attractive."

Section III. POSSIBLE PROMINENT ELEMENTS OF THE 1980-2000 TECHNOLOGICAL MILIEU

During any given period of time, certain technologies acquire a prominence in use that makes them central features of spacecraft or mission design. For instance, integrated circuit technology has led to the replacement of analog by digital techniques in a sufficient number of spacecraft subsystems that spacecraft presently under design are assuming many of the characteristics of programmable computers. This trend may have profound effects which can only be dimly perceived at this time.

Following are a few other examples of technologies that we expect to acquire this sort of importance, for the space program, in the next two decades. Their growth is expected both because of evident technical promise and because clear national needs are expected to assure a continued high level of financial support.

A. CRYOGENICS/SUPERCONDUCTIVITY

Cryogenic techniques have been well advanced by the needs of aerospace and atomic-age systems, and were already the basis of a multi-billion-dollar business in the late 1960s. The Nation's energy program's needs for energy savings, offered by superconducting transmission lines and other power equipment, seem likely to promote a similar large investment in the development of superconductivity technology (Refs. 6-5, 6-6, and 6-7). The annual national investment in applied superconductivity was already about $26 million in FY'74 (Ref. 6-6).

The discovery of materials that can be made to be superconducting at temperatures above 20°K has made the refrigeration problems appear much simpler than when temperatures below 10°K were required. Prior to this discovery, it was necessary to cool materials almost to liquid helium temperatures; whereas now, superconductivity can be maintained at the temperature of boiling hydrogen. Although this critical temperature has so far only been achieved with thin films, it is predicted to be achievable with wires or ribbons by 1980 (Ref. 6-6). Still higher critical temperatures will be required if high-field devices are to be feasible at hydrogen temperatures, however.

Superconducting coils in space will be important for magnetic analyzers used to study energetic particles (cosmic rays, solar flares, radiation belts). Such coils may well be essential for fusion reactors and advantageous for other spacecraft power and propulsion systems. Superconducting materials are already in use in the laboratory for high-Q radio and microwave resonators and for various computer elements. Cryogenic temperatures are essential for several important classes of electromagnetic radiation detectors, some of which employ superconducting materials. The ubiquity of superconductivity in future space technology is indicated by the judgment expressed on Figs. 6-1 through 6-4 that the science of superconductivity will impact developments in more than 35 of the technologies.

All of the above suggests that cryogenic subsystems might be important and customary features of future spacecraft design. With superconductivity and its attendant cryogenics being commonplace technology, one can expect a burgeoning of new classes of devices: electronic, propulsive, and others, which will exploit the opportunity to use these techniques.

Several specific applications are discussed in other Parts of this report. More general projections on this subject have been given by B. Matthias (Refs. 6-7 and 6-8).

B. MICROSTRUCTURES

A major challenge in forecasting this subject is to avoid "predicting" something that already exists. Examples of this technology are discussed in the Management of Matter forecasts (see Part Five, Section III) of this report. We merely call attention here to one natural extrapolation.

Although the fabrication techniques for microelectronic devices (e.g., ion implantation, scanning electron microscope use as a machine tool) are somewhat sophisticated by previous standards, many of them seem to be achievable without the use of large-scale components. Add the further point that such fabrication can be made to proceed under computer control, and it becomes likely that manned space vehicles or stations might carry their own microelectronic fabrication shops capable of manufacturing new devices according to coded instructions communicated from Earth. This would add a considerable degree of self-sufficiency to such vehicles (e.g., space stations) providing for extraordinary versatility in terms of apparatus repair, replacement, or upgrading, or even new device fabrication. It will probably be considered essential for space or Lunar habitats, and at some point will even be cost-effective for satellites that have regular traffic to Earth.

C. COHERENT RADIATION AND INTEGRATED OPTICS TECHNOLOGY

We cannot hope to do credit to coherent radiation techniques, whose subfields are now the subject of entire books, but here we can only suggest

their impact by a quote from Allan Bromley (Ref. 6-9) concerning the laser: "Perhaps no other development in physics has so quickly been transformed into a powerful tool throughout science and technology; nor is there any end in sight to the laser developments themselves or their applications." The importance of laser applications is also implied by their appearance in all Parts of this report.

Integrated optics, a subject so new that it is not even mentioned in Physics in Perspective (Ref. 6-2), is directed toward creating the analog of coherent microwave technology in the optical region. Key ingredients are microscopic lasers for coherent wave generation, high-transmission thin films and optical fibers for waveguides, periodic structures for couplers, and a number of other counterparts of microwave components. Laboratory versions of the components named have already been demonstrated. The discipline's most obvious application is to the processing, transmitting, and storing of information at the immense rates inherent in modulated laser beams (see the corresponding forecasts in Part Three, Section III). According to John R. Pierce (Caltech, private communication), integrated optics offers the greatest advance in communications since the invention of the transistor. This promise alone should assure that broadly based R&D funding will probably be available in amounts to advance the state-of-the-art at a pace limited only by the imagination of the researchers.

As the basic components become widely available, they will be applied in virtually all of the ways that microwaves are now -- transforming certain fields (e.g., spectroscopy) and introducing entirely new ones. Recent experiments that have demonstrated the direct conversion of fission fragment energy into laser radiation (Ref. 6-10) add a further new perspective whose implications are yet to be explored.

Gamma-ray lasers, an ambitious, hoped-for extrapolation, are the subject of serious research (Refs. 6-11 and 6-12) and offer potential new areas of application probably comparable in scope to those of the laser.

Section IV. SUMMARY AND CONCLUSIONS

A. SUMMARY

Science more often provides an environment to stimulate and enable exploitation of technological ideas than it serves as the origin of technological ideas (H. Brooks). The forecast advances in space technology will require this "enabling" support from a large number of disciplines in the physical sciences. Although NASA may make only a small fraction of the global investment in some areas, it must be represented by research in each area in order to have meaningful access to other work in that field. Scientific disciplines of most widespread applicability to NASA technologies are those that concern the electromagnetic properties of solids.

In some instances (e.g., certain aspects of remote sensing), advances in fundamental technique may contribute as importantly to increased capability as advances in hardware technology.

B. CONCLUSIONS

This Part has offered a limited view of the role of science in advancing space technology between now and the end of the century. Inasmuch as breakthroughs, by their very nature, usually arise from unexpected syntheses of diverse disciplines, it is not clear that a more detailed treatment could produce an explicit set of predictions with much increased credibility. Historically, it has been difficult to judge in what research areas breakthroughs will occur (Ref. 6-1).

A major gap in the report has been the omission of new developments in biology which will contribute to space technology. Other forecasts of which we are aware do not contain these, either. However, the many insights into fundamental biological mechanisms currently being revealed must have a profound and far-reaching impact, affecting all aspects of technology, including space technology.

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