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NASA SCIENCE AND TECHNOLOGY ADVISORY COMMITTEE FOR MANNED SPACE FLIGHT

Proceedings of the Winter Study on Uses of Manned Space Flight, 1975-1985

VOLUME II — APPENDIXES

A CONFERENCE HELD IN

LA JOLLA, CALIFORNIA

DECEMBER 6-9, 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Preface

In preparation for the four-day study at La Jolla, a series of "white" papers was written in advance, covering each discipline. These are published here in Volume II as appendixes to Volume I. They were prepared under the direction of STAC members, drawing on staff assistance from Bellcomm, Inc., and NASA offices as follows:

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March 19, 1967

CONTENTS

APPENDIX A–MANNED SPACE-FLIGHT CAPABILITIES

Introduction 1
Apollo Applications Program 1
Space Station 5
Low-Cost Transportation 7
Lunar Exploration 9

APPENDIX B–LOW-COST SPACE TRANSPORTATION

The Dimensions of Low-Cost Space Transportation 15
Why Not Reusability? –The Facts of Life About
Rocket Vehicles 19
NASA'S Role in Low-Cost Space Transporation 24

APPENDIX C–THE LUNAR PROGRAM

Introduction 29
Lunar Exploration, 1969-1974 30
Potential Lunar Program Objectives, 1975-1985 34
Lunar-Base Technological Support Operations 39
References 49

APPENDIX D–ASTRONOMY

Introduction 51
Goals and Objectives of Astronomy 52
Role of the Manned Program 55
Observing Sites for Astronomy in Space 61
Critical Issues 66
Conclusions and Recommendations 69
References 70

APPENDIX E–SPACE PHYSICS

Introduction 73
High-Energy and Cosmic Ray Physics 74
Behavior of Solids, Liquids, and Gases in Zero-G 76
Relativity, Cosmology, and Gravitation Physics 76
Micrometeoroid Measurements 79
Magnetospheric Physics 79
Critical Issues 80
Orbital Considerations 81
Conclusions and Recommendations 81
References 83

APPENDIX F–EARTH SCIENCES AND APPLICATIONS

Introduction 85
Objectives 85
Space Accomplishments as of 1968 86
The Needs in Earth Sciences and Applications
as We See Them Today 88
Post-1968 Earth-Orbital Systems
for Earth Sciences and Applications 98
Man's Interaction with the Instruments in Earth Orbit 102
Critical Issues 104
Recommendations 108
References 109

APPENDIX G–LIFE SCIENCES

Introduction 111
Passive Role of Man 112
Active Role of Man 112
Critical Issues 118
Conclusions 120
Goals and Research Activities
in the Life Sciences 121
Bibliography 161

APPENDIX H–MATERIALS SCIENCE AND PROCESSING IN SPACE

Introduction 163

Properties of the Space Environment Relevant to
Materials and Processing 164
Opportunities Provided in Zero-G 166
Requirements for a Space Facility 169
Conclusions 170
Limitations on Zero-G 171
References 173

APPENDIX A
Manned Space-Flight Capabilities

INTRODUCTION

This paper presents systems descriptions of NASA manned space-flight capabilities in a program extending from the early 1970's to 1980 and beyond. For the relatively near-term Apollo applications program (AAP), these capabilities are well on their way toward realization. Toward the mid-1970's commitments are less definite, but specific plans are being laid which could culminate in a space station as early as 1975 and in some kind of lunar scientific station in the latter half of the 1970's. As part of the space station system, a low-cost transportation shuttle development is planned. Whether or not these systems come along as projected here will depend largely on decisions made at the national level as to the pace and scope of the program. Nevertheless, the systems described in this paper are representative of our thinking, and many of them, or systems of similar capability, are highly desirable and can be expected to come into being sooner or later.

APOLLO APPLICATIONS PROGRAM

The Apollo applications program, which follows Apollo, was conceived to make optimum use of the manned space-flight capability developed during Gemini and Apollo. The program takes advantage of the space vehicles, facilities, and organizations as they are made available by the Apollo program. Flights will begin in the early 1970's, and the technology provided will be important to future, long-duration space station design and development. The AAP missions use five Saturn IB launches, three manned and two unmanned, to perform three interrelated missions beginning in the latter half of 1971 and ending in 1972.

The Saturn I workshop mission (AAP-1/AAP-2) uses the empty hydrogen tank of the S-IVB stage (after its use as a launch vehicle stage) as the nucleus of an embryonic space station. In orbit, the workshop consists of the modified stage plus two modules: an airlock and a multiple-docking adapter. The airlock module provides access to the stage interior, to the docking adapter, to space for extravehicular activity, and to space for experiments requiring it; it also provides environmental control, power, communications, and control functions. The multiple docking adapter provides docking accommodations for an Apollo command and service module and the Apollo Telescope Mount, which is brought up in the third mission; experiments and several habitability systems are stored here during launch. Workshop electrical power is supplied by solar panels and batteries.

The workshop, with its auxiliary equipment, is launched unmanned. The three-man crew with its logistic support will rendezvous with the Saturn I workshop in an Apollo command and service module (CM and SM) modified to extend mission duration and to interface properly with the workshop. Following venting of the tank, the crew will complete outfitting of the workshop for living and working, and initiate the experimental phase of the mission. The mission duration will be open-ended up to 28 days.

This Saturn I workshop mission is designed to provide space and facilities for a broad spectrum of experiments and provide a foundation of basic information essential to the design and development of follow-on space station systems. It emphasizes medical and habitability experiments, but also supports a number of science and technology experiments.

The first workshop revisit mission (AAP-3A) uses a single Saturn IB launch of the modified three-man command and service module to rendezvous and dock with the Saturn I workshop set up in the previous mission. This mission is the first flight test of the concept of reusing a habitable space structure after several months of uninhabited operation in orbit. The planned duration of up to 56 days is the next step in the progressive extension of mission length to test and evaluate systematically the ability of both men and spacecraft to function effectively over long periods of time in space. For this reason the primary in-flight experiment emphasis will be on the medical area. This will probably be the first mission in which a medical doctor is a member of the crew.

The solar astronomy mission (AAP-3/AAP-4) uses the Saturn I workshop as a base of operations for the manned Apollo Telescope Mount (ATM) solar observatory. One Saturn IB launches a modified three-man CM and SM configured for up to a 56-day mission; a second Saturn IB launches the unmanned lunar module/Apollo Telescope Mount (LM/ATM) with its payload of solar instruments. After the CM/SM rendezvous and dock with the Saturn I workshop, the crew reactivates the workshop.

The LM/ATM then accomplishes rendezvous, unmanned, with the workshop and is docked to the docking adapter under the control of an astronaut in the workshop. This will be the first time we have performed an unmanned rendezvous, a technique which we expect will be of great importance in the future. This technique will be used to bring subsatellites into a space station, service them, and then send them back out–a function which may become one of the major uses of space stations. The unmanned rendezvous technique will also be used in the future to bring payloads up to space stations and return payloads to Earth, as in the LM/ATM mission.

The LM/ATM uses a modified ascent stage of the Apollo lunar module plus an Apollo Telescope Mount. The ATM consists of a structural rack carrying the solar astronomy instruments, a coarse-pointing control system, including control moment gyros which can also maintain the orientation of the entire workshop ATM assembly, a fine-pointing gimbal system to aim the solar telescopes to an accuracy of ±2–1/2 arc-seconds, the thermal control system, and the array of solar cells and the power conditioning and distribution system which power the ATM. The solar instruments payload consists of two X-ray telescopes, a combination spectroheliograph and spectrograph operating in the extreme ultraviolet, a scanning spectrometer in the extreme ultraviolet, and a white-light coronagraph. The ascent stage serves as the experiment control station during ATM operations, provides propulsion and flight control for rendezvous and docking the ATM to the workshop, and serves as the base for extravehicular activity to retrieve film from the solar telescopes. The complete workshop/ATM cluster is illustrated in figure A-1.

This mission will give us about 2 months of solar observation time. Should the Saturn I workshop not be available for reuse, contingency plans have been made to fly the solar astronomy mission decoupled from the Saturn I workshop orbital assembly.

The Apollo applications program will provide criteria important

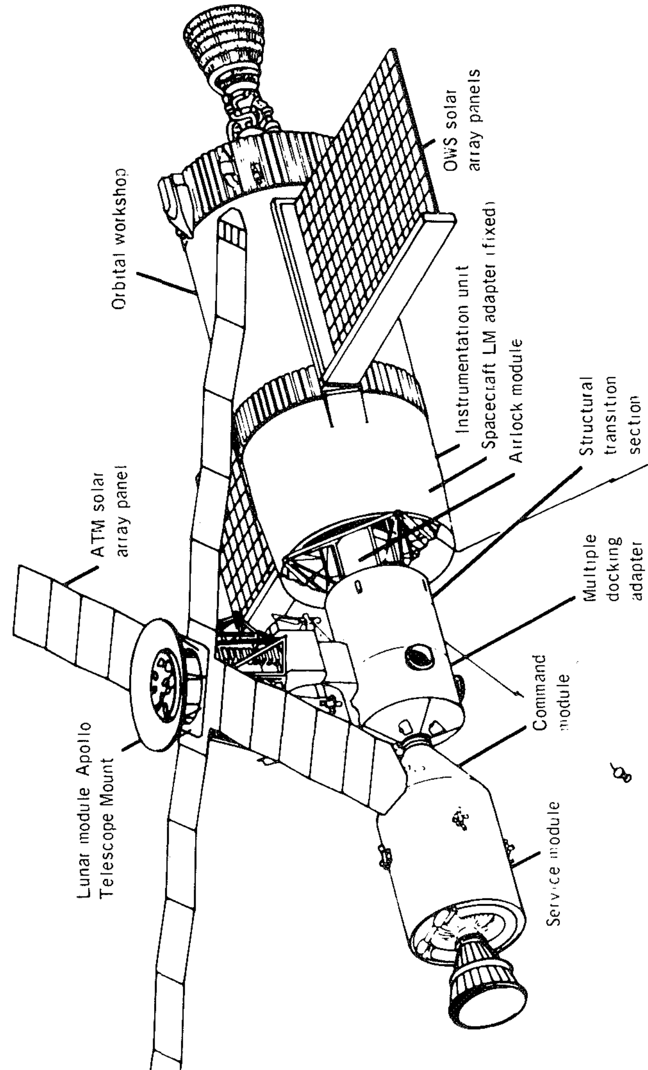


Figure A-1.–Apollo applications program cluster.

to future space station programs in the following areas: physiological effects of long-duration zero-gravity, crew performance, habitability requirements, work station requirements, extravehicular capabilities, vehicle engineering and system qualification, mission operations, and experiment operations.

SPACE STATION

NASA will shortly embark on the formal definition of a space station program, with flight occurring as early as 1975. This is a significantly more advanced concept than the Saturn I workshop in the Apollo applications program and will possess a high degree of mission and operational flexibility as well as adaptability to a broad band of schedule and funding possibilities. The goal of this program is the establishment of a multipurpose, general-usage laboratory for a variety of disciplines including astronomy, Earth sciences and applications, industrial processes, physics, life sciences, and advanced technology. The present view is that the best way to approach this capability is not to try to design the ultimate space station now, but rather to design those parts of the space station, which we call modules, that we are sure will be needed. Basically there will be three kinds of modules–utility modules, living modules, and experiment modules. The living modules are sent up first, and later, as the development of the experiments is finished, an experiment module is sent up and latched onto the living quarters. The experiment modules would be laboratory-type modules designed with the instrumentation and flexibility to carry out a range of experiments within a given discipline, such as cosmic ray experiments, much like ground laboratories. In this way these experiment modules could be used over a long period of time for different observations, and consequently achieve economical operation through a high degree of utilization. The module diameter should be about 22 feet, and the weight will be in the range of 40 000 to 100 000 pounds. A certain number of these modules could be combined and launched at the same time on a single Saturn V, or they could be launched separately on Saturn IB's, or intermediate launch vehicles. The exact size and weight for which these modules should be designed will be better defined in studies to be carried out this year.

The space station will be designed for as much as 10 years of continuous operation. This will be achieved by fundamentally highly reliable subsystem designs plus provisions for maintenance and repair, expendables replenishment, and refurbishment and replacement. Crew productivity over this period of time will be assured by rotation at 3- to 6-month intervals and by bringing up new experiment packages and modules as they become available and can be accommodated by the station workload. Productivity will be further enhanced by the use of a comprehensive onboard data system for checkout, experiments system monitoring, communications, and other functions, thereby freeing the crew's human capabilities, as much as possible, for research and experimentation.

The station is initially planned for a crew size of 12 men. Enlarging the station for larger crew sizes can be accomplished by modular techniques, the same as for accommodating changing mission requirements. The internal payload support volume will be at least 10 000 cubic feet.

The environmental control and life-support system for the station will provide a two-gas, nitrogen-oxygen atmosphere. It will provide a shirt-sleeve environment and maintain regulated suit loops for extravehicular-activity (EVA) payload support. The oxygen loop will be open, at least initially; however, the water loop will be closed except for fecal water.

Electrical power will probably be supplied by solar panel arrays, but incorporation of a nuclear electrical power supply may be desirable for some applications. The power to be provided for the initial module may run as high as 30 kilowatts and may go as high as 100 kilowatts as additional modules are added to the station.

A relatively high-accuracy attitude stabilization system will be incorporated for both Earth-centered and celestial-inertial orientations, according to the nature of the experiment program requirements. Systems of horizon scanners, star trackers, and rate gyros and conventional thrusters can furnish activation forces adequate for most station and experiment requirements ($\sim 1/2^{\circ}$). Experiment stability requirements beyond the basic station capability will be provided by the particular experiment package.

The space station and its launch system will be compatible with operation of the space station in orbits of 200- to 300-nautical-mile altitudes and any orbit plane ranging from polar to equatorial. The 200- to 300-nautical-mile altitude range represents a compromise between the requirements of Earth-viewing experiments for low altitudes and the penalties associated with atmospheric drag. The space station will also be adaptable in some form to operation in an Earth-synchronous orbit. Ultimately, we may wish to operate multiple space stations, the orbit altitude and inclination of each being selected in accordance with the special purposes of that station. We may also develop new technological uses for space stations, such as using them as staging points, to which propellants could be carried from Earth by a low-cost logistics vehicle, for deep-space missions. Another potentially important use of space stations in our future programs is for providing a support facility for checking out, servicing, and repairing unmanned satellites.

In the process of the space station program, manned systems will become operational for the purpose of fulfilling scientific, technological, and space applications objectives. The space station program will also (1) extend the present knowledge of the long-term biomedical and behavioral characteristics of man in space; (2) continue the development of systems and technology required to maximize the utility of man in space; and (3) develop practical solutions for establishing, operating, and maintaining long-duration orbital stations by evaluation of actual flight experience.

LOW-COST TRANSPORTATION

A low-cost transportation system development will be implemented in parallel with the space station. Logistics systems for personnel rotation, expendables resupply, and experiments and experiment-module delivery represent a major share of the manned Earth-orbiting space station flight program costs. Planning studies conducted by both DOD and NASA, past and present, unanimously underscore the importance of, and the need for, a more operationally effective and cost-efficient manned, round-trip, Earth-orbital transportation system. Figure A-2 illustrates the economic significance of logistics costs in the space station program. Based upon current Saturn or Titan class launch vehicles and Apollo or Gemini type vehicles for the logistics spacecraft, logistics cost could represent about 40 percent of the total program cost for the first year, and about two-thirds of the recurring cost for each additional year of operation. The viability and success of long-duration space station flight programs are therefore directly related to the availability of a more cost-effective and versatile round-trip transportation system. NASA has studied a wide range of concepts

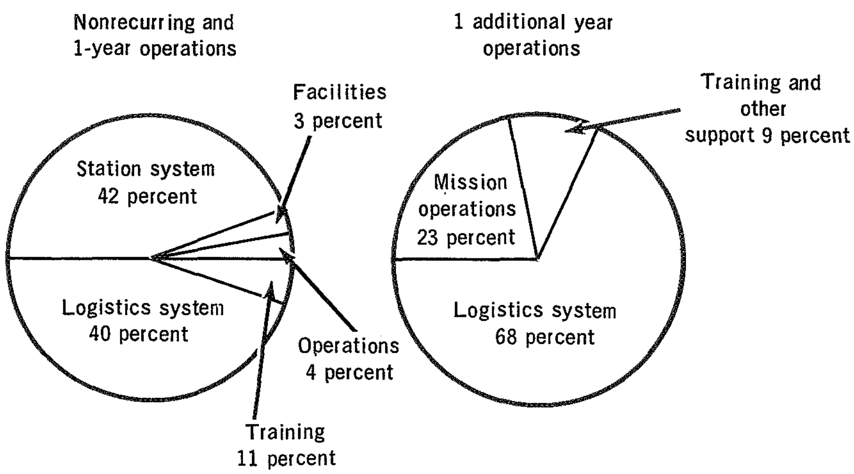


Figure A-2.—Economic significance of logistics to the space station program.

for new logistics vehicles, including conventional expendable systems, new high lift/drag (L/D) spacecraft, and reusable systems.

Conventional expendable launch vehicles with new ballistic spacecraft can achieve small steps towards cost reductions with correspondingly small technological risks and investment requirements. In view of the relatively high launch rates anticipated, this approach does not offer sufficient potential for cost reduction.

Another concept would utilize a low-to-medium L/D advanced logistics spacecraft which could be reused and an expendable launch vehicle designed with emphasis on operations economy and safety. This concept includes consideration of solid- and liquid-boost stages of simplified design. The spacecraft would be large, providing ample crew size and internal cargo capability, and have an advanced landing system utilizing a decoupled mode for terminal flight. For maximum economy, the guidance system and orbital propulsion systems would be integral with the spacecraft, so that these relatively expensive systems would also be reused. The configuration and operational mode would be selected to provide cost effectiveness in terms of checkout, turnaround, recovery, and reuse. The extent of savings achievable in this approach is limited by the fact that significant and expensive elements of structure and propulsion would be thrown away on each flight.

The most advanced concept in the spectrum is a new, integrated, logistic space vehicle system that would utilize more advanced technologies and techniques, such as medium-to-high L/D, requiring one and one-half stages to orbit, and consisting of a reusable, integral launch-and-reentry vehicle with low-cost, high mass-fraction, expendable propellant tanks attached to the sides of the vehicle. The recoverable vehicle would contain all of the systems required for boost into orbit (including the booster engines), mission accomplishment in orbit, and reentry. It would be a vertical-takeoff, horizontal-landing vehicle which would contain all of the costly hardware elements of the system, thus permitting the recovery and reuse of these elements. The boost propellant tankage would not be recovered, because it is one of the least costly elements of the system and one of the most penalizing to recover in terms of added weight to the reentry vehicle.

This system is characterized by extensive technological demands and investment costs, but promises a great reduction in manned-system operational costs. It would utilize a number of technological improvements, which are within our capabilities to develop, in order to achieve routine and economical airplanelike operations. It would have advanced heat protection and structural systems which would minimize the cost of refurbishment and maintenance associated with each flight, onboard checkout to minimize the ground crew required for preflight and postflight operations, high-pressure hydrogen/oxygen rocket engines to minimize propellant usage and throwaway tank weight, and advanced landing techniques such as variable geometry and/or jet engines to allow horizontal landing at speeds typical of conventional airplanes. Although this concept presents more of a technical challenge than the others, its design should be started soon, in view of its potential for greatly lowering operational costs.

LUNAR EXPLORATION

Continued lunar exploration will parallel the Apollo applications and space station programs. The first successful manned lunar landing will be followed by several repeat missions modified in only minor ways. Following these missions, the Apollo systems will be improved, and the first half of the 1970's will see increased staytime on the lunar surface, improved astronaut mobility, extended range of traverses, establishment of lunar-wide geophysical networks, and the conduct of photographic and remote-sensing surveys from lunar orbit.

As with the Apollo applications program, the lunar program in the early 1970's will make maximum utilization of Apollo hardware. The duration of the lunar module on the lunar surface will be extended from about 36 hours to 3 days. A small lunar flying unit could be carried along which would provide a high degree of mobility, up to 10 kilometers from the lunar module, allowing the astronaut to visit special features, deploy equipment, return samples, or rescue a second crewmember. Preliminary studies indicate that such a flying unit would weigh nearly 200 pounds and use residual propellants from the lunar module descent stage. It would carry the pilot with his personal equipment and 400 pounds of payload, or an additional crewmember. The possibility of using flying vehicles for more extensive transportation on the lunar surface is also being studied.

For missions later than the 1972-73 time period, NASA is studying the development of a roving vehicle that can be operated either manned or unmanned. During manned operation, the rover will conduct loop sorties up to 10 kilometers from the spacecraft, with a round-trip distance of 30 kilometers and a speed up to 15 kilometers per hour. In the automated mode, the rover will make traverses of approximately 1000 kilometers at an average speed of 1 to 2 kilometers per hour. It will be capable of operating in rugged terrain to investigate regions of high scientific interest. The vehicle will make scientific measurements along the traverse, deploy automated scientific stations, and collect lunar samples. Vehicle power will come from a combination of solar panels, batteries, and a radioisotope thermoelectric generator.

The internal structure and energy budget of the Moon will be investigated primarily by seismic networks that will require simultaneous operation of widespread, long-lived stations. Measurements of heat flow and lunar gases will also be conducted with these arrays. The Advanced Apollo Lunar Surface Experiments Package (ALSEP) will comprise a central station with standard experiment interface for power and data, and a number of pallets carrying modular surface experiments. Power will be supplied by a radioisotope thermoelectric generator. A remote geophysical monitor and a science station would be similar to the ALSEP, but contain smaller and more compact experiment systems.

Orbital measurements are essential for lunar-wide understanding and geodetic control. Consideration is being given to the use of instrumentation in the manned, orbiting, command and service module after the lunar module is dispatched to the lunar surface. Orbital surveys would be conducted using the techniques of metric photography, radar, altimetry and tracking, high-resolution photography, and spectroscopy.

Determination of the interaction of the Moon and the space environment includes disturbances of solar wind plasma (shock front and shadow zone), penetration of the solar-wind magnetic field into the interior of the Moon, and nuclear reactions induced in the lunar surface material by cosmic radiation. A "clean" orbiter, free from magnetic and radiation interference, can be deployed in lunar orbit as a subsatellite from the command and service module, or launched directly from Earth, like the anchored Interplanetary Monitoring Platform (IMP), Explorer XXXV.

During the mid-1970's, further extensions of Apollo-derivative systems could be used in increasingly ambitious missions. For example, modifications to the Apollo hardware could extend lunar surface staytime to 2 weeks and could lead to substantially increased scientific payload and astronaut mobility. A 7- to 14-day lunar module taxi would be employed to deliver the two crewmen, along with equipment, to the lunar surface for field geology investigations and return them to an orbiting 20-day command and service module. During their staytime on the Moon, the crew would live in a shelter that may be environmentally attached to the lunar module taxi, or provided by a previously landed lunar payload module. The latter vehicle would be delivered by a manned flight to lunar orbit and landed unmanned at a site of scientific interest. The payload would typically consist of a lunar roving vehicle, two-man shelter, small laboratory, advanced ALSEP, and lunar flying units.

A further step in lunar capability would involve use of at least three men on the surface for periods in excess of a lunar day. These missions would be used for extended exploration or for site revisit. A new three-man lunar module would land three astronauts on the lunar surface and return them and scientific data to lunar orbit for rendezvous with the command and service module. A 90-day, quiescent command and service module could deliver a three-man crew to lunar orbit, and would wait up to 90 days in quiescent mode for crew return. After reactivation by the crew, it would then return them to Earth.

An unmanned lunar module truck would deliver as much as 10 000 pounds to the lunar surface. A suitable shelter providing convenient accommodation and life support for the crew would weigh about 2000 pounds, including fuel cells, radiators, and breathing oxygen. The astronauts would use the standard Apollo lunar orbit rendezvous mode, except that the entire three-man crew would transfer to the three-man lunar module. After landing, the three-man lunar module would either remain dormant, waiting to return the crew, or a following lunar module would be used for crew rotation and site revisit. Weight additions required to provide for quiescent standby (meteoroid protection, electrical power, radiator, etc.) will require propulsion-system upratings.

A lunar base of some kind could be available in the late 1970's or early 1980's. Such a semipermanent base or scientific observatory would be capable of supporting 6 to 12 men continuously for a year or more. The base system would be modular and comprised of sequentially launched cargo landers carrying shelter modules, power (nuclear) modules, and life-support and communications modules. Mobility devices, operating with attachments, would be available to provide at least partial burying of the modules.

Cargo delivery could be based on an uprated Saturn V (60-percent uprate), which would launch new braking and landing stages into a translunar trajectory. The braking stage would remain in lunar orbit and the landing stage would then descend to the surface with a 50 000-pound payload. Personnel delivery would also be based on use of the same launch vehicle, with braking and landing stages carrying a six-man modified Apollo command module and ascent stage for Earth return. During the period of lunar stay, the personnel carrier could be placed in a dormant, standby condition.

After the Apollo landing has been accomplished, the next phase of lunar exploration will gain sufficient knowledge of the Moon to determine the nature and direction of additional exploration or exploitation. Considerable progress toward resolving questions of the composition, structure, and processes of the Moon's surface and interior, and the history of events by which the Moon arrived at its present configuration can be expected. Comparative study of the Earth-Moon system will have advanced our understanding of our own planet, and the entire solar system. Results of exploration missions will determine how the Moon's unique environment can be exploited to utilize it as a space platform for astronomy, research, and applications.

APPENDIX B
Low—Cost Space Transportation

THE DIMENSIONS OF LOW—COST SPACE TRANSPORTATION

As the Apollo program comes to a close and with it the end of man's first decade in space, many thoughtful people are asking "What next?" Two extremes of thought delimit the answer to this question.

On the one hand, our remarkable progress has erased almost all doubt about man's ability to travel in space and has led many to believe that space offers a worthy challenge for the human spirit. To these people it is only a matter of time until we make the planetary system inhabitable and interconnect it with a vast space transportation network. At the other extreme are those who oppose the large expenditures of the space program and urge that it be terminated and its budget be used in solving some of our more immediate and pressing problems. A sober appraisal shows that the dreams of the space enthusiasts may never materialize if the taxpayers become disenchanted and are no longer willing to pay the costs.

A major factor in the debate has been the high costs of the space program. With each space flight costing tens or hundreds of millions of dollars it is difficult to argue that space travel can ever become commonplace. Why is the space program so expensive and what are the prospects of reducing space costs to reasonable levels?

To place various costs in perspective, table B-I has been constructed. The scale on the left is logarithmic and shows dollars ranging over 12 powers of 10.

In the first column a few pertinent annual rates have been listed. The U.S. gross national product stands at about 12 powers of 10, Table *B-I – Various Cost Comparisons in Relation to NASA Costs*

Cost in dollars	Annual rates	Development costs	Per vehicle	Per flight	Per ticket
10^{12}	USGNP				
10^{11}	Federal budget				
10^{10}					
	NASA	Saturn V			
10^{9}		SST		Saturn V	
			Saturn V		
10^{8}		707			
			SST	Saturn IB Titan III	Saturn V
10^{7}			707		
10^{6}					
10^{5}		Early airplanes			
10^{4}	Individual salaries		Autos	SST 707	
10^{3}					
10^{2}					Airline
10^{1}				Auto	Bus
10^{0}					

the Federal budget at about 11, and NASA's annual expenditure at about 9-1/2. Considerably lower, we see salaries of individual citizens ranging from 3 to 5 powers of 10.

In the second column we have listed the cost of developing various systems that are of interest here. The total development cost for the Saturn V system is about 9-1/2 powers of 10. The projected cost of developing the supersonic transport is about 9, and the development of the 707 jet airplane cost about 8. The cost of developing early airplanes must have been about 5.

When we ask about purchasing individual vehicles, we see that a Saturn V costs about 8 powers of 10, an SST about 7-1/2, and a 707 under 7. Automobiles are about 3-1/2.

The cost of a single flight of Saturn V is about twice that of the vehicle alone, that is, between 8 and 9. Saturn IB and Titan III are a little less–between 7 and 8. And now we come to the significant fact that the cost per flight of a 707 is just over 3 powers of 10 and the cost of an SST flight is not going to be much more. The cost of the average auto trip ranges from 0 (i.e., $1) to 1-1/2 powers of 10.

Finally we examine the price of purchasing a ticket. If you were to go to NASA and ask to buy a ticket on Saturn V, NASA would have to charge you between 10^7 and 10^8 dollars. On the other hand, if you go to an airline it is difficult to pay more than 3 powers of 10–or to pay less than 1. Bus fares are somewhat less.

Now that we have completed the table, let us stand back and take an overall look. The most penetrating fact is that there are about 4 to 6 powers of 10 difference between the cost of a ticket on Saturn V and that on a commercial airliner.

The Saturn V ticket price is appropriate for NASA because it represents a reasonable fraction of NASA's budget. And the airline ticket is reasonable for the average citizen to pay because it is an appropriate fraction of his annual salary. Similarly, the price of a Saturn V and that of an automobile are each reasonable for the person buying them. But if space travel is to become commonplace for the average citizen, it is abundantly clear that ticket prices cannot be based on NASA's budget.

Hereafter, when we speak of low-cost space transportation, we define low to be so low that the average citizen can afford to buy tickets for space. Short of this, space transportation can never become commonplace.

Is it a dream to talk of reducing space costs by 4 to 6 powers of 10?

First, let us see why costs are high. Here one finds the technical and public literature filled with myths. A typical myth says that money for space has been easy to come by, and as a result funds have been squandered to a point where costs have become exorbitant. A different version of this myth claims that costs are high because we have overemphasized safety and because the testing program has pushed costs out of sight. Common sense says that waste and/or caution may account for modest increases, but not 4 to 6 powers of 10.

The table bears this out. The supersonic transport is not too different in size, weight, and complexity from Saturn V, and its development cost is within a half a power of 10 of being the same. And even with its billion-dollar development cost, it is expected to be a commercial success, with tickets selling in direct competition with subsonic aircraft. If space and airline tickets were in direct proportion to their development costs, space transportation would be low-cost transportation. Clearly, development costs are not the cause for which we are searching.

Another myth states that space travel is inordinately expensive because rocket engines have enormous appetites. This myth clinches the point by saying that if commercial airliners had to use rocket engines for propulsion, they would be economic failures. Let us take a closer look.

A space vehicle and a jet transport, each in its own environment, are comparably efficient. The rocket starts off with an enormous gulp of propellant, but afterwards it goes on and on, and on—free. The jet airplane uses fuel at a much more modest initial rate, but must use and use and use throughout its entire flight. The propellant and fuel costs of Saturn V and the supersonic transport are less than 1 power of 10 apart; sufficiently close, in fact, to show that these costs cannot explain 4 to 6 powers of 10.

Another version of this myth claims that space transportation is inherently expensive because the distances involved are so great. This argument goes on to say that in fairness to space transportation, costs should be reckoned on a dollars-per-mile basis. Such an argument, if correct, would refute the belief that space transportation can ever become commonplace. However, the numbers themselves do not stand up. At 10 cents per mile, a round-trip ticket to the Moon should cost $40 000, which is several powers of

10 short of the actual cost, and more than the average citizen can afford.

We could go on examining purported causes for the high cost of space transportation, but it is more profitable to ask–what is the real reason. This is not hard to find.

If a supersonic transport lasted for only one flight and carried only a handful of passengers, a ticket would cost within 1 power of 10 of that for Saturn V. This leads inescapably to the conclusion that we must get vastly increased utilization in proportion to the expensive investment required for a space vehicle. To do this we must:

(1) Reuse the same vehicle over and over (several powers of 10).

(2) Reduce the cost of each reuse (including refurbishment and relaunching) so that it is small when compared to the cost of building a new vehicle (by several powers of 10).

(3) Increase the utility or productivity of the space vehicle. In the case of probes, laboratories, and observatories, this means obtaining a vast amount of scientific or technical information during the lifetime of the spacecraft. In the case of space stations, factories, and the like, it means processing or producing sufficiently large amounts of data or materials to pay for the large initial cost. In the case of space transportation, it means carrying a large amount of revenue-paying cargo and passengers. Item 3 does not concern us, because engineers have a natural aptitude for moving in this direction. It is items 1 and 2 that require attention.

WHY NOT REUSABILITY? THE FACTS OF LIFE ABOUT ROCKET VEHICLES

In view of the preceding discussion, one would think that there should be a great hue and cry against throwing away space vehicles after only one use. But there are perfectly good reasons why this is not so. Let us look at the basic facts about the design of rocket vehicles.

As a rocket vehicle sits on the pad, ready for launch, its gross weight W can be divided into three significant parts. The first is payload P, which consists of everything that the "customer" would be willing to pay revenue to take along. The second is weight F of the propellants used during the flight. The third is all the remaining weight, which we shall call "structure" and designate by S. This last item includes tanks, rocket engines, electronic components, guidance, etc.

The fundamental equation for rocket vehicle performance is

$$V = -C \log_e \left(\frac{S}{W} + \frac{P}{W}\right)$$

where V is the integrated velocity achieved by the vehicle (including the effective velocity needed to overcome gravity and air resistance) and C is the exhaust velocity of the rocket (which is the specific impulse multiplied by the acceleration of gravity).

Now let us look at the significance of the various terms in this equation. Velocity V depends on the mission. About 26 000 ft/sec are required to go into orbit and about 36 000 ft/sec to break away entirely from the Earth's field. With regard to exhaust velocities C, early rockets achieved velocities of 8000 ft/sec and modern rockets have pushed this up to about 14 000 ft/sec. Concerning weights, one finds that for a given vehicle it is possible to exchange payload for propellants on a nearly even basis, without altering the gross weight. One also finds that the ratio of the structural weight to the gross weight depends almost entirely upon the state of technological development, and very little upon the size of the spacecraft. In early space vehicles, the ratio for S/W was about 0.24; in current technology, S/W is more nearly 0.06. The net effect of the above statements is that the designer first obtains the best ratio of S/W that he can. He next determines the propellant ratio F/W to suit his mission requirements (if he can), and then scales the entire spacecraft up or down to meet the size of payload desired.

To see how all this works, we have plotted in figure B-1 the ratio of vehicle velocity to exhaust velocity versus the ratio of gross weight to payload for various ratios of structural weights to gross weight. Let us first examine the problem faced by an early designer in trying to place a vehicle in orbit and having at his disposal an exhaust velocity of the order of 8000 ft/sec and a structural weight ratio of 0.24. Because orbital velocity is approximately 18 000 ft/sec, he needs a V/C of 2.3. Having picked a payload weight, he enters the chart along the line S/W=0.24, hoping to run up the gross weight to a point where he can achieve V/C=2.3. Following out along the S/W=0.24 curve to larger and larger values of gross weight, he quickly finds that the curve reaches an asymptotic value of V/C=1.43, and that even an infinite-size vehicle would not permit him to achieve an orbital value of V/C=2.3. Stopped on this front,

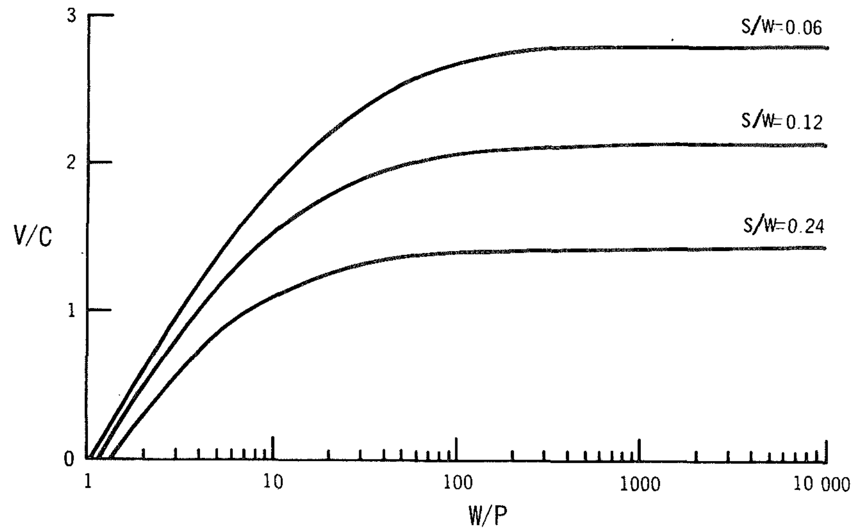


Figure B-1.–Ratio of vehicle velocity to exhaust velocity versus ratio of gross weight to payload for various ratios of structural weights to gross weight–single-stage.

he exercises his ingenuity in the following way. Using a modest size vehicle to carry his primary payload, he carries this vehicle along as the "payload" of a larger vehicle which, if necessary, can be carried along as the payload of a still larger vehicle, and so on. This use of multiple stages has the following powerful advantage. As the rocket uses up its propellants it lightens its load and thus obtains the greatest increase in velocity during the final moments of burning. This last burst of speed is limited by the onboard weight which, for a hard-pressed vehicle, is largely structural weight. With tanks nearly empty, much of this structural weight is no longer needed, and if it could be discarded, the final burst of speed could be greatly increased. Staging is the designer's way of progressively discarding no longer needed weight to achieve just such an advantage.

With optimum proportioning of stages, the performance equation, with n as the number of stages, becomes for a vehicle of n stages

$$V = -C \log_e \left[\frac{S}{W} + \left(\frac{P}{W}\right)^{1/n}\right]^n$$

When this is plotted, as we have done in figure B-2, the advantages

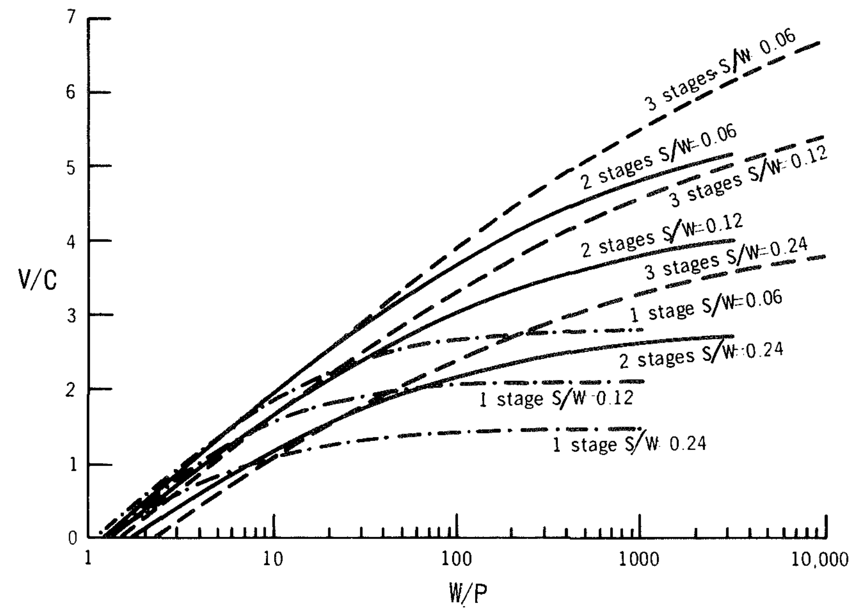


Figure B-2.—Ratio of vehicle velocity to exhaust velocity versus ratio of gross weight to payload for various ratios of structural weights to gross weight—multiple-stage.

of using multiple stages is at once apparent. Now the designer is readily able to achieve his goal of V/C=2.3 for orbit. Furthermore, as he contemplates going to the planets and returning, he is no longer confronted by an asymptotic ceiling on the V/C's he can achieve. If he is willing to use successively larger vehicles and a successively greater number of stages, he can increase his mission capabilities virtually without limit.

With these thoughts about the great advantages of using multiple stages fresh in our minds, let us return to the question of costs. We immediately see why space vehicles are thrown away after only one use. During launch, each stage is used and discarded, with the largest and most expensive being discarded first. Everyone is so glad to get rid of the expended weight that few mourn the tens or hundreds of millions of dollars of equipment that falls into the sea. And it is easy to argue, convincingly, that recovery and reuse of our present systems could never be done for a cost substantially less than the cost of building new vehicles. Accordingly, it is quite understandable that space engineers generally do not think in terms of the reusability operations that characterize other forms of transportation.

If one reads the early history of aeronautics, one finds that as long as aircraft speeds were comparable with the speed of the wind, fear of the wind loomed large in aeronautical thought. In a similar way, as long as it is a major effort to get into orbit, the problem of staging will loom large in the thought of space engineers. But once we can readily achieve orbit with a single stage, space economics will take on a whole new dimension. Space vehicles will be able to shuttle from the Earth's surface (or other planetary surfaces as well) into orbit and back with operations similar to those of the airlines. Furthermore, staging for interplanetary travel will no longer require the discarding of used vehicles. Once a vehicle can go directly into orbit, it can deposit its cargo in a space depot and return for another load. And an interplanetary vehicle can go into orbit, refuel at the space depot, voyage out into space, orbit around one of the other planets, and descend—all as a single-stage vehicle. When this becomes possible, people will begin to ask innocently what the problem of economical reuse was all about.

How close are we now to being able to achieve orbit with a single stage? Rocket exhaust velocities have risen to 14 000 ft/sec. For orbital velocities of 26 000 ft/sec, this gives a V/C of 1.8. Structural weight ratios have decreased to about 0.06. Entering figure B-1 with these numbers, we see that we are now able to launch single-stage vehicles directly into orbit. This ability has come only with the last generation of space vehicles. The door is thus open for the next generation to usher in low-cost space transportation.

In closing this section, let us put the larger problem in perspective. If we are to have an economical, reusable space transportation system, we must abandon such archaic techniques as parachute landings and recovery by task force. There will be penalties in structural weight for vehicles which will be part of a smoothly flowing transportation system, but technological progress will certainly make this possible.

NASA'S ROLE IN LOW-COST SPACE TRANSPORTATION

We are at the end of one era and the beginning of another. We will soon complete President Kennedy's goal of going to the Moon, and must now plan for the next decade. Thus far, the slate is virtually blank.

Let us look at the avenues open to NASA. We begin by focusing attention on two important variables. The first is the total amount of money that NASA may have to spend during the 1970's, and the second is the approximate level of flight activities that NASA will elect to pursue. This latter variable is measured in terms of pounds of payload launched into space. Our discussion will center around figures B-3 and B-4, where these two variables appear as ordinate and abscissa.

From figure B-3, we can immediately indicate some of the constraints upon the space program. Federal expenditures for the 1970's will total about $\$2 \times 10^{12}$. It is inconceivable that NASA's budget could exceed about 10 percent of this figure. This gives a ceiling of about $\$2 \times 10^{11}$ for NASA's expenditures. Furthermore, if one examines the basic necessities for conducting space operations (tracking network, launch facilities, etc.), one finds that over a 10-year period this gives a floor of about $\$10^{10}$, which is about one-fourth of NASA's present rate. Concerning flight activity, a typical flight now places about 10^5 pounds of payload in space. If NASA launched less than one flight per year, the whole program would cease to be viable, because operational teams could not maintain their proficiency and the taxpayers would feel the results were not worth the cost. This gives a lower limit of 10^6 pounds of payload to be launched into space during the decade.

Because we are plotting cost versus payload into space, we can place on our chart (fig. B-3) a scale of cost per pound of payload. This has been done by means of the diagonal lines. Referring to our earlier discussion where "low-cost space transportation" was defined to be that which brings the price of a ticket within the reach of the average citizen (and accepting the fact that the average citizen, with baggage, weighs 200 pounds and can afford to pay \$500 to \$5000 for a space ticket), we can label that portion of our scale lying between \$2.50/lb and \$25/lb as "low-cost transportation."

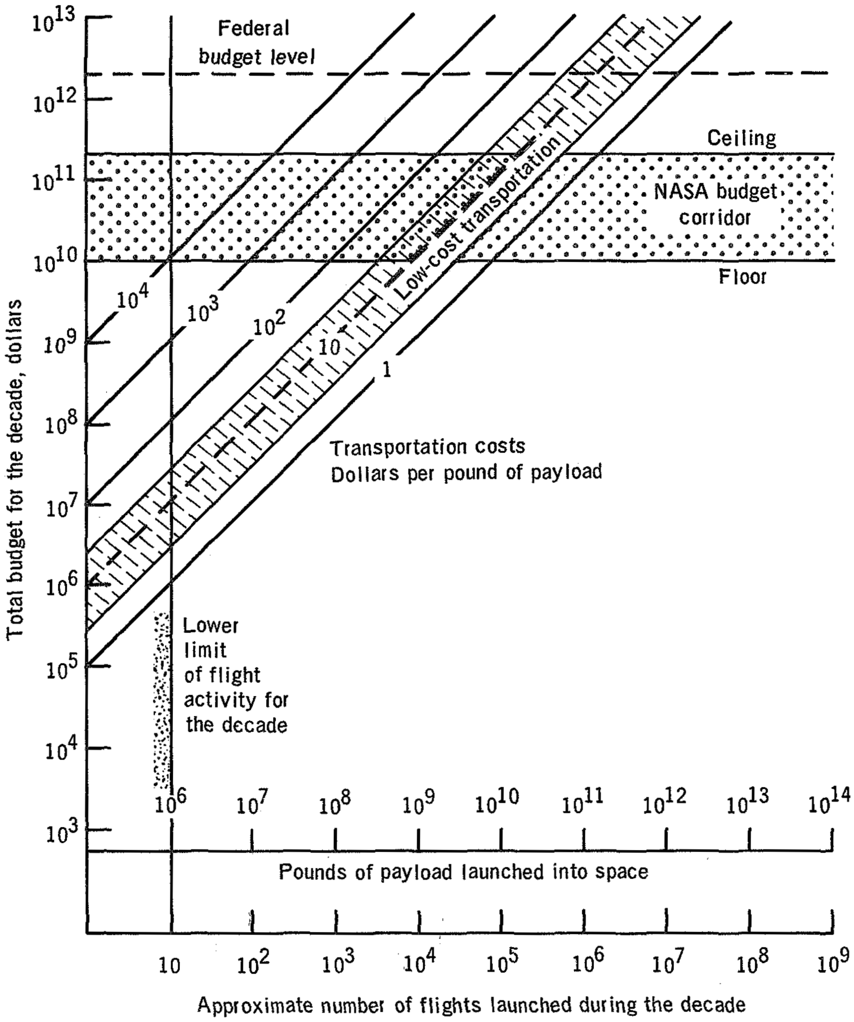


Figure B-3.–Space budgets and flight activities during the decade of the 1970's–NASA costs in relation to low-cost transportations.

Across the bottom of the chart, we can place an approximate scale showing the number of space flights undertaken during the 10-year period, if we assume typical payloads of 100 000 pounds per flight. This figure may be in error by a factor as great as 5, but it will serve to give an indication of flight activity to be expected during the decade.

Even with no further data on the chart, we can immediately see the potential impact of low-cost transportation on NASA operations. If low-cost transportation were a reality, NASA could plan to undertake somewhere between 4000 and 40 000 flights before flight costs would begin to absorb a major share of their base budget. At these levels, the nation would surely feel that it was getting its money's worth.

Let us now examine what it takes to go from where we are now to the situation in which low-cost space travel would be a reality.

The cost of a Saturn V flight is about $\$2 \times 10^8$. If we assume that the "learning curve" or the "law of economic improvement with increasing scale" permits flight costs to drop by 20 percent each time the number of flights is doubled, then accumulated flight costs will not rise in direct proportion to the number of flights, but instead will go up approximately as the two-third power of the number of flights. On figure B-4 we have drawn a line showing projected Saturn V costs. To use only Saturn V throughout the 1970's is not very imaginative, but the curve we have drawn shows, surprisingly, that NASA could launch approximately 40 million pounds of payload into space before flight costs would begin to absorb a major share of their base budget. At this level, the cost of each flight would have dropped by a factor of 7. To see more explicitly how such activity might affect NASA's budget, let us assume that the Saturn V costs are added to the base budget of $\$10^{10}$ needed to keep NASA in existence. We then obtain curve A on figure B-4. From this we can draw the conclusion that using Saturn V alone will not permit NASA to get into the realm of low-cost transportation, because the ceiling we have placed upon NASA would be exceeded before such a goal would be reached. However, without undue strains upon even the minimal budget, NASA could readily launch many more flights than are now under discussion. If there is a lesson to be gained from this, it is probably that serious pressure upon NASA to increase its flight activity could produce dramatic results.

Turning to the question of reducing costs below those of Saturn V, two different options would appear to be open. One would be to retain our present techniques but to make straightforward improvements that would reduce costs by factors of perhaps 2 or 4. The other would be to make a major change, designing single-stage-into-orbit vehicles capable of cheap multiple reuse. Here the goal would be to reduce costs by factors of 10 or 100. As we saw in the

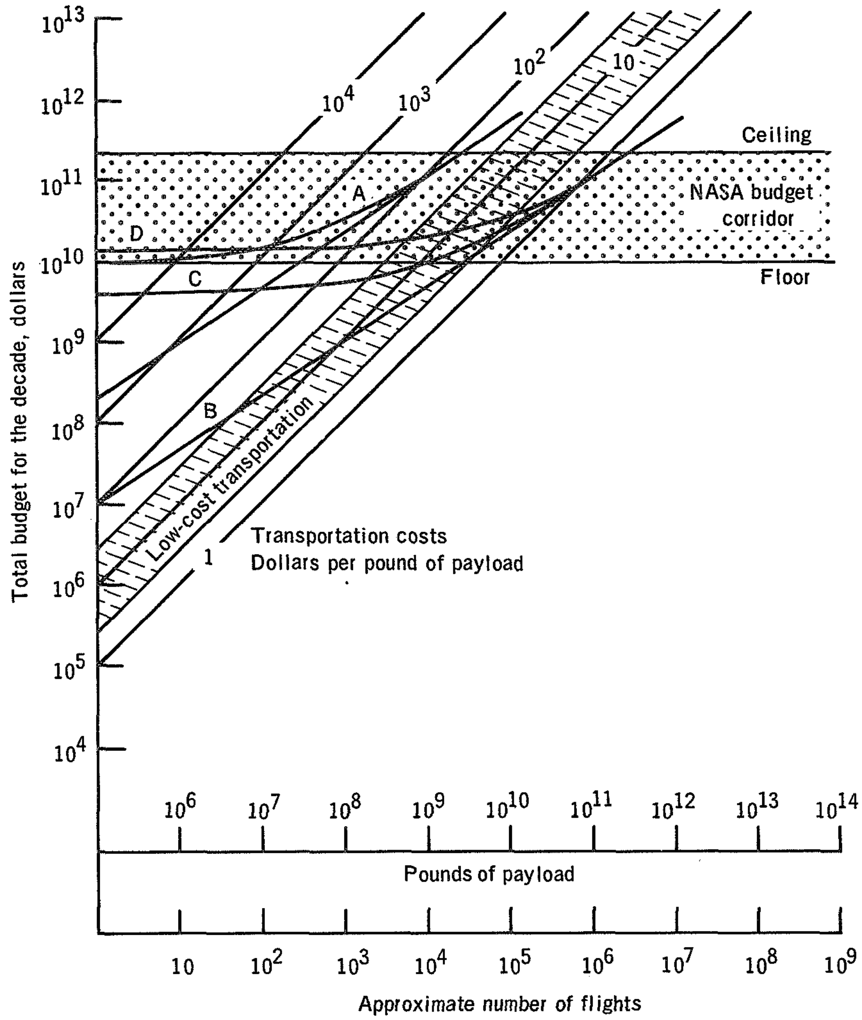


Figure B-4.–Space budgets and flight activities during the decade of the 1970's–Saturn V costs in relation to single-stage development option costs.

preceding section, our technology has now advanced to a point where this latter option would appear to be an attainable goal for the next generation of space vehicles.

Let us examine this latter option more carefully. First, let us assume that it would permit us to reduce flight costs to one-twentieth of those of Saturn V. On figure B-4, this has been shown by curve B. Because it is likely that the development costs for such a system would be as great as those for Saturn V, curve C reflects the costs when we add this development cost to the flight costs of curve B. Finally, if we add the costs of curve C to the base budget necessary to keep NASA in existence, we obtain curve D.

Let us now compare the costs of such a system with those of Saturn V as given by curve A. We see at once that if NASA were to pursue a policy of limited flight activity (less than 100 flights during the decade), then the Saturn V system is cheaper. On the other hand, if NASA launches many flights, the revised system is cheaper. Furthermore, the revised system would permit NASA to launch literally thousands of flights before flight costs would make a substantial increase in the total budget. What is most significant is that such a system would readily enable NASA to get into the "low-cost transportation" belt.

I can give no guarantee of NASA's ability to produce a system that would yield costs of the order of magnitude represented by curve D. To me, the evidence is convincing that curve D is a feasible goal. If it can be achieved, the results would open whole new vistas for the future of the space program.

APPENDIX C
The Lunar Program

INTRODUCTION

At this time in 1968, only months before the first manned mission to the Moon, it is not possible to predict a specific course of manned lunar activity in the 1975-1985 time period. So much of what we do then depends intimately on what happens between now and 1975. The factors involved include: the success of the Apollo program (defined as the first successful attempt by the United States at manned lunar landing and return); utilization of Apollo or modified-Apollo hardware in a lunar exploration program; what we find on the Moon; the usefulness of the Moon for science, space logistics operations, or lunar-based technology; the rate and manner of space technology advances; the Soviet space program; and finally, on the balance between our lunar, Earth-orbital, and planetary efforts.

We could guess at the answers to all the obvious questions and arrive at false or misleading conclusions, but it now makes sense to wait a few years for real data before focusing on any one mode of lunar activity in the post-1974 period. What can be done now, however, is to examine the options that will likely be available in 1975, predict a probable course of events within each option, determine what information would be needed to make a decision on which path to take by about 1972 or 1973, and then examine the lunar program options of the early 1970's to see if they will indeed provide the necessary information.

The approach of this paper, therefore, will be to sketch briefly the likely lunar activities for 1975-1985 using as a basis the Lunar Exploration plan and other current ideas concerning the progress of lunar activities in the 1969-1974 time period. We will concentrate, however, on the concept of a lunar base and what one might do with such a base, since the alternative—continued multisite exploration—is largely an extension of programs of the 1969-1974 time period, all of which have been previously discussed in great detail (refs. 1 to 7).

LUNAR EXPLORATION, 1969-1974

Any program for 1975 to 1985 must build upon the program of the early 1970's, planning for which has been actively pursued by many competent groups (refs. 1 to 7). While we do not yet know in detail what that program will be, the Lunar Exploration Program Memorandum (ref. 7) indicates what is likely to occur, depending upon the level of funding, in terms of five options.

The construction of the options for the 1969-1974 time period was based upon a set of scientific and technological objectives, which we quote (ref. 7), and add to below:

> The *initial* objective, which the Nation undertook with the Apollo program is to *accomplish the manned lunar landing mission.*
>
> During this mission, the astronauts will conduct limited but significant scientific exploration, and return samples of the lunar surface to Earth.
>
> The *next* scientific objectives which are believed achievable by the mid-1970's are:
>
> 1. Surface Features and Regional Relationships
>
> Investigate the form, regional setting and subsurface nature of major lunar surface features and study regional problems by landings at key sites and by extended traverses over the surface.

Of particular importance are measurements and sampling which will enable better interpretation of the recently discovered "mascons." Such information will be significant in explaining the origin of the circular mare and in determining the interior structure and thermal regime.

> 2. Composition of Lunar Materials
>
> Completely characterize the samples collected at each site and during each traverse by detailed analysis on Earth including rock identification and chemical composition.
>
> 3. Age Dating

Establish the absolute (radiometric) ages of samples representing significant lunar events in order to obtain an "absolute" understanding of the relative sequence of events deciphered through years of Earth-based photogeology. Compare this history with that of the Earth and meteorites.

> 4. Internal Structure and Energy Budget
>
> Determine the gross internal structure and processes, ephemeris, and mass

distribution by measuring seismic activity, heat flow, gases and librations with emplaced instrumentation.

5. Lunar-wide Understanding and Geodetic Control

Survey and measure the lunar surface from orbit about the Moon, tying together studies and traverses into a regional framework, providing detailed information for science planning of surface missions, obtaining lunar-wide control of surface positions and profile, and measuring the gravitational field and local variations.

6. Interaction of Moon and Space Environment

Investigate the lunar environment, the interaction of the Moon with the solar wind, associated magnetic fields, atmospheric components resulting from neutralized solar wind, micrometeorite flux, and impact effects, by long-term monitoring on the lunar surface and in orbit.

The technological and operational objectives believed achievable by the mid-1970's as an integral part of missions directed toward the scientific objectives are:

1. Extension of Knowledge of Man in Space

Determine biomedical and behavioral performance including physiological responses and aptitudes, post-mission adaption, and increments by which mission duration can be increased. Study man-machine relationships including sensor operation, discrimination, data selection and evaluation, manual control, maintenance and repair, assembly and set-up, and mobility operations on the lunar surface.

2. Extension of Astronaut's Staytime and Mobility

Increase the ability to conduct observations and experiments on the lunar surface. Extend investigations beyond the immediate vicinity of the landing site.

3. Long-Range Surface Traverses

Extend exploration to regional problems with the capability of supporting geophysical profiles, atmospheric investigations, sample collection, and deployment of science stations along traverses.

4. Extension of Operational Techniques

Develop surface rendezvous capability. Expand manned landing capability to a significant portion of the lunar surface with long-duration mission control, inflight test and qualification of advanced systems.

5. Critical Data for Decisions on Future Uses of the Moon

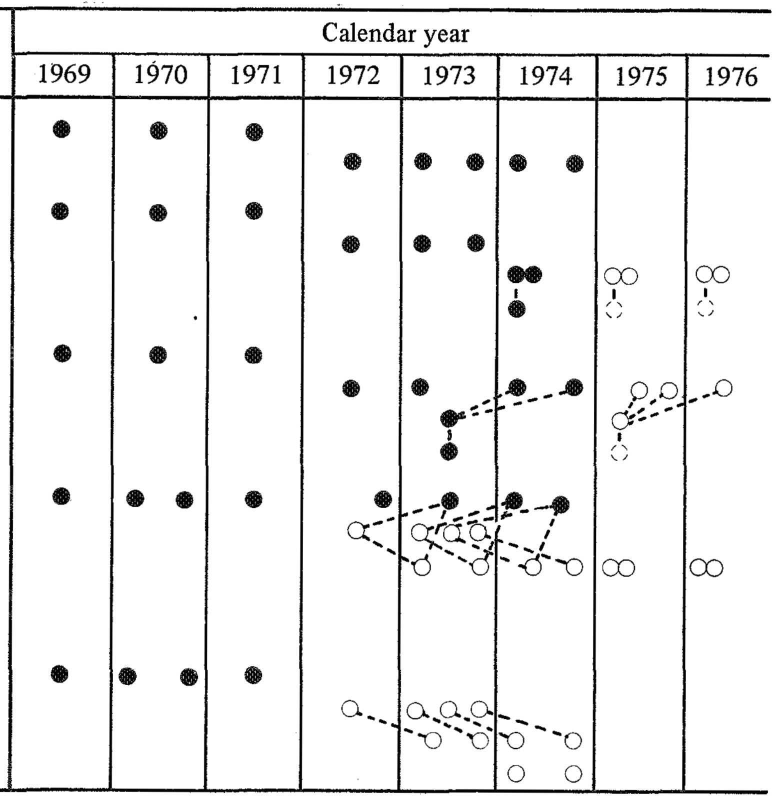
Investigate techniques necessary to make man independent of Earth consumables (e.g., extraction of water, hydrogen and oxygen from lunar rocks), and to use lunar materials for construction and protection. Study the effect of lunar environment on instrumentation, and the suitability of the lunar surface (thermally and structurally) for an astronomy observatory and research laboratory.

To accomplish an effective program of lunar exploration, engineering developments and relevant scientific disciplines must be combined to achieve a series of logically interrelated investigations and missions ranging in scale from specific features to the whole Moon.

The options themselves are briefly enumerated below and shown schematically in table C-I. These program plans assume that the initial Apollo landing is accomplished with Apollo/Saturn 506. They have been structured around the baseline Apollo buy (through SA 515), with modifications introduced to meet the various substrategy requirements.

Table C-I.—*Lunar Exploration Plans*

Plan	Major components
Extended Apollo (1B)	Apollo–Post-Apollo Extended Apollo
Early dual-launch (3B)	Apollo–Post-Apollo Extended Apollo Dual-launch (Manned orbiter)
Revisit (3D)	Apollo–Post-Apollo Extended Apollo Site-revisit (Manned orbiter)
Mixed (3A)	Apollo–Post-Apollo Extended Apollo Advanced orbiter Automated surface vehicle Dual-launch
Automated (3C)	Apollo–Post-Apollo Advanced orbiter Automated surface vehicle Particle-and-fields satellite



● Apollo/Saturn systems 506-515 ○ New systems

Extended Apollo (1B).–Continue multisite manned missions through the end of the Apollo buy of spacecraft and Saturn V launch vehicles. Introduce extended Apollo missions with increased staytime on the lunar surface, and lunar flying units for astronaut mobility after three Apollo-like missions.

Early dual launch (3B).–Introduce the dual launch in place of the last two missions in the Extended Apollo plan. This provides logistic support, the roving vehicle on the surface, and manned orbital science. This plan implies continuation of dual-launch flights, requiring a new buy of Saturn/Apollo hardware.

Revisit (3D).–Introduce the automated LM logistics carrier (LPM) by the fifth launch of the Extended Apollo plan and use the succeeding two ELM missions to revisit the LPM. This plan also implies a new buy of Saturn/Apollo hardware which will permit reuse of equipment and the conduct of preliminary baselike operations.

Mixed (3A).–Continue manned lunar exploration as in the Extended Apollo plan, adding automated support with orbital and roving vehicle missions. This plan can be continued into either a new buy of Saturn/Apollo hardware for dual-launch or mission-and-a-half mode operations.

Automated (3C).–Terminate manned exploration after four missions and continue with the automated orbital and traverse missions of the Mixed Plan. Add automated particles-and-fields satellites launched from Earth to lunar orbit.

The options of the early 1970's are in reality based on the concepts of multisite exploration and site revisit, with the site-revisit option (3D) being a type of minibase built upon Apollo-derived hardware. The site-revisit option can be looked upon as providing early experience in the conduct of lunar-base operations, but it compromises somewhat the exploration of the Moon by reducing the number of sites investigated.

A recent fiscal year 1970 submission to the Bureau of the Budget contains only three options:

Plan A: Similar to 3A, but one additional post-Apollo mission, only three ELM missions, and the dual missions moved up a year earlier to calendar year 1974.

Plan B: Three post-Apollo missions, one ELM in calendar year 1972, and dual launches in calendar year 1973 and calendar year 1974.

Plan C: Two post-Apollo missions (calendar year 1970 and 1971) and two ELM (calendar year 1973 and 1974).

Plans A and B would result in reasonable lunar program progress in fiscal year 1970, while plan C is barely a survival effort.

POTENTIAL LUNAR PROGRAM OBJECTIVES, 1975-1985

The gross options of the 1975-1985 time period will not be different from those of the earlier explorations. One can either extend the multisite exploration mode, or concentrate on establishment of a lunar base.

CONTINUED MULTISITE EXPLORATION

This strategy depends largely on the assumption that the justification for continuing lunar activity is primarily scientific—an assumption that few are willing to make. However, we cannot discard the possibility that the results from early missions will produce a strong desire to continue this mode. As such, it would be an extension of a strategy already in existence. A continuance of the multisite strategy would presumably follow along the lines discussed for the early 1970's, with the possible addition of more sophisticated hardware (e.g., self-contained, habitable, roving vehicles) and larger scientific payloads.

ESTABLISHMENT OF A LUNAR BASE

We have been asked to assume for the purposes of this study the existence of a lunar base and to show what would be done there. The assumption of the existence of a lunar base presupposes that it has been justified. Several studies (e.g., ref. 2) have been made which assumed that scientific exploration would be the justification. It is more likely, however, that science will be only one of the justifications. Other factors to be considered include technological, political, prestige, and military aspects, all of which must be dealt with in an in-depth study of a lunar base.

The establishment of a lunar base is more likely to occur if it is declared a goal of a manned space program. To be so declared, it must offer certain qualities which make it a clearly equal or superior goal over the alternatives–those alternatives most likely being, in the 1975-1985 time period, either an Earth-orbiting space station or a manned planetary exploration.

A new NASA goal comparable to or greater than Apollo in scope must:

1. Make challenging demands that force technological advance.

The Apollo program has, for obvious reasons, focused attention on production and test. A major new program should be designed to force concentration of effort on design and innovation. Possibly inherent in this idea is the concept of a schedule of activities that does not artificially escalate costs. Consider, also, that establishment of a goal that is now completely feasible (from an engineering point of view) will not necessarily stimulate new and innovative technologies.

2. Be of relevance and exciting to the man-in-the-street.

Hit-and-run lunar exploration has only transient appeal. A continued occupation of a lunar site would represent a permanent extension of man's presence on new territory. A possible goal, which benefits by not being dead ended, is the ultimate self-sufficiency of a lunar base.

3. Offer an opportunity for accomplishment of subsidiary objectives.

In the following subsections, several of the broad categories of potential base use are outlined in a plausible chronological order of occurrence. A more detailed summary of the possible base operations, resources, and necessary developments is given under the "Lunar-Base Technological Support Operations" section of this paper (p. 39).

Continued Scientific Exploration of the Moon

By 1975, we may have detailed site information on 5 to 10 selected lunar front-side sites, solutions to some regional lunar problems based on data and samples obtained by dual-mode rover traverses, rudiments of seismic networks, a developed 10-kilometer-radius-of-action, lunar manned-mobility system (small flying unit and/or roving vehicle), and a CSM remote-sensing capability. Through use of the extended LM and/or dual-launch missions, with their associated hardware developments, staytime on the lunar surface should progress to ~ 12 days.

The next phase of exploration, 1975-1985, will need to establish geophysical observing stations where gaps exist in preexisting nets. This might include more front-side stations and certainly back-side stations. From a base, this will require either extensive manned/unmanned surface mobility to deploy stations (or to repair existing stations), or individual unmanned landings of automated stations. In any case, development of lunar far-side communications will be required.

The particular use of a base in geophysical monitoring would probably be in the establishment of a semipermanent observatory (remote stations for the mid-1970's are envisioned as having lifetimes of up to 5 years). Efforts to conduct high-caliber seismic studies would conceivably include layout of a LASA-type (large-aperture-seismic-array) array of stations, of short baseline, and the detonation of large explosive sources to excite the Moon artificially. Such an array of stations could alleviate the need for many individual stations.

The location of a lunar base will be determined by operational convenience and the availability of particular resources (e.g., H_2O). It is likely, however, that this area will be geologically interesting, possibly volcanic, and will afford the first opportunity for extensive investigation of a lunar "geologic" problem. This presumes that, even on the 12-day dual missions of the mid-1970's, there are insufficient man-hours to devote to EVA activity of a geologic nature. It is an established terrestrial fact that the solution of most geologic problems requires, sequentially, an initial exploration, a period of laboratory work, and a site revisit to do further experiments or collect more samples. A strategically located base provides that opportunity and, with the development of suitable mobility, actually enables one to continue multisite exploration on traverse loops originating at the base.

The concept of deep-drilling on the Moon, with coring, has been considered for at least the past 8 years. By deep-drilling we mean a minimum depth of several hundred meters. For scientific purposes, drilling is done after the delineation of problems that could be solved by drilling. This presupposes a backlog of geological, geochemical, or geophysical data at the site. With the possible exception of the site-revisit option, early-to-mid-1970 missions do not allow for that sequence of events. Deep-drilling is, therefore, an operation that would be considered at a lunar base location after extensive surface study of the complete site.

The Moon as a Base for Nonlunar Science

Besides serving as a subject of scientific exploration for its own secrets, the Moon may be an important base for outward-looking space science programs of the future.

Astronomy appears most likely to profit from lunar-based instruments. The advantages of lunar versus Earth-orbital location are discussed more fully in appendix D of this series (ref. 8). Briefly, the Moon may eventually support large optical telescopes, though the advantages of the Moon over Earth-synchronous orbits for these telescopes are not yet clear. On the other hand, there is strong evidence that the most ideal location for large radio telescopes will eventually be the rear side of the Moon. This may be the only place within our convenient reach where the Earth, which will become increasingly noisy as a radio source, may be completely screened out. In addition, the large, stable base of the lunar surface with only 1/6 g, no wind disturbance, and no atmosphere absorption, at any wavelength, are all advantageous for large radio-telescope installations. Another attractive possibility is the use of the Moon-Earth line as a radio interferometer base for highly precise directional radio astronomy. In view of the rapid growth in importance of radio astronomy and the large sums now being invested in radio telescopes, far-side lunar operations within 15 years should be considered seriously.

There are also attractive possibilities for installing large X-ray and gamma-ray telescopes on the Moon and using the atmosphere-free lunar horizon as an occulting edge that rotates uniformly about the sky (ref. 9). These, unlike the radio telescopes, need not be on the far side, since Earth noise is not a problem here.

The Moon is certain to serve as a valuable permanent base for monitoring the environment of our solar system, especially particles and fields. Solar wind, solar storms, magnetic perturbations, meteorite infall, and cosmic rays will all be worth monitoring continuously from a lunar base. This will augment Earth-based observations with data taken at a significant distance and time away from the Earth. Such data stations, strategically placed on the Moon with large separations in latitude and longitude, could probably be combined with the automated geophysical stations.

A third scientific and technological use of the Moon might be for radio, radar, and laser communications with Earth, and with spacecraft in cislunar space and on planetary missions. The lack of atmosphere (clouds or ionosphere) at the lunar terminal will give it obvious advantages over continuous communications channels that must penetrate the Earth's atmosphere.

Use of the Moon as a Refueling and Launch Platform

Because of its low gravity, it requires 20 times less energy to escape from the Moon than from the Earth. Hence, if one can eventually generate rocket propellants from lunar resources there will be an enormous advantage in using the Moon as a supply-and-launch base for interplanetary operations. It could even be profitable to send fuel from the Moon to tanker stations permanently orbiting the Earth, for resupply (ref. 10). Because of the Moon's lack of atmosphere, one could also eventually send spacecraft back to Earth by acceleration on a long (4 to 20 miles) launch track built on the lunar surface (ref. 10). Such a launch would be efficient, since it would dispense with the large mass of propellant normally required in the early stages of rocket acceleration, and would avoid most of the gravity losses encountered in vertical launches.

Rocket propellants generated on the lunar surface could also be stored in a lunar base, both for lunar flying-vehicle operations and for abort missions back to Earth. The most probable source of rocket propellant on the Moon is water, either as liquid or ice. Once the supply is found, it would be a rather simple matter to hydrolyze the water into H_2 and O_2, which could then be liquefied for storage. The oxygen in water also has obvious utility in life support.

Return of Lunar Materials to Earth

In the first few years of lunar exploration, we can expect a steady return of scientific samples from all sites visited, for Earth-based analysis. It is possible, though it seems unlikely at this time, that there will be certain minerals in the lunar surface that are costly or impossible to prepare on Earth, even in small quantities. For example, long exposure to vacuum ultraviolet light or solar protons at the lunar surface may produce unexpected mineral forms. For these minerals, there could eventually be a useful traffic back to Earth, if Moon-to-Earth transportation becomes sufficiently inexpensive.

Construction and Processing on the Moon for Space Systems or Return to Earth

Construction of life-support bases from lunar soil or materials and assembly of large instruments and stations on the lunar surface would probably occur early in a lunar base program and will be covered in "Lunar-Base Technological Support Operations" (see below).

Probably latest in chronology, would be use of the Moon's unique environment (a vacuum of 1/6 g) to make and process materials, manufacture parts, and construct specialized hardware. The prospect of manufacturing products on the Moon for Earth use, however, appears very remote to the authors.

Because of the energy advantage in launching from the Moon versus from the Earth, heavy components for a space system that could be manufactured from lunar raw materials may eventually become one of the goals of lunar programs. Very extensive vacuum operations, such as coating large optical surfaces or preparing large solar-cell surfaces for space use could conceivably become lunar industries.

LUNAR-BASE TECHNOLOGICAL SUPPORT OPERATIONS

Mission-support facilities, materials for base construction, shelter modules, power installations, communication systems, astronomical and ecological laboratories, surface transportation and hauling facilities, propellant production, storage and fueling facilities–these and others will require extensive supporting technologies.

In this section we will briefly review some of the thought that has been given to lunar-base operations and the potential problems. Much of it is speculative, but Surveyor remote analyses and theory convince one that essential elements, construction materials, and various metals are present on the lunar surface. Their location and availability in forms amenable to concentration or processing is yet to be established; however, a good multisite exploration strategy in the early 1970's should supply the necessary information (p. 43).

ENGINEERING REQUIREMENTS

In preparing this subsection, the writers have drawn largely upon references 11, 18, 22, and 31. The subsection on the "Use and Processing of Raw Materials" (p. 43) relies heavily upon references 16, 19, and 25 for sequence and for the data presented.

Construction of a Base Station—General

The scientific mission-base requirements advanced by North American's Lunar Exploration System for Apollo study (ref. 2) define a three-phase base concept to support the scientific investigations in the 1970 to 1974 period. The first phase consists of several modules or crew shelters plus a surface vehicle. These modules would merely house three men for 3 months, and serve as a base for reconnaissance. The second phase would house six men for 3 years and serve as a center for geological, geophysical, topographic, and astronomical studies. This facility would include a laboratory-shelter module, two vehicles, and a powerplant. The third phase would provide for a dozen men for 5 to 10 years, and would have a facility that would include two shelters, an astronomical observatory, radio-astronomy facilities, and two vehicles. The entire system was proposed as feasible for the period 1970 to 1974, with support operations for this period being Earth-based.

Construction of a lunar base station will require proximity of useful raw materials, heat, water, and favorable conditions for producing and maintaining a habitable environment. Mining, processing, building, and other essential activities will depend upon numerous advantageous environmental and resource conditions. Vital to any base construction program that will depend upon local resources is the ability to excavate and tunnel, extract atmospheric gas and water, obtain working fluids, devise the means for concentrating usable raw products, and develop techniques for fabricating structural elements from environmental materials. Some of the engineering and resource considerations involved in such construction are discussed below.

Surface Mobility

The 1967 Lunar Science and Exploration Summer Study Summary (ref. 6) states that the more important recommendations of the conference concern lunar surface mobility. It was proposed that, to obtain significant benefits from lunar-surface exploration, it would be imperative that there be a working radius of 10 kilometers. (On early Apollo missions the astronauts' on-foot radius may be about 500 meters.) Recommendations include development of manned or automated wheeled vehicles for the purpose of exploration, sample collection, geophysical studies, in situ analyses, and transportation and haulage. Such mobility devices would also be necessary in base operations and base construction.

Hall (ref. 11), in a study of the engineering implications on the Moon's surface, concludes that trafficability will be lower on the Moon than on Earth. Traction for equal-footing areas will be less, because of the relatively reduced weight, and wheel sinkage and minor obstructions may be major obstacles to vehicle mobility. To establish a basis for exploratory and construction-vehicle concepts, analyses need to be made of the characteristics of lunar-surface materials and landforms. Soil-testing techniques for use under hard-vacuum conditions will be necessary on early lunar-surface missions, to assist in the design of vehicles that will be adaptable for mobility in soft soils, on unconsolidated materials at high angles of repose, and for mixtures of rubble and finely pulverized materials.

Before haulage-roadways and surface-transportation routes may be delineated, studies are needed to determine the range in engineering properties of the surface materials for filling, grading, excavation, compaction, and cutting. These behavioral properties will have to be considered in terms of penetration-resistance, shearing strength, bearing capacity, and effective stress and dilatancy (refs. 12 to 14).

Drilling Operations

Drilling for subsurface exploration and tunneling for base installations will be early engineering problems on the Moon. NASA's Lunar Drill program has as its objective the development of a system to take core samples to at least 100-foot depth. The drill system will be required to operate in dense igneous rock, vesicular lavas, unconsolidated heterogeneous materials, and fines of varying degrees of competence. Such a drill will also operate dry, without air- or water-flushing. Westinghouse has developed a suitable rotary, diamond-core drill-bit that is operable in basalt under high-vacuum conditions (ref. 15).

Drilling and tunneling may be enhanced somewhat on the Moon because of low gravity and the existence of a meteorite-pulverized debris layer. Frictional losses will be lower, and haulage of broken rock will be easier. On solid rock, however, considerably heavier drill collars, possibly made from lunar basalt or meteoritic iron (ref. 16), may be necessary to meet required bit pressures; otherwise, drilling times will be considerably longer than on Earth. Analysis of data on drilling rates by Morlan (ref. 17), applied to probable lunar conditions, shows that a terrestrial rate of 50 ft/hr may slow to 3 ft/hr on the Moon.

Excavation and Mining

Excavation of surface materials will be an essential supporting operation for a lunar-base program; however, such excavations may be unlike conventional terrestrial methods, for as Hall (ref. 11) notes, compacting fine material on the Moon may necessitate greater applied loading than on terrestrial materials of the same density. Hall also postulates a greater angle of internal friction for lunar materials because of interlocking of the predominantly angular particles and possible high adhesion of the grains. (Analysis of Surveyor data, however, indicates that the lunar soil has an angle of internal friction and low cohesion not unlike terrestrial sandy loams.) Loose materials, for whose existence there is much evidence, could be excavated with ease.

The selection of lunar-surface mining and dredging systems has been analyzed by Schotts (ref. 18), based on such factors as environment constraints, recovery-to-waste ratio, depth and grade, and the proximity to base facilities. Among environmental problems is the high range of surface temperatures, which will require special suits for miners for day/night, light/shadow, or the use of environmental cabs. Portable structures have been suggested, from which mining may be undertaken by remote control. The lunar vacuum will present problems in the use of solid lubricants in place of the abundant grease used on terrestrial mining equipment. Nighttime mining will require much artificial lighting and a high heating load for equipment, and there will be the danger that working fluids will freeze.

Lunar mining and dredging methods are envisioned to include scraping by bulldozers, digging by shovels and draglines, and the fragmentation and scraping of materials. Irregular "ore" and terrain profiles will likely preclude automation for all but the most simple operations.

USE AND PROCESSING OF RAW MATERIALS

Water

Green (ref. 16) believes that water is the most critical raw material for the lunar base and lists the following possible water sources: combined water in volcanic extrusives, ice in permanently shadowed zones in volcanic craters, crystallized water in volcanic sublimates, permafrost, and water in nonvolcanic rocks and carbonaceous chondrites. Of these possible sources, water is more likely obtainable from serpentine (12 percent), lavas (< 1 to 5 percent), and certain carbonaceous chondrites (10 percent). (Ruzic (ref. 19) notes that 1 percent by weight of water in the various hydrous volcanic rocks considered approximates between 1 and 2 quarts of water per cubic foot.)

On the other hand, Baldwin (ref. 20), an advocate of a Moon with a hot interior, believes that water vapor and other gases have been extruded from the Moon's interior and largely lost to space, because of the Moon's low gravity. However, water vapor may yet be evolving, and it may remain as ice in permanently shadowed zones or be trapped underground where the temperature is below the freezing point.

Hapke and Goldberg (ref. 21) suggest that the flow of low-pressure water vapor through a porous lunar soil could form permafrost at a moderate depth. If the Moon had a degasing history like the Earth, they doubt if permafrost would exist in the equatorial regions, but suggest that it is likely to occur relatively close to the surface in polar regions.

Fuels

Water is envisioned as the source of hydrogen for fuel and of oxygen for oxidizers and life support. Free water or ice, if it does occur, will be restricted to deep fractures, buried craters, debris layers, or permanently shadowed zones (especially in small areas around the poles). Interstitial free water is likely to be highly contaminated with salts and fine, particulate, mineral matter.

Schotts (ref. 22) considers subsurface mining of ice, regulated devolatilization of the frozen water and soil, and "pneumatic" transmission of the vapor and solids to a surface vessel in which recondensed vapor would be freed of the mineral solids. Several other methods for mining subsurface lunar ice have been proposed, including Frash-type processes, circulating brines, use of nuclear reactors, and in situ hydrolysis.

Recovering water from serpentine or other hydrated minerals by a Frash-type process employing nuclear or resistance heating would be feasible if heat conductivity were good in the rock. Shotts proposes that heating serpentine to 500° C at one atmosphere would produce superheated vapor. Mining hydrated rock for surface processing would require retorting to win the water, possibly using a solar furnace.

Water obtained from lunar rocks would have to be decomposed, electrolytically, for the production of oxygen and hydrogen. The decomposition, requiring either solar or nuclear power, would be followed by liquefication for storage.

Gases

The Moon may be considered as free of any atmosphere, except for possibly a tenuous presence of water vapor, carbon dioxide, hydrogen, helium, and rare gases (refs. 23 and 24). Such rare gases are unlikely to be available to support lunar base activities, but those associated with active volcanism or which are present in thermal areas might be tapped by proper drilling techniques.

Green (ref. 25) pictures the lunar surface as mostly covered with lavas characterized by large vesicles, initially formed by entrainment of water vapor and other gases which may be recoverable by simple crushing. Although most of the gas and water vapor in the surface debris layers may have escaped, it is likely that such fluids could be impounded in rocks at moderate depth (several tens of meters). Terrestrial vesicular rocks typically contain H_2O, CO_2, HCl, Cl_2, H_2, CO, CH_4, N_2, and O_2.

Sulfur

Green (ref. 16), Ruzic (ref. 19), Schotts (ref. 22) and others have considered the possible occurrence of sulfur on the lunar surface. Shotts considers that sulfur may be present in elemental form and also as hydrated soluble sulfates, as metallic sulfides (FeS, MgS, CuS, CoS, Cu_2S_4, etc.), as well as H_2S and SO_2. Ruzic proposes that initial housing on the Moon could be in lava tubes, properly mortared by melted volcanic sulfur, while Green, who has done extensive research in the area of lunar sulfur technology, proposes the use of sulfur as cement, sealant, insulator, construction material (mixed with ash), as a source of H_2SO_4 and of H_2S (using meteoric Ni as a catalyst), and as a working fluid in powerplants and in mineral dressing.

Using anerobic thiobacilli for the production of H_2SO_4, Green envisions the manufacture of fertilizers for hydroponic gardens, the production of explosives for lunar construction uses, and the eventual production of essential chemicals. Sulfur used as a fluid (which has a wide range in behavior and viscosities) could be employed in metal reduction, as a lubricant, and as a moderator in nuclear reactors.

Chemicals and Minerals

Alpha-particle backscattering analyses of the lunar surface material by Surveyor V, VI, and VII show the lunar soil to be similar in composition to terrestrial basaltic lava. Table C-IIa shows the Surveyor analyses in the elemental form (ref. 26), while table C-IIb is an estimate of the equivalent oxide composition, based upon many assumptions about specific elements and element ratios (ref. 27). In addition, roughly 5 percent of the meteoritic material on the Moon is believed to be of the Ni-Fe type, which typically contains about 88 percent Fe, 6 percent Ni, 2 percent P, and minor amounts of Cr, Co, etc. Only the Ni-Fe appears to be volumetrically significant.

Rubey (ref. 28) proposed that many of the elements present in terrestrial sea water were derived from fluids emanating from the depths of the Earth. Following that line of thought, Green (ref. 16) suggests that defluidization in a low-vapor pressure environment such as the Moon's would permit most gases to escape, but that Br, As, S, Se, B, I, F, Sb, Rn, Os, Cd, Hg, Pb, and Zn may be somewhat enriched on the lunar surface. Shotts (ref. 22) considers the overall lunar composition to include olivine, pyroxene, anorthite, albite, orthoclase, troillite, chromite, and apatite. He lists the following mineral groups as likely to be found on or near the lunar surface: water, hydrated silicates (chlorite, serpentine, mica, zeolites), hydrocarbons (C_2H_2, C_2H_4, etc.), carbon (graphite, CO_2, Fe_3C, $MgCO_3$, CaC_2), hydrated soluble salts (halides, sulfates, chromates, phosphates), elemental sulfur and sulfur gases, boron

Table C-IIa.—*Chemical Composition of the Lunar Surface at the Surveyor Landing Sites—Preliminary Results (ref. 26)*

Element	Chemical composition, atomic percent[a]		
	Mare sites		Highland site
	Surveyor V	Surveyor VI	Surveyor VII
C	<3	<2	<2
O	58±5	57±5	58±5
Na	<2	<2	<3
Mg	3±3	3±3	4±3
Al	6.5±2	6.5±2	8±3
Si	18.5±3	22±4	18±4
"Ca"[b]	13±3[c]	6±2	6±2
"Fe"[d]	....	5±2	2±1

[a]Excluding elements lighter than beryllium.

[b]"Ca" here denotes elements with mass numbers between approximately 30 and 47 and includes, for example, P, S, K, and Ca.

[c]Results from Surveyor V, in this case, included both the "Ca" and the "Fe" groups. A lower limit for "Fe" was set at 3 percent.

[d]"Fe" here denotes elements with mass numbers between approximately 47 and 65 and includes, for example, Cr, Fe, Co, and Ni.

compounds, nitrogen as N_2, NH_3, TiN_3, various halides, and metallic sulfides.

Beneficiation

Developing processes for the separation and concentration of diffuse mineral materials under Moon surface conditions is a primary problem for lunar-base technology. Many concentration methods that are well established on Earth will have negligible chances of success on the Moon. On the other hand, separations which are practically impossible on Earth might be accomplished with relative ease under lunar-surface conditions.

The efficiency of most dry-gravity separation methods will be less on the Moon, where lower gravity will slow down conventional processes. Interactive forces between the surface charges on

Table C-IIb.–*Estimate of Lunar Chemistry in Weight Percent Oxides*[a] *(ref. 27)*

Oxide	Surveyor V	Surveyor VI	Surveyor VII
SiO_2	46	52.5	49
Al_2O_3	13.5	13	18.5
MgO	5	5	7.5
FeO	17.5	14.5	6.5
CaO	15.5	12.5	14
K_2O	0.5	0.5	1
Na_2O	2	2	3.5
	100	100	100

[a]Original analyses (Table C-IIa above) were in atomic percent. See references 26 and 27 for assumptions, errors, and element groupings (e.g., Na is an upper limit).

particulate materials may also seriously affect dry classification. Open wet processing, such as flotation and heavy-liquid separations, would be unsuccessful because of the high volatilization rate of liquids, according to Gaudin (ref. 29). Green (ref. 16), however, suggests that such wet processes might be practical if undertaken in an enclosed system. Such processes as leaching, amalgamation classification, and flotation, when carried out in covered vessels, could take advantage of such phenomena as a deeper nucleation of bubbles. Green (ref. 16) proposes consideration of fluid sulfur in mineral dressing techniques on the Moon, citing that pyrite, expected to be found as the stable iron sulfide on the lunar surface, would sink in 155° C sulfur on the Moon at several times the rate it would sink in water on Earth.

Electrostatic separations are seen as feasible (refs. 16 and 29), because induced charges are proportional to particle surface areas, while the weight of the particles is related to their volume.

Metallurgy

Ruzic (ref. 19) notes that lunar near-vacuum conditions might aid in the production of several metals. Refining of the base metals could be accomplished by heat alone, without reducing agents. Copper, iron, nickel, mercury, zinc, molybdenum, cobalt, and many of the rarer metals are expected to be found in the lunar surface rocks, or in the meteorites.

A probable metallurgical attempt on the Moon will be to process naturally occurring surface rock without prior treatment. Cast basic rock (basalt) technologies have been developed in France, Germany, Poland, and Czechoslovakia (refs. 16 and 30). Czechoslovak studies indicate that the best available basalts for casting contain over 60 percent pyroxene, less than 10 percent magnetite-olivine, and about 20 percent total of nephelene and plagioclase. Green (ref. 16) suggests that basalt casting on the Moon would be favorably affected by the lower gravity, which would reduce the onset of turbulence of a specific particle size. Among the numerous proposed applications for cast basalt are construction materials, furnace materials, pipes, mill linings, tiles, bricks, ties, etc. Sintered basalt may be fabricated for tubing, bearings, wheels, furniture, axles, tools, etc. Spun basalt may be used as fabric, pads, insulation, fillers, filters, and packing.

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APPENDIX D
Astronomy

INTRODUCTION

The potentially useful role of man in space astronomy is described in this paper on the basis of certain fundamental assumptions that are believed plausible in the post-1975 period. Justification of manned space flight is not intended; rather, the purpose here is to describe what man could do, if he were available. The fundamental assumptions are:

1. Logistics and rendezvous are cheap and safe, from the Earth and from interorbit shuttlecraft.
2. Man is as useful in space as on Earth, providing that the man-machine interface has been properly designed.
3. Continuously manned stations are available in space, in low orbit, in synchronous orbit, and/or on the lunar surface.

The need for the availability of telescopes in space for astronomical research has been expressed by many scientists (e.g., refs. 4, 5, 33, and 34). Of primary importance to understanding the physical processes that take place in the universe is the accessibility afforded by space to whole regions of the electromagnetic spectrum that cannot be detected from Earth. Wavelengths shorter than about 2900 Å and longer than about 60 meters cannot penetrate to the Earth's surface at all, and only limited spectral regions in the wavelength range between about 0.8 microns and 8 millimeters are visible through the Earth's atmosphere. In the spectral regions that can be seen from Earth, spatial resolution is also limited, because the Earth's turbulent atmosphere restricts the angular resolution to about 1 arc-sec in the optical and millimeter regions. Variability of transmission, scattering by the Earth's atmosphere, airglow, and auroral emission limit the accuracy of any intensity measures at optical wavelengths of astronomical objects, and consequently limit also the degree of faintness to which one can see and the time resolution that is possible for transient and rapidly varying astronomical phenomena.

A space observatory would allow astronomical observations of very high angular resolution, ultimately limited only by the imaging properties of the telescope over the entire electromagnetic spectrum. Accuracy of intensity measures and time resolution would not be limited by the Earth's atmosphere. The faint limit of instruments would be determined by the instruments themselves, or by extraterrestrial "noise," such as zodiacal light, galactic background, Lyman-alpha emission, or plasma oscillations of the interplanetary medium.

In this paper, the scientific goals of astronomy are briefly stated first in very broad terms, because they have been discussed in detail in the reference publications. The instrumentation that is considered necessary to accomplish the scientific goals is described next. Farther on, man's general role in space astronomy is outlined, and his specific function with the described instruments is explained. There follows an enumeration of the relative scientific merits of low Earth orbit, synchronous orbit, and lunar base for various types of observation. The final two sections present some critical questions and end with conclusions and recommendations.

GOALS AND OBJECTIVES OF ASTRONOMY

The goals and objectives of astronomy have been described in various places, such as the "Woods Hole Report" (ref. 1), NASA "OSSA Prospectus" (ref. 2), the "PSAC Report" (ref. 3), and by Spitzer (ref. 4), Kopal (ref. 5), Tifft (ref. 6), and most recently by various panels of the Astronomy Missions Board.* From the PSAC Report, we quote the following concise statement of questions that can be studied by astronomical techniques:

1. Does life abide in places other than the earth, and if so what is its nature, how did it evolve, and what are its possible forms elsewhere?

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*The Astronomy Missions Board, Leo Goldberg, *Chairman*, has formed the following panels: X-Ray and Gamma Ray: W. L. Kraushaar, *Chairman*; Radio: B. F. Burke, *Chairman*; Solar: J. W. Evans, *Chairman*; Optical: L. Spitzer, *Chairman*; Planetary: J. W. Chamberlain, *Chairman*; and Fields and Particles: J. A. Simpson, *Chairman*. These panels are advisory to the Board, which has to review and approve their recommendations and forward them to NASA.

2. What is the origin and evolution of the Universe, and what is its ultimate destiny? What is the place of our sun and solar system in it? Do natural laws as we know them on earth indeed govern the behavior of every observable part of the vastness of space?

3. What are the physical conditions on the moon and on the other planets in our system, and how did our solar system evolve? What dynamic relationships between the sun and the planets shape their environment?

The scientific objectives of astronomy can best be approached with specific types of instrumentation. The "Woods Hole Report" (ref. 1), the "OASF Study" (ref. 7), and the General Dynamics Study (ref. 8) describe instrumentation goals that will allow us to handle the scientific questions.

A program for developing astronomical instrumentation should be designed to place the following major instruments (ref. 1) in space in the next 10 to 15 years to cover the more than 20 decades of the electromagnetic spectrum (from 10^{25} hertz down to 10^3 hertz).

A. An optical space telescope of very large diameter, with a resolution corresponding to an aperture of at least 120 inches [studied in more detail by the Spitzer Large Space Telescope Committee (ref. 4)].

B. An optical solar telescope of 1- to 1.5-meter aperture with a focal length of 50 to 75 meters.

C. An XUV solar telescope of about 1-meter aperture, designed to operate from about 1500 Å down to 300 to 500 Å. It must not have folded optics. This instrument is unique to solar astronomy, because it is predicted that interstellar matter is opaque to Lyman continuum radiation (below 912 Å). It is important, however, to verify this by using the XUV solar telescope for some stellar observations.

D. A coronagraph with an external occulting disk. Because of the extreme dynamic range from the inner to outer corona, at least two coronagraphs of different aperture would be required.

E. A grazing incidence-focusing X-ray solar telescope. Because the solar flux between 1 and 500 Å (where this instrument is effective) is high, a small-diameter instrument, about 20 centimeters, is adequate.

F. A grazing incidence-focusing X-ray telescope for observations of galactic and extragalactic sources. An aperture of at least 1 or 2 meters is required: the Woods Hole Report recommends a diameter of 10 meters; however, nested mirrors offer a more reasonable approach (ref. 9). The focal length is at least 10 times the aperture.

G. A large array of gas-filled proportional counters to cover the energy range from approximately 1 to 50 keV. These arrays, with collecting areas of 10 or more square meters, would be mechanically collimated to arc-minutes. Collimation becomes more difficult as the size of the array increases, but observations of very faint sources are desired, and hence large arrays are needed. This 10-square-meter array might thus be augmented to 100 square meters, but with a collimation of only a few degrees for the overall array.

H. A 1-square-meter array of lithium-drifted germanium crystal detectors for observations in the energy range from about 50 keV to a few MeV, mechanically collimated to an arc-minute. New techniques can be expected to allow larger, more sensitive arrays.

I. An array of scintillation crystals up to 10 square meters in area would be usable in the difficult energy range between about 3 and 10 MeV. Collimation is difficult because X-rays of this energy can pass through thin collimator materials. New techniques can be expected for all the higher energy observations in the MeV and multi-MeV range.

J. An array of cubic-meter spark chambers to detect gamma rays in the 10-MeV to 1-BeV range. Ten to a hundred such spark chambers would be used in the array. Each spark chamber would most likely be limited to about 1 cubic meter to avoid dead-time problems.

K. A large Cerenkov counter with a volume of thousands of cubic meters for gamma rays above 1 BeV.

L. A large millimeter-wave and longwave infrared telescope with an aperture of 10 meters or more for nonsolar observations in the wavelength region between a few millimeters and 10 microns.

M. A very large longwave radio telescope for observations at frequencies below the ionospheric limit of about 30 MHz. This would most likely be a filled-aperture (rhombic) antenna of 10 kilometers (ref. 10).

The instruments described above for hard X-ray and gamma-ray astronomy (G through K) are based on current techniques. Several of the instruments are described in the "Kraushaar Report" (ref. 11). Innovations in these areas are likely and might significantly alter the instrumentation used, such as the recently proposed X-ray and gamma-ray scatter-hole camera (ref. 12).

Other instruments of potential value are:

1. Optical stellar interferometer, either of the Hanbury-Brown and Twiss type or the Michelson type (refs. 13 and 14).

2. Solar millimeter telescope. To obtain high resolution at this wavelength without too much heat input will probably require an interferometer or a partially filled aperture. It might be possible to mask the instrument described in item L to perform as a partially filled aperture.

All of these instruments are technologically feasible in the post-1975 time period. They are major instruments that are required to reach into new frontiers of scientific research. Each of these major instruments must be supported by ground-based telescopes and by other smaller space telescopes. Tasks that can be performed by smaller special-purpose instruments should not occupy the time of the very large telescopes.

ROLE OF THE MANNED PROGRAM

In the Goals of Astronomy section, 13 specific telescopes were described which cover the electromagnetic spectrum from a frequency of about 10^3 hertz to 10^{25} hertz. In this section, the possible role of man in connection with each of these instruments will be described. Innovations in technique and instrumentation may alter specific tasks, but the general role of man in connection with instruments performing a specific function in a specific spectral region will probably not be altered significantly.

GENERAL ROLE OF MAN

Observational astronomy is wholly data collecting; we are interested in knowing the flux in a given frequency and the direction from which it comes. In some cases, we are further interested in phase and polarization information. Because we want to obtain this data with the most efficient use of time, the instrumentation is automated to the greatest possible extent. In ground-based observatories automation is being introduced gradually, as funds and technology permit. Any space astronomy would essentially be completely automated. It is too expensive to have man using valuable time to point at stars, operate filter wheels, or reset shutters. Man is not infallible in recording times, positions, or dial settings; hence, all these operations must also be automated, as they are done in modern Earth-based astronomy.

Even completely automated systems, however, cannot operate without the assistance of man. Man alone is the general systems overseer, diagnostician, and repairman. He is a "supertechnician," without which complex automated systems could not function long. Man's role with automated instruments can be divided into the following categories: maintenance/repair, retrofit/replacement, deployment/checkout, alinement/calibration, and operation/data management. Man's general usefulness in these areas has been studied by the Perkin-Elmer Corp. (ref. 15), the Boeing Co. (refs. 16 to 18), McDonnell-Douglas Corp. (refs. 19 and 20), Lockheed Missiles & Space Co. (ref. 21), the Space Station Requirements Steering Committee (ref. 22), and others.

Each of these areas encompasses the following activities, broadly stated:

Maintenance/Repair

Automated space astronomical instruments should be designed for modular maintenance, because a manned visit may be deemed possible, even if not originally planned. The most vulnerable parts of an instrument (e.g., a photomultiplier, a thin-window X-ray detector, or an offset guider) must be readily accessible for maintenance. In some cases, single units might be repaired, but generally we would picture replaceable plug-in modules, much as modern computers are repaired. As with computers, any sophisticated space instrument should have built-in diagnostic procedures, so that man might perform preventive maintenance by replacing weak sensors or faulty amplifiers, thereby permitting failure analysis.

Retrofit/Replacement

One of the most difficult design problems of a sophisticated automated instrument is to envision the parts that will become obsolete. However, this must be done with any large space instrument, so that man may update the instrument by replacing old detectors with more sensitive ones, or retrofitting a telescope with a new state-of-the-art spectrograph or reflection grating. Thus, if an instrument is properly designed, man can play a very important role in prolonging the productive life of that instrument and providing it with versatility by keeping it up with the state of the art, or modifying it to perform the science of most current interest.

Deployment/Checkout

Here there will be a great variety of one-shot tasks that are involved with the initial deployment of an astronomical instrument. Most instruments will be launched readymade and automatically deployed, so that man's function will be primarily a visual inspection to insure structural integrity and proper deployment. This "eyeball" checkout is an important task that cannot be eliminated except by use of a TV camera with the mobility and discrimination of man. Delicate instruments, such as telescope mirrors or X-ray detectors might be specially blocked or packed for launch, and would require man's assistance in deployment. Instruments which exceed spacecraft dimensions, such as large area X-ray arrays or large optical or focusing X-ray telescopes, might require man to assemble major subsections.

Alinement/Calibration

Alinement and calibration, which will be done both initially and probably periodically, will probably be mostly automated. A sensitive optical instrument must be alined and calibrated in the same environment under which it will normally operate, so that in most cases man will not be involved. Initial coarse alinement might be necessary, if after launch and deployment the instrument is misalined beyond the range of any automatic system.

Operation/Data Management

As previously discussed, man in space may have little part in functioning as an actual observer or as part of the data-collection procedure in nonsolar and low-resolution solar astronomy. Naturally, we would have man perform periodic checks on the observations, presumably by selective data readout, to insure that all was operating normally, as perceived by human judgment. Operation and data collection would all be computer run under ground control, with the computer programed to point the instrument and record all pertinent data. Any "target of opportunity," such as a supernova or new comet, could be easily programed in as long as there was a good communication link with Earth. Man's much-discussed role as a film-handler is not considered here. It is presumed that in the post-1975 period electronic imaging will be the major mode of image recording. If this is not the case, then many of the optical, XUV, and X-ray telescopes will probably require regular visits for change of film.

For high-resolution observations of the Sun, man can play an important role in the pointing/data-collecting loop by selecting only those areas of the Sun that are of special interest. These are generally low-contrast areas, such as plages, filaments, sunspots, etc., where man's judgment is very useful. If a broadband communications link is available, man's physical presence at the telescope may not be necessary.

SPECIFIC ROLES OF MAN

Optical Nonsolar Astronomy

The 120-inch telescope described in item A under Goals of Astronomy is used for this type of astronomy. To be versatile, this telescope will have at its focus the following general types of instruments: (1) spectrographs/spectrometers, (2) photometers, (3) cameras (field-imaging; possibly with film, but with electronic techniques as soon as possible), and (4) polarimeters.

The large-aperture telescope will be of extreme importance to astronomy, and can be used for its entire operating lifetime. The instrumentation at the focus will change from time to time as we develop new ideas and new techniques. This telescope would probably not be operated in physical conjunction with any other equipment, to insure freedom of pointing. Because of the extremely precise nature of this instrument, man will generally play little, if any, role in the actual operation or in precision alinement. General monitoring of observations would be performed to check on inconsistency or unexpected results. On the other hand, the delicacy of these instruments may require that man play an important role in keeping them operating, by performing some routine preventive maintenance and being available to repair any system malfunction. As was pointed out, the optical telescopes themselves would be expected to have long lives, but instrumentation at the focus would be changed as new technology or new techniques evolved, thus giving man the important duty of changing instruments and updating these telescopes. Deployment procedures would probably be minimal, unless possibly certain sensitive components were specially packed for launch, or the telescope structure was too long to launch as one unit.

Millimeter Astronomy

The infrared telescope described in item L under Goals of Astronomy is used for this mode of operation. Most of the optical astronomy discussion applies here. The equipment is not quite as precise, at least in terms of absolute dimensional tolerances. However, the sensors are generally very delicate, and deployment might involve installation of the sensors. Because this equipment must operate at extremely low temperatures, man would be necessary to replace or refill cryogenic storage on the telescope/spacecraft (his presence is undesirable during operation because of the heat he radiates). Updating of sensors will be very important in millimeter astronomy, because the technology is in a great state of flux. The dish is so large that man might be required to assemble it, perhaps by attaching various sectors together.

Long-Wavelength Radio Astronomy

The rhombic antenna described in item M is used here. Man would probably be least involved in this area. The telescope is large, and mechanical tolerances are not critical. The instrumentation consists of suitable amplifiers, which can be quite reliable. Therefore, man would probably be involved only in visual inspection of the automatic deployment of the instrument in orbit and in very infrequent maintenance. If large radio telescopes are to be deployed on the lunar surface, man will necessarily be involved in their construction.

Gamma-Ray Astronomy

The spark-chamber array and Cerenkov counter described in items J and K are used. The spark-chamber array and the Cerenkov counter itself would be assembled by man, because they are so large. Maintenance could involve gas-refilling and repairing any meteoroid damage. There will probably be little retrofitting, since in this field complete new systems are more likely. Man would not be involved in the operation.

Hard X-ray Astronomy

The arrays described in items G, H, and I are employed in this operation. Some X-ray astronomers feel that man will probably play a limited role. Very large arrays may have to be assembled in space by latching together manageable-sized portions of the array. Retrofitting would most likely involve new collimators or new detectors, but completely new systems could be expected in this new frontier.

XUV and Soft X-ray Astronomy

The instrument described in item F is employed. The focusing X-ray telescope would probably be quite permanent, like the large optical telescope, and man would play an important role in updating, changing, and maintaining the instrumentation at the focus. As in millimeter astronomy, cyrogenic resupply could be important. Man would probably play no significant role in operation, but the telescope may be too long to be launched in one piece, thus requiring man to assemble the tubular sections in space.

High-Resolution Solar Astronomy

This type of solar astronomy involves unique use of man, with the following co-located (and possibly optically alined) instruments: (1) optical telescope, as described in item B; (2) XUV telescope, as described in item C; and (3) focusing X-ray telescope, as described in item E.

As with all other instruments, man will maintain and update these three "permanent" solar telescopes. The optical and XUV telescopes may be so long as to require manned assembly.

Solar astronomy (and possibly high-resolution, Earth-orbital planetary astronomy) is unique for man as an observer because we want to observe specific low-contrast features with a detector that has a spatial resolution significantly finer than the target at which we are looking (the Sun or a planet). Rather than taking automated high-resolution scans of the entire target, we can use man to improve significantly the data-taking efficiency by selecting only "pertinent" areas to observe. The best way to accomplish this would be to provide the observer with a visual display of the Sun in some specified wavelength region, with the observing aperture (e.g., spectroscope slit or spectroheliograph scan area) superimposed. The observer, with a servo control, could move the aperture to any desired area (in reality, slewing the telescope), and have the capability to zoom to the point where the aperture essentially fills this field of view. There is no reason why the observer need be physically located at the telescopes. Continuous TV communication is required, which is possible either: (1) from nearby, as a space station in a similar orbit, or from a lunar base if the telescopes are on the Moon; (2) from the Earth if the telescopes are in Earth-synchronous orbit; or (3) from the Earth via a data-relay satellite if the telescopes are in low Earth (possibly Sun-synchronous) orbit.

Low-Resolution Solar Astronomy

This type of solar astronomy involves instruments that stay Sun-centered, such as: (1) a coronagraph (as described in item D); and (2) whole-Sun imaging instruments in various wavelength regions.

Such instruments generally will not be man operated, but will, of course, depend upon man maintenance. The coronagraph requires a very long boom with carefully alined occulting disks. Man may be necessary in the deployment of the coronagraph and possibly in the alinement, although automatic alinement should be possible.

OBSERVING SITES FOR ASTRONOMY IN SPACE

According to the fundamental assumptions of this study, the following observing sites are equally accessible, although the cost per pound may be considerably different (approximate ratio 1:3:10): (1) Low Earth orbit (200 to 300 nautical miles), (2) synchronous orbit (19 350 nautical miles), and (3) the lunar surface. The scientific advantages and disadvantages of each site will now be described. Most of the publications referenced so far in this paper have dealt primarily with low Earth orbit, since that is presently the only economical location for large payloads. Except for a Boeing Study (ref. 18), the merits of synchronous orbit have only briefly been described to date; e.g., Spitzer (ref. 4), Tifft (ref. 6), and the Woods Hole Report (ref. 1). Considerably more attention has been given to the merits of lunar-based astronomy. Of particular interest are Tifft (ref. 6), the "Santa Cruz Conference" Report (ref. 23), and the "Falmouth Conference" Report (ref. 24).

With few exceptions, all of the astronomical instruments described in the "Goals and Objectives of Astronomy" section (p. 52) can operate and yield extremely valuable new scientific data from any of the three sites. However, each type of instrument has certain unique properties and requirements that will determine which site is better.

Low Earth orbit clearly has few advantages when we are not constrained by launch costs, except for X-ray and gamma-ray astronomy. The latter have the advantage that the Van Allen belts shield a low orbit from high-energy solar protons. However, even low orbit is not free from radiation, because of the extensive South Atlantic anomaly. Major disadvantages of low orbit are:

1. Passing through the Earth's shadow, every orbit will create thermal cycling problems, especially with the large structures envisioned here.
2. Earth occultation may interrupt viewing as frequently as every 50 minutes.
3. Ground communication is more difficult, especially if we want real-time TV linkage and experiment control.
4. Gravity gradients and airdrag may create engineering and orbit-keeping problems with these large structures.
5. There is sufficient residual atmosphere to affect some observations, especially between about 400 and 800 Å.
6. Some amount of airglow and aurora occur at low-orbit altitude and even higher altitudes.
7. Large orbital velocity, in a continuously and rapidly changing direction, produces appreciable Doppler and relativistic aberration effects when high-resolution spectral or spatial work is important.

The lunar surface is potentially very advantageous for radio astronomy (ref. 25), where we need exceedingly large structures and a radio-quiet environment, outside of the Earth's magnetosphere. It is clearly disadvantageous for solar astronomy, because each 2 weeks of "day" is followed by 2 weeks of "night." There are several special interest observations that are probably done most easily on the Moon, using the lunar horizon as an occulting edge. We can, just after sunset or just before sunrise on the Moon, (1) study the outer solar corona without worrying about instrumental light scattering problems; (2) study the planet Mercury and highly eccentric comets without concern for the proximity of the Sun; and (3) measure the relativistic bending of starlight.

In X-ray and gamma-ray astronomy, the use of the lunar horizon, sweeping across the sky at a low angular rate, can assist in locating more precisely these high-energy sources. A problem, however, is that the lunar albedo is high in the very high energy regions, and that the occulting horizon will be a contributor to the gamma-ray background, being possibly 10 times greater than the isotropic background itself. Thus the use of the lunar horizon as an occulting edge for gamma rays will be limited to reasonably bright sources.

Tifft (ref. 6) has presented the best case for doing optical nonsolar astronomy on the Moon. Accordingly, it is appropriate to discuss his work.

Geometric Factors.–The Moon has the advantage of guaranteeing 14 days of total darkness, during which nearly half the celestial sphere is accessible. General sky accessibility is difficult to evaluate. On the Moon, there may be a delay of 14 days before one can view in a given area (e.g., a supernova). In high Earth orbit virtually any area is immediately accessible, unless in the proximity of the Earth, Moon, or Sun. Tifft has presumed that any object less than 45° from the limb of the Sun, Moon, or Earth is inaccessible. To view down to 20° of the Sun or sunlit Earth would require providing a lightweight tubular baffle that extends in front of the secondary mirror-support structure a distance of 2.9 times the telescope aperture, in order to prevent any thermal warping of the secondary mirror support or prevent any light scattering from it. Since the Moon is considerably less intense from Earth orbit, its limitation angle might be about 10°. If this is true, 90 percent of the celestial sphere is accessible at any instant from synchronous orbit, in comparison to about 45 percent from the lunar equator. If complete absence of sunlight and earthlight is required for some types of observations, then the back-side of the Moon is the only reasonable site.

The unique problems of solar astronomy were previously discussed. The Moon is most suitable for these observations.

Orbital Doppler shift and aberration of starlight are much more strongly marked in Earth orbit than on the Moon. It should not, however, be difficult to account for the changing Doppler velocity component with a slowly rotating element in the spectrograph. In synchronous orbit, the half-angle of the field of view of a 120-inch telescope at 5000 Å would be limited by relativistic aberration to about 18 arc-minutes, on a long exposure. This again may not be a serious limitation, since geometric optical aberrations may well limit the field even more. Most high-resolution studies will be over very small fields of view (multiple stars, galaxies, planets) until large-area, high-resolution detectors are perfected.

Environmental Factors.—The radiation environment of space is detrimental to man and film. As was already pointed out, low Earth orbit, except for the South Atlantic anomaly, offers the best natural shield from energetic particles. By preparing underground shelters and storage areas, the Moon offers protection from energetic cosmic particles.

The thermal environment in low Earth orbit is the least desirable of any site, because of repeated 45-minute cycling in and out of the Earth's shadow. In high orbit, a great degree of thermal equilibrium can be established, because the telescope is in direct, uninterrupted sunlight for about 6 months. It only passes through the Earth's shadow when the line of nodes of the satellite's orbit points near the Sun. The Moon also thermally cycles, but at a much slower rate than low Earth orbit cycling. It should be possible on the Moon to build a large structure to maintain constant shadow on the telescope.

Because there is no evidence of an intrinsic lunar magnetic field, the Moon certainly represents a superior low-magnetic environment. In synchronous orbit, the Earth's magnetic field is about one one-hundred-and-eightieth that of the surface. On the Moon, it is more than 1000 times less than at synchronous altitude.

The microparticle environment due to primary particles is essentially the same on the Moon and in synchronous orbit. The main concern is degradation of optical surfaces, and this depends on the solid angle of space that the mirror sees. Theoretical considerations show that secondary ejected particles on the Moon will generally follow low trajectories and be of consequence to a lunar telescope only when pointing near the horizon. Such near-horizon viewing is one of the special reasons for lunar-based telescopes.

The optical environment must be very good for faint astronomical work. As has been mentioned previously, low Earth orbit is undesirable for some wavelengths because of residual Earth atmosphere. At synchronous altitude, spacecraft effluents are of serious concern, because the telescope will be in continuous sunlight. With careful engineering design, it seems possible that sufficiently low optical absorption and background can be realized even with a manned spacecraft. A lunar-based observatory would be just as susceptible to local contaminants (except for reaction control jets).

Evidence of a possible lunar atmosphere or dust haze is inconclusive at the present time. Since the zodiacal light, even at the ecliptic poles, is about 4×10^{-14} the brightness of the Sun, any local background does not need to be much lower than that, especially if its time variation is slow.

Operational Factors.–The Moon may provide a very stable base upon which to provide 0.01 arc-second or better guidance for large telescopes, especially interferometric telescopes. All present evidence is that the Moon is not seismically active.* But if the Moon is not stable–if there is constant microseismic activity like that on Earth–then such fine guidance may be best provided in orbit. Engineering studies (e.g., Perkin-Elmer, (refs. 15 and 26) indicate that extremely accurate pointing precision is possible in orbit.

An operational man-machine interface might be easier on the Moon. One would picture a lunar observatory intimately associated with a manned lunar base. However, all the preceding discussion has shown that we generally do not want man in the operational loop. For shirt-sleeve maintenance, it may be no more difficult to fly a "garage" to the orbital telescope than it would be to build a pressurizable observatory dome on the Moon.

Because of the extreme cold available during the lunar night, millimeter astronomy, especially to very low signal levels, might best be done on the Moon during the night. A very large antenna for millimeter astronomy might be constructed to be essentially fixed on the Moon, much as the Arecibo Observatory is constructed.

Communication with ground-based astronomers is most limited in low Earth orbit, probably less limited on the Moon, but certainly least limited in synchronous orbit.

To summarize, we find that generally one site cannot be used to attack all astronomical goals, but neither can one site be ruled out as not assisting in the attack on any goals. Various instruments are needed at all three sites, as described below:

1. Optical nonsolar astronomy. Several special-interest studies would profit from a lunar-based observatory, but one cannot depend on doing all high-resolution and dim-light astronomy on the

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*The passive seismic experiment emplaced on the Moon by the Apollo 11 astronauts indicates that the Moon may be seismically active. (Note added in proof.)

Moon (or in synchronous orbit) until more is known about each environment. The Moon might be especially attractive as a solid base for an optical interferometer.

2. Millimeter astronomy.There is no clear-cut difference between the Moon and synchronous orbit. However, the Moon may have the advantage of allowing a very large fixed dish to be constructed with a movable "feed," and operable only during lunar night.

3. Long-wavelength radio astronomy. The Moon may be advantageous as a support for extremely large filled-aperture radio telescopes many kilometers in extent, depending upon the nature of the lunar surface and any possible atmosphere. Such astronomy is impossible below synchronous altitude.

4. Gamma-ray astronomy and X-ray astronomy. Low Earth orbit has the advantage of low background and is where general survey work with large arrays should be conducted. Special purpose less extensive arrays would be useful on the Moon for finer position determination using the lunar horizon as an occulting edge. A large focusing X-ray telescope might best be in synchronous orbit, because its size would require the small gravity gradients and thermal stability available there, assuming that the detectors could be adequately shielded. Such a structure probably could not operate under lunar gravitational conditions.

5. Solar astronomy. Synchronous orbit clearly has the advantage of about 99 percent annual solar visibility, compared to about 50 percent on the Moon and even less effective time in low orbit. A Sun-synchronous low orbit will yield nearly 100 percent solar visibility, but it is subject to all other low-orbit drawbacks already enumerated. However, the small focusing X-ray telescope for solar viewing is the only instrument that might better be placed in low Earth orbit to avoid the effects of the solar wind. The Moon is advantageous as a site for studying the outer corona.

CRITICAL ISSUES

The development of the instruments described in the "Goals and Objectives of Astronomy" (p. 52), and their use in answering our questions about the universe depends on supporting research and technology in many areas and also on the answers to several critical questions. The areas of supporting research and technology development required have been described in the OASF Study (ref. 27), Woods Hole Report (ref. 1), Astronomy Program Memorandum (ref. 28), the ASTRA (Astronomical Space Telescope Research Assembly) Study (ref. 29), and by the Astronomy Missions Board. The list of important developmental areas is too extensive to enumerate here. What will be considered are certain critical questions, the answers to which could produce major changes in program direction.

Should the various major high-resolution and high-sensitivity astronomical instruments be integral monolithic structures or modular, and possibly active? This general wording includes these specific questions in various subdisciplines:

1. Should a large diffraction-limited telescope be monolithic or segmented? Should it be passive or active?
2. Should a focusing X-ray telescope of large collecting area be one very large aperture mirror or nested mirrors of smaller aperture?
3. Is aperture synthesis possible at radio wavelengths on the order of kilometers, or must we use one very large antenna?
4. Are arrays of smaller spark chambers better than one large spark chamber? The same question can be asked about Cerenkov counters.

Some of these questions must be determined by building and operating in space prototype, scalable instruments. Theoretical investigations are also important, but may not be definitive in all instances.

Can dim-light astronomy be done in direct sunlight? We have no definitive measures of how dark space is.* The darkest part of the zodiacal light (at the ecliptic poles), as determined from the Earth, is about 4×10^{-14} of the solar disk brightness, or about 22.8 mag/(arc-sec)^2. It must be determined if the effect of sunlight on the spacecraft and on any possible spacecraft coma can be kept below this level.

What is the lunar environment as it pertains to astronomy? It is imperative that we determine the following about the Moon before we can consider large astronomical instruments there:

1. What is the radiation level (X-ray and gamma ray) of the lunar horizon?

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*Observations made with OAO-II are establishing the background light levels in space. (Note added in proof.)

2. What is the lunar magnetic field, if any?

3. What is the bearing strength of lunar soil: how deep is "bedrock?"

4. What is the nature of lunar seismic activity, if any?

5. What is the flux, angular distribution, and size distribution of secondary meteorites?

6. Is there a lunar atmosphere or dust haze?

7. What is the dielectric homogeneity of the lunar surface?

What is the best man/machine interface? There are certain critical questions that can only be answered by testing systems in space:

1. Can a telescope operate in the immediate presence of man in space? We are concerned about pointing, optical environment, and thermal balance. The ATM-A can provide some answers to these questions; however, any failure of ATM-A on these counts does not necessarily mean that it is impossible to operate a telescope near man.

2. What is the best way to maintain a large scientific instrument in space? Should we plan on any normal EVA? Would the maintenance shuttle be a huge garage, engulfing the entire instrument to be repaired, or should the scientific instrument be designed with a docking port and a pressurizable walk-in instrument compartment?

These critical questions must be answered as soon as possible to prepare the way for the large astronomical instruments. The Orbiting Astronomical Observatory can assist in determining sky brightness and the potential of dim-light astronomy in the Sun. The possibility of OAO/man interfaces has been investigated by Hallam (ref. 30), Perkin-Elmer (ref. 15), Grumman (ref. 31), and Kollsman Instrument (ref. 32). The OAO is too small to answer all questions regarding interfaces with man, and too small to test many prototype instruments. The ATM and the proposed ASTRA (ref. 29) offer a much better capability for determining whether we need passive or active large mirrors, whether we can use nested, focusing, X-ray telescope mirrors, and what should be the interfaces with man.

As early as possible in the lunar exploration program we must determine the astronomical environment of the Moon. As on Earth, some lunar sites may be more desirable than others, so that several landing sites should be tested.

CONCLUSIONS AND RECOMMENDATIONS

The availability of man in space is indispensable to the continued, efficient operation of complex astronomical instruments in space.

Man does not *need* to play the role of observer in space. In situations where man is required in the observation program (as in high-resolution solar astronomy), the transmission of TV pictures to scientists on Earth and the ability to point the telescopes from Earth may be desirable as the normal manned operation mode.

To observe over the entire electromagnetic spectrum, a great variety of instruments is needed. The ideal program would call for these instruments to be situated in a variety of locations; low Earth orbit, Earth-synchronous orbit, and on the Moon. However, a viable program could certainly be carried out with the major instruments located exclusively in orbit or exclusively on the lunar surface.

To determine the best instruments to use for space astronomical research, the best places to locate them, and the best use of man, several critical decisions must be made, based upon actual, manned, astronomical investigations in orbit and on the Moon. These decisions involve: (1) integral versus modular instruments, (2) active versus passive optics, (3) dim-light astronomy in sunlight, (4) the Moon as an observatory site, and (5) the nature of man-telescope interfaces.

It is recommended that, to make these decisions, immediate effort be made to build and operate in space prototype, scalable telescopes and other astronomical instrumentation, in such programs as ATM and ASTRA, for optical, solar, X-ray, gamma-ray, and millimeter astronomy. All scientific satellites should be designed for modular maintenance, even if there is no intent for man to visit them in space. This would provide for experience in such construction techniques, the possibility of repair if it were later deemed advisable, and simplified environmental testing.

It is recommended that any lunar exploration program include an astronomical site survey, including the deployment of a large radio telescope on the lunar surface, to seek answers to the questions presented in "Critical Issues" (p. 66).

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APPENDIX E
Space Physics

INTRODUCTION

The study of the physics of our space environment has been one of the most rewarding areas of space science. This study has been carried out thus far almost entirely with automated satellites, and should continue. However, as an increasing manned capability develops, we can see great potential advantages accruing to certain areas of space-physics activity (refs. 1-6).

In this paper we will assume that a substantial manned space station capability will be available in the post-1975 period. We expect large-weight, frequent-supply missions, long lifetime (not necessarily manned continuously), and high reliability. The astronaut will add a degree of versatility unattainable by other systems; while some experiments can be performed automatically, the presence of man is essential in the early stages. Other experiments require a degree of interaction with the experimental subject that only a scientist can provide.

We will consider here the most important of the foreseeable physics research areas that will benefit from the available manned-station capabilities: (1) high-energy and cosmic ray physics; (2) behavior of solids, liquids, and gases in zero-gravity; (3) relativity, cosmology, and gravitation physics; (4) micrometeoroid measurements, gegenschein, zodiacal light, and matter at the libration points; and (5) magnetospheric physics and study of the trapped radiation belts and aurora, wave propagation in a dilute plasma, and interaction of the solar wind with the Moon.

These fields will be discussed briefly, with reference sources cited for more detailed information.

HIGH-ENERGY AND COSMIC RAY PHYSICS

The electromagnetic radiation that reaches the solar system has been one of the most important tools for man's quest into the origin, behavior, and perhaps even the end of the universe to which he belongs. Together with this radiation we are reached by a steady flux of particles, some of them with energies higher than are envisioned as ever being attainable on Earth. The study of the energy spectrum (extending into the 10^{20} eV region), antimatter and nuclear composition, charge spectrum, and directionality of this radiation is expected to yield invaluable insights into the age and origin of the universe and of the elements, nuclear processes in stars, the mechanisms responsible for supernovae, and matter and magnetic field distributions in our galaxy (ref. 7).

Because these particles are strongly interacting, small amounts of atmosphere create backgrounds within which the primary information can be lost. This factor, together with the long exposure time necessary to accumulate significant amounts of information regarding the high-energy end of the spectrum, makes satellites the natural vehicle for the study of cosmic rays.

Man's search for knowledge of and control over his environment has led him into the realm of the very small, and his advances have been intimately related to his ability to create and use sources of higher and higher energies. Cosmic rays afford one such source. While a 200-GeV proton beam should be operational early in the 1970's and a 200-GeV center-of-mass facility could be available in the late part of that decade, cosmic rays reach well beyond the range of these machines. Relatively simple orbiting facilities could answer some extremely important questions in the field of high-energy physics. We could easily measure certain correlations among transverse and longitudinal momenta, multiplicity, and total energy, and match these measurements against the predictions of the multiperipheral theory, thus settling whether it is valid or not. The measurement of the proton-proton total cross section as a function of energy, done to 5 percent statistics, would establish the asymptotic behavior of the interaction*—another quantity of extreme significance. Proton-proton differential cross sections at high energies would settle the argument between the optical and Regge Poles theories (the former predicts that the diffraction peak

*Recent cross-section measurements at 706 eV tend to indicate that we may have been overly optimistic in expecting asymptotic behavior in the few hundred GeV region. (Note added in proof.)

stays constant, and the latter leads one to expect the peak to shrink as log E). Another set of questions to which the answers are within reach is: Does the transverse-momentum distribution law change at very high energies? How do weak interactions behave at these energies? Are there heavy particles being created with large transverse momenta as some Earth-based experiments seem to indicate?

While unmanned payloads can study cosmic rays, a relatively small increment in instrumentation, together with the versatility made available by the use of man to rearrange and service the hardware, would give us an experimental facility that would also provide vital information in the field of high-energy physics in the energy region below 10^{15} eV. (This would involve alinement of massive instruments to an accuracy of within a few microns over distances of many meters.)

Cosmic ray physics, together with the questions posed above, could be researched by use of only one major piece of equipment: a superconducting magnet of 2 to 3 meters diameter. The operation of this magnet would require either periodic supplies of liquid helium, or the development of a liquid-helium refrigerator, or better superconducting alloys. Success in the latter two will be of momentous consequence on Earth as well as in space. Complementing the magnet, there would be a liquid-hydrogen target, an energy-measuring device, and instruments such as proportional wire chambers, digitized readout spark chambers, solid Cerenkov counters, plastic scintillators, etc.

A second magnet and the addition of a streamer chamber at a later time will be possible and highly desirable. It must be emphasized that the key to a versatile facility is the periodic presence of man to rearrange experiments and service the hardware as needed. Operation will be automatic.

We feel that such a space station will continue to make important contributions in the study of high-energy and cosmic ray physics for the next 10 to 15 years, and that the equipment, once in orbit, could be used later in other facilities.

BEHAVIOR OF SOLIDS, LIQUIDS, AND GASES IN ZERO-G

(The Materials Science and Processing in Space white paper, found in appendix H, describes in considerable detail the behavior of solids, liquids, and gases under zero-g conditions.)

Our understanding of the physics of materials can benefit in two major ways from the zero-g environment: (1) The pressure in a fluid can be made uniform throughout the container, and (2) structures and materials do not need to support their own weight. The uniformity of pressure in a fluid is particularly important in experiments on phase transitions and fluctuations—a field currently of wide interest. As a specific example, we can cite the lambda transition in liquid helium, where the gravity-induced pressure gradient smears the transition temperature over regions so wide that studies of thermodynamic properties cannot be made as close to the lambda point as desired. In general, phase transitions in Earth-based experiments extend over a range of temperatures because the pressure varies throughout the fluid. Uniformity of pressure in a fluid may also be useful in studying the dependence of chemical reaction rates on pressure (refs. 8 to 10). While gravitational energy terms are small in comparison to the electromagnetic binding forces in materials, the absence of the former may produce interesting effects.

For instance, the crystal surface structure of drops allowed to solidify under zero-g conditions, free of any contact, is of long-standing interest to crystallization theory. The dynamics of these drops, suspended in free fall, can also be studied.

Experiments of this type could make use of a common, man-operated, physical sciences laboratory. With such a laboratory in space, experiments that are identified late in the space station planning could be added without too much additional effort. The presence of man also permits changes in experiments as new directions for research are identified.

RELATIVITY, COSMOLOGY, AND GRAVITATION PHYSICS

The importance of experiments in general relativity is that they are concerned with the large-scale physical laws that determine the structure and behavior of the entire universe. There are some experiments in this field that can be performed on the Earth (refs. 11 to 13); however, there are other experiments that can only be done in space. A few have already been identified, and further space experiments will certainly be defined in the future. Most, if not all, of the candidate experiments could probably be automated. The justification for their inclusion in manned missions is that they could be simpler (and perhaps more effective) if operated by man. Some of these experiments, and the part that man plays in them, are listed below.

SPACE STATION EXPERIMENTS

Starlight Deflection Experiment

This experiment employs a small coronagraph to measure the relativistic deflection of starlight passing near the Sun, with much greater precision than can be done from the Earth because of atmospheric limitations. The justification for the experiment is that if it were precise enough, it might discriminate between the Brans-Dicke and Einstein theories of relativity. There is some disagreement among theorists that this experiment can discriminate among different theories of gravitation (ref. 14), for there is a heuristic derivation of this effect which is based only on the principle of equivalence and special relativity (ref. 15). However, the validity of this type of derivation has been seriously questioned. Indeed, in the original paper by Brans and Dicke (ref. 16), they show that their theory leads to a value for the deflection of starlight which is different from the value of Einstein's general relativity theory.

Thus, this is an important experiment not only because it might discriminate between two conflicting theories, but also because it may answer some theoretical questions concerning the proper way to do certain relativistic calculations. High precision is desirable, for the Brans-Dicke theory contains an adjustable parameter, and the higher the experimental precision the more meaningful are the bounds that can be placed on this parameter.

A man can perform the careful collimation of the telescope, which will enable it to measure star positions to the required high precision. The presence of man also permits film to be used as the data-collecting medium, which significantly simplifies telescope design and data reduction.

Isotropy and Spectrum of the Cosmological Blackbody Radiation

Many of the possible detectors for the radiometers used in this experiment require cryogenic cooling to achieve the desired signal/noise ratio. The cryogens needed will probably be available on a manned space station. The availability of man will also enable a much simpler experiment design, because the calibration procedures need not be automated. Again, the presence of man will permit long-term measurements that will yield good statistics.

LUNAR EXPERIMENTS

Of the many man-deployed experiments that will be developed on Apollo missions, two will yield information that will be useful for relativity theory: lunar gravimeters, and laser retroreflectors.

The discovery of gravitational waves on the Moon would be an extremely significant event. A sensitive lunar gravimeter placed on the lunar surface will provide useful selenological data and allow the Moon to be used as an antenna for the detection of these waves. The availability of men on the Moon in the mid-1970's will enable placement and adjustment of more advanced versions of this instrument. Manned maintenance will keep these gravimeters operating over the long periods necessary to establish whether there is a significant number of coincidences between possible gravitation wave events on the Moon and on Earth.

Laser retroreflectors are precision optical devices that can return laser beams to Earth to enable precise tracking of the Moon's motion. This information would yield a variety of data, including information on cosmological questions such as the possibility of variation in the gravitational constant. Men will place these instruments on the Moon early in the Apollo program, but replacement will be needed throughout the 1970's as the reflectors become eroded by micrometeorites. This replacement will be necessary to insure that reflectors are available for the 8 to 10 year period needed to obtain sufficient data to determine if the gravitational constant G changes as the universe expands.

MICROMETEOROID MEASUREMENTS

Identifying the differences between asteroid and comet material may provide clues to the history of formation of the solar system. Since the relative speeds between the Earth and interplanetary matter are about 15 km/sec., sample collection will consist of deploying extremely pure traps (i.e., tungsten blocks), and recovering, resealing, and delivering them to Earth laboratories. In situ analysis by onboard ionization and mass-spectrometry may also be feasible. Manned versus unmanned operating modes should be determined by cost effectiveness, convenience, and reliability.

A related field is the study of the gegenschein, zodiacal light, and Earth-Moon libration points. These phenomena all consist of sunlight scattered from interplanetary material and so give clues about its distribution in the solar system. Man is quite useful in this area because the equipment required, small wide-angle cameras, is so simple. This is an example of an experiment that may not justify an unmanned launch because it is so small it can be carried into space on a manned launch at essentially no cost. Also, it makes use of man's ability to calibrate and repair equipment, identify new targets for study, and re-program the observing schedule.

MAGNETOSPHERIC PHYSICS

The Van Allen belts, aurora, auroral precipitation, ionospheric disturbances, magnetic storms, the magnetosheath, the magnetospheric tail, solar wind, and solar flares are all separate manifestations of a more comprehensive phenomenon which, for lack of a better name, can be called solar system weather. To date, however, they have been studied separately because initial requirements have been for detailed and specific descriptions of the morphology of these phenomena. Large numbers of unmanned satellites and space probes have been used to explore and determine just what the environment of Earth is. (The existence of the Van Allen belts was not proved until 1958, while the solar wind was first probed in 1962!) Because of the United States exploratory program, man now has a reasonably complete picture of his environment. What is lacking, however, is a comprehensive understanding of the interplay of all these separate phenomena and their eventual relation to the Sun and solar phenomena (ref. 17).

To obtain this synoptic view of the fundamental interaction of Earth and Sun, a manned orbiting laboratory can be most useful. It seems reasonable to assume that the charting of the environment will continue to be done by highly specialized unmanned satellites, because the detectors have been developed, are generally small, and because of the desire to have many of them in a network providing world-wide coverage. These instruments could be taken to the manned station and then launched individually into orbit, if economic considerations warrant this deployment mode.

The orbiting laboratory could conduct experiments within the magnetosphere which would provide valuable information on the dynamics of the region. Except for the Starfish event that created an artificial Van Allen belt, there have been no experiments of this type performed in space. It is possible, for example, to inject electrons into the magnetosphere and follow their motions along the magnetic field lines. It is even possible in this way to form an artificial aurora. Environment-modifying experiments of this type could study wave propagation, particle diffusion, and the dynamic coupling of magnetospheric phenomena. Subsatellites offer a wide range of experimental opportunities. Controlled from the laboratory, these might be used to probe regions inaccessible to the station and to study the wakes of vehicles, radio transmission characteristics, wave-particle interactions, and whistler propagation (ref. 18).

CRITICAL ISSUES

The realization of the goals described in this paper are not dependent on major technical innovations. Neither is there a reason to expect that the goals outlined in the four previous sections (pp. 74-80) will undergo substantial changes. Implementation by manned or unmanned modes will depend on technological developments, cost, and political considerations.

High-energy and cosmic ray physics must be given a different priority. This program is by far the most ambitious one in terms of cost, weight, and power consumption. Particle detection techniques may undergo radical changes, and continuing accelerator and theoretical work could make today's questions irrelevant 10 years hence. It is with these facts in mind that we present "Conclusions and Recommendations."

ORBITAL CONSIDERATIONS

High-energy and cosmic ray physics.–An orbit providing low radiation background is preferable, but not imperative.

Behavior of matter in zero-g.–Because of atmospheric drag, the lowest allowable orbit will depend on the requirements of the experiment. The table below shows values calculated for the Apollo VII command and service modules.* Accelerations are given in g's, and d is the distance a body would move if subjected to the respective constant acceleration for 5 minutes.

Altitude, km	a/g	d, cm
200	5.7×10^{-7}	25.0
300	5.6×10^{-8}	2.5
400	8.3×10^{-9}	0.4

Gravitation physics.–No orbital preference. The experiment on starlight deflection by the Sun (see p. 77) depends on observations over long periods, but not on a continuous basis; thus a Sun-synchronous orbit is unnecessary.

Micrometeoroid measurements.–No orbital preference.

Magnetospheric physics.–No orbital preference for the station. It would be used to launch and service small probes that will be part of a global network.

CONCLUSIONS AND RECOMMENDATIONS

We feel that if technology, cost considerations, and/or national goals, make available a manned capability, the presence of man in space will make possible the implementation of the programs described above. Man will deploy, calibrate, and repair instrumentation as needed. His role as an observer will be particularly useful while working on the behavior of matter under zero-g conditions. Experimental programs described in previous sections of this paper could be very attractive if integrated within a large manned facility. The particle physics facility should be separate from the main

*R. W. Newsome, private communication, 1968.

station, because its electromagnetic noise output may provide an intolerable background for some of the other experiments described. Only periodic visits will be necessary, and the key to its success will be the versatility introduced by having men rearrange the hardware as necessitated by the established program and new developments in the field.

We recommend that NASA follow progress in this field quite closely so that the programs and facilities will not be obsolete when orbited.

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APPENDIX F

Earth Sciences and Applications

INTRODUCTION

Space accomplishments over the past 10 years have tremendously advanced our understanding of the Earth and our capabilities for long-distance communication and navigation. Projected programs over the next several years are designed to capitalize on this early investment and produce even more remarkable gains. Examination of the needs in the various disciplines of the Earth Sciences and Applications program, however, indicates that the requirements for observations and operations in Earth orbit far exceed these plans. The period 1975-1985 could be one of the most informative and beneficial eras of our space age for the people of this Earth if these needs are pursued in an aggressive manner.

OBJECTIVES

The objectives for an Earth Sciences and Applications program might be conveniently stated as follows (ref. 1):

1. A more precise knowledge and understanding of man's environment on Earth and of the forces controlling it, to allow accurate short and long term forecasting and to allow man's eventual control of his environment.
2. A more precise knowledge, inventory, and use of the Earth's resources, particularly those of the United States.
3. The extension of communications of all types to world-wide coverage, particularly to the areas inaccessible by past techniques, to greatly improve the efficiency, economy, and reliability of communications, worldwide and national.
4. The development and adoption of systems of navigation and traffic control to achieve safe, economical, and swift air and sea transportation at much higher traffic densities.
5. The accurate location of geographic features.

SPACE ACCOMPLISHMENTS AS OF 1968

NASA's flight program of space experiments is preceded by a ground-based research phase. Early experiments in space either determine the need for further basic research, or they can progress to the development of an operational flight system. In three of the five areas mentioned in the section "Objectives" (p. 85), NASA has already achieved first-generation operational systems. These include meteorology, which is part of objective (1), communications (3), and geodesy (5). The other two areas have not yet advanced beyond the early stages of flight investigation.

TERRESTRIAL ENVIRONMENT (EXCLUDING RESOURCES)

Most of the activity in this area has been in meteorology. The early Tiros satellite has achieved operational status (operated by the Environmental Science Services Administration) and currently provides imagery of the Earth's cloud cover during daylight hours. Operating in Sun-synchronous orbits, two types of cameras are carried on different spacecraft. The automatic picture-transmission (APT) camera provides direct readout to ground stations with inexpensive receivers, while the advanced vidicon camera system (AVCS) stores its data on magnetic tape and requires special ground receiving equipment. Ground resolution is about 1 kilometer from 800-kilometer altitude for the AVCS camera.

The Nimbus satellite program provides a test bed for new sensor instruments, as well as providing meteorological data for operational use. The high-resolution, infrared, radiometer scanning system senses thermal radiation from land, water, and cloud surfaces and produces imagery of the nighttime hemisphere in the 3.6- to 4.2-micron region of the spectrum (ref. 2). Ground resolution is about 8 kilometers, and the accuracy of the temperature measurements is about 1° K. Five-component multispectral imagery (ground resolution of $\sim$50 kilometers from 1100-kilometers altitude) between the visible and 30-micron region has revealed information on the temperature and water-vapor content of different regions of the atmosphere. This type of experiment was also carried on Tiros III, IV, and VII.

Operating at geosynchronous altitudes, the Applications Technology Satellite (ATS) program has provided synoptic (black and white, and color) photography of time-varying cloud systems, including a number of storm phenomena (ground resolution of ~4 kilometers with the spin-scan camera).

In addition to meteorology, the Terrestrial Environment discussion in this paper includes the disciplines of geology, oceanography, and hydrology. Gemini photos have been used for the study of large-scale geologic features which far exceed the range of coverage of aerial photography surveys (ref. 3). Satellite optical imagery has also provided data on such things as pack-ice distribution on the ocean, snow cover on the land, and the location of water in remote areas. Nimbus high-resolution, infrared-radiometer (HRIR) imagery has detected ocean currents through their surface temperature differences.

EARTH RESOURCES

As part of a preliminary research program, a number of Earth resources-oriented sensors have been flown on aircraft to determine appropriate techniques for data gathering and interpretation. These are aimed at such resources as minerals, water, and agriculture. Space-flight data of potential interest to the mining and fishing industry, for example, have been provided by the Gemini, Tiros, and Nimbus programs, although these were not the prime experiments. Specific resource-oriented satellites have not yet been flown.

COMMUNICATIONS

The NASA communications satellite program, which began with the Echo balloon in the early 1960's, has progressed through the Relay system, capable of one-way television or 300-channel telephony, to the present operational Intelsat program, capable of transmitting television or up to 240 voice channels from point to point (from geostationary orbit). In addition, the ATS program is carrying out communications experiments for possible future space-operational systems (ref. 4). Examples of these experiments include: (1) a microwave communications transponder capable of operating in either a wideband or narrowband access mode; (2) an electronically despun microwave antenna; and (3) a VHF transponder with associated electronically despun antenna.

NAVIGATION, TRAFFIC CONTROL, AND DATA COLLECTION

NASA is just beginning experiments in this area of the ATS program to determine the locations of surface and airborne craft. ATS-C (1967) carried an experiment involving a transponder to use the Navy's Omega Navigational System for craft position determination.

GEODESY

One major objective of the National Geodetic Satellite program is the establishment of a network of about 90 control stations around the world with a positional accuracy of ±10 meters. The successful launch of Geos II in January, 1968, may provide enough data to complete this objective, although an additional Geos could be required.

The second major objective of this program—a description of the Earth's gravity field out to the 15th harmonic—is being met largely by tracking various satellites already in orbit.

THE NEEDS IN EARTH SCIENCES AND APPLICATIONS AS WE SEE THEM TODAY

TERRESTRIAL ENVIRONMENT

Meteorology

Weather Forecasting

At the present stage, weather forecasting is primarily based on ground-based observations (refs. 5 and 6), with the data from meteorological satellites playing a secondary role in filling in some gaps in these data (such as providing storm warnings). Operational use of global-circulation models, extending the forecasting period to

1 to 2 weeks, will require a continuous supply of global data on atmospheric variables. Such a network is likely to encompass thousands of long-lived balloons in the stratosphere, a number of satellites in a variety of orbits, and a battery of ground stations.

The estimated minimum continuous-data requirements for effective weather prediction include: (1) atmospheric-mass field (given by temperature and pressure) and wind vectors (in the tropics), (2) the coarse distribution of tropospheric humidity, and (3) the distribution of clouds. These parameters must be measured as a function of latitude, longitude, and height. Observations must be obtained over the entire globe, and made at regular intervals once or twice in each 24-hour period. Initially, a horizontal grid spacing of about 500 kilometers between observations at several (three to nine) altitude levels below about 35 kilometers is needed.

Heat Budget

One of the key problems in meteorology, which focuses the needs for observational data and increased understanding, is the question of the heat budget of the Earth's surface and atmosphere. This budget depends on a very delicate balance of the radiation incident from the Sun, its reflection, scattering, and transmission by the atmosphere, the radiation absorbed by the Earth's surface and re-emitted, and the passage of this re-emitted radiation through the atmosphere (ref. 7). Key factors in adjusting the heat budget are the water vapor, carbon dioxide, and ozone concentrations in the atmosphere, its cloudiness, and turbidity caused by aerosols. It is not entirely clear how much of the greenhouse effect is to be attributed to carbon dioxide and how much to water vapor, nor are sufficient quantitative data available on cloudiness. Even less is known of atmospheric turbidity. This permits only crude estimates on secular variations of the terrestrial heat budget. The most sophisticated computations (refs. 8 to 10) show that an increase or decrease by a factor of 2 in CO_2 concentration is accompanied by a surface temperature change of 2 to 3° C; no account was taken in this computation of atmospheric turbidity.

Scattered observations over the last century indicate that the CO_2 content of air in the northern hemisphere has increased from ~280 ppm in 1860 to ~320 ppm in 1960; this is most likely because of the burning of fossil fuels. Observations carried out on a regular basis since IGY show a steady rate of increase of 0.7 ppm/year over the last decade. But data over most regions of the world are still lacking. A steady heating trend of the surface temperature was evident until the 1940's, which was ascribed to the increase of CO_2 concentration. Since then, this trend appears to have been reversed; this is tentatively attributed to the increase in turbidity. The latter appears to have been mounting at a rate of tens of percent per year (ref. 11).

Relatively coarse but selective measurements (as described above) directed at simple atmospheric parameters may be sufficient even for long-range (~2 weeks) weather forecasting. A truly quantitative understanding of the Earth's heat budget, however, and a realistic assessment of trends occurring in it require increasingly refined measurements on a global scale of both the distribution of components critical for the terrestrial heat balance, and of the different components of solar and terrestrial radiation. To separate these, spectral and spatial resolutions may be required that far exceed those needed for the conventional meteorological purposes of the future.

Weather and Climate Modifications

A 1966 report by the National Academy of Sciences (ref. 12) reviewed the current progress and problems in weather modification. Some of the conclusions are summarized as follows. On the subject of fogs and clouds: (1) data on the effects of cloud seeding for precipitation control are largely ambiguous; and (2) dissipation of localized "cold" fogs is practicable, but there has been little recent progress with respect to "warm" fogs. On the subject of large-area weather and climate modification: At our present stage of understanding, "to embark on any vast experiment in the atmosphere would amount to gross irresponsibility."

Unfortunately, man is inadvertently modifying the atmosphere (and its surface interface) by increasing the CO_2 content, polluting the air and water with heat and chemicals, and changing the radiative properties of the surface by the construction of cities.

Clearly we wish to know the short- and long-term effects of inadvertent climate modification. There are also positive changes in our weather which would be desirable to implement. The above report (ref. 12) outlines a series of recommendations for both field investigations and studies, all of which require data that are not presently being obtained. Much of this is required on a continental or global basis and is best obtained by satellites.

Geology (Excluding Resources)

Many geologic occurrences, such as mountain building, faulting, and sea-floor spreading take place on a continental or global scale. Some of the resulting features would be evident in surface imagery. However, the view of the geologist has been limited, with aircraft regional surveys providing the greatest perspective (single pictures cover less than 10 miles on a side). The need here is for photography of large areas for the purpose of investigating basic geological problems involving features extending over hundreds to thousands of miles, and which may be located in such remote areas as central Asia, the African rift valleys, the Amazon basin, and the Arabian desert. To photograph such areas by conventional aerial and surface methods would be extremely expensive and time consuming, in addition to presenting problems of cartographic control.

While most of the geology referred to above is more or less constant over the lifetime of any proposed observation program, there are short-term occurrences for which comparative "before and after" pictures are the most revealing measure of what has happened. For example, coastal geology of a continent can change markedly over a period of years, if erosion conditions are severe enough. Visible changes in the Earth's crust caused by earthquakes may also be detected in this way.

In the case of other transient phenomena where the active process may actually be observed, volcanic eruptions and other dynamic thermal activity are candidates of interest. The need here is to monitor for the occurrence of such events, with the possibility of predicting and locating potential catastrophes. In the case of volcanoes, the perspective of orbital observation would also be an advantage in estimating the amount of ash thrown into the atmosphere. Volcanoes are important to the atmospheric heat budget problem, as they are a source of atmospheric turbidity which counteracts the effect of increased CO_2 by decreasing the amount of visible sunlight reaching the lower atmosphere and surface.

Earthquake prediction and damage assessment are another significant area of geology. A number of surface in situ measurements have been suggested, with the possibility that a significant change in any one of several parameters might provide a few hours or days notice of impending disaster (ref. 13). The satellite application here would be the collection of transmitted data from implanted ground sensors.

Oceanography (Excluding Resources)

In a 1966 report, the National Academy of Sciences (ref. 14) summarized the areas in oceanographic research where, although some new insights had been achieved, much remained to be done. In physical oceanography alone (as opposed to marine chemistry and biology, for example), eight areas were cited where sufficient understanding and availability of data are lacking. These include:

Near-surface currents and their seasonal variations.—Both direct and indirect measurements are being made of near-surface current properties, but the view is far from synoptic.

Deep circulation and oceanic structure.—New measurements of deep-ocean properties are causing old theories to be revised or rejected.

Scales of motion in the sea.—The energy content in sea motions at frequencies below one cycle per day tends to increase with decreasing frequency. There is a requirement for long-term observations over large areas.

Upwelling and upward mixing.—Cold water rising to the surface can have a profound effect on local weather and climate.

Turbulence and diffusion.—There is a large amount of turbulence caused by wind and waves in the near-surface layer, but the energy budget and the way in which the energy is dissipated are not known in detail.

Internal waves.—Internal waves at tidal frequencies have been detected, but in general, their origin and frequency of occurrence are unknown.

Surface waves.—Wind-driven, sea-surface waves can be predicted if the wind field is known—which it generally is not.

Ocean tides.—World-wide measurements of tidal variations have both oceanographic and geophysical implications.

Any coordinated program of research and data collection designed to investigate these several areas should include ships, buoys, and satellites. Certainly for the vast bulk of the oceans beneath the immediate surface, satellite observations are of limited value. However, satellites will still play an important role as part of the data-collection system.

In a recent draft report by the National Council on Marine Resources and Engineering Development–Committee on Ocean Exploration and Environmental Services (April 25, 1968), a 10-year plan for ocean exploration and mapping (TYPOE) is outlined. This is an interagency plan for the 1970's, designed to coordinate the efforts of the Departments of Commerce, Defense, Interior, and Transportation, in addition to agencies such as NASA, the AEC, and the NSF. Interestingly enough, the implementation plan that concludes the report is based solely on the use of ships—approximately a hundred of them. Ships have clear advantages in direct surface measurements and subsurface soundings, but they have equally clear disadvantages in extent of coverage. Many of the needs for observational data that are outlined for both the U.S. continental margins and the deep oceans may best be satisfied, at least in part, by satellite observations. Among these are included:

1. Monitoring nutrients, dissolved gases, and chemical and radionuclide pollutants in the shelf areas of the U.S.
2. Data in support of studies of the Labrador Current, especially as it transports icebergs and affects Gulf Stream dynamics.
3. Further data in support of existing studies of North Pacific Ocean currents, especially the Kuroshio-Oyashio Systems and the California Current, if the large-scale dynamics are to be understood.
4. Data on the effect of the extent of sea-ice cover in the Arctic Ocean on global circulation patterns and the climate of North America.

It should be clear that the problems in oceanography cannot be completely separated from those of other disciplines. Considering the question of the atmospheric heat budget, for example, the CO_2 content of the oceans is roughly 50 times that of the atmosphere. Changes in the content of either one can upset the thermodynamic equilibrium. Pack ice floating in the polar regions reflects about three-fourths of the incident solar illumination and modifies the energy exchange between the ocean surface and atmosphere. The temperature and sea state of the oceans' surface water are also important contributors to this exchange.

Hydrology (Excluding Resources)

Much of the interest in hydrology is in its use as a resource study; this subject will be considered in the following section. However, nonresource needs for hydrologic data can arise, for example, in connection with the heat-budget problem. A typical instance is a situation in which lower temperatures accompanied by increased precipitation result in glaciation. Various authorities have estimated that if the average temperature should decrease by 1.5° to 8° C, glaciers would again cover an appreciable fraction of the Earth's surface (ref. 10). One of the central questions motivating the recent years of Antarctic investigation has been: Is the amount of ice remaining constant, or is there gradual melting? If a small percentage of this ice were to melt, the world's coastal cities would be flooded. Based on results to date, Dr. Albert Crary, Antarctic specialist for the National Science Foundation, has commented: "One area or another may be out of balance—precipitation and ice flow vary—but on the average, the amount of ice seems to be remaining about the same" (ref. 15).

Another important contributor to the heat-budget problem is plantlife, which depends for its sustenance upon the availability of water. Plants are the major organic users of atmospheric CO_2, taking it out of the atmosphere during photosynthesis. The organic cycle replaces this CO_2 through the processes of respiration and decay, and equilibrium is approximately maintained. The annual exchange volume in this organic cycle far exceeds that caused by man's burning of fossil fuels or the volume included in the inorganic exchange cycle. The extent of plant growth depends on climatic factors, such as temperature and precipitation, as well as inorganic soil components.

EARTH RESOURCES

Our natural resources are limited in quantity. In order to insure that the appropriate planning is done whenever there is a dependence on these resources, it is necessary to have an up-to-date inventory of the status of each resource. In general, these resources are distributed throughout the world, so that a global survey technique is required. While some resources are relatively stable with time, others, such as in agriculture, can change markedly in a period of several days. The availability of current inventories is an economic advantage to the United States, and it could also become a vital information factor in our international relations.

Examples of Earth resources that may be subject to satellite survey are:

Oceanography.–Coastal water pollution, fish school migration, sea state (for shipping), and sea-ice location (also for shipping).

Hydrology.–Water storage in snow and ice cover and in lakes and reservoirs; water pollution.

Agriculture.–Detection of crop disease and prediction of crop yield.

Geology.–Mineral sensing and inventory.

A number of attempts have been made to estimate worldwide "dollar benefits" that might accrue from a vigorous program of space observations. Table F-I (refs. 16 and 17) shows estimates of annual benefits made by three relatively independent groups. The point to be made is that "benefits" could be measured in terms of billions of dollars. However, most individual proposals have not been tested. The Space Applications Summer Study group (ref. 6) emphasized that the time had come for substantial investments of venture capital; that the current NASA budget in this area ($100 million) was too small by two to three times, at least. They deemphasized benefit estimates for any one application, urging that the overall return would be large, certainly much greater than the cost of achieving this return.

COMMUNICATIONS

With the formation of Comsat and the partial completion of its satellite network, our immediate goals in point-to-point communications are nearing realization. Looking to the future, the needs for space communications may be divided into four areas.

Improved frequency utilization.–One of the key areas here is the investigation of the usefulness of the frequency spectrum below 1 GHz and above 10 GHz. Millimeter waves are particularly important, as they would provide increased antenna gain per unit area and possibly increased bandwidth.

Small user/multiple access communication.–Eventually the need will arise to provide voice and data links between small-capacity users and remote ground terminals on a reliable, low-cost basis. The small users may be aircraft, ships at sea, or small mobile or fixed ground stations. This would require constant satellite coverage with

Table F-I.–*Dollar Benefits from Space Applications (Worldwide) ($ 10^6 where quantified)*

Activity	TRW[a] (ref. 16)	Summer Study 1967[a]	Summer Study 1968[a]	PRC[a, b] (ref. 17) (5 case studies)
Agriculture/forestry	40-60	10's	Many 10's	1. Rice: increased production ~20 2. Wheat rust control ~300
Hydrology (water resources)	35-100	Substantial	Enormous	3. Power management ~40 (hydroelectric)
Geography (land use planning)	10-50		Many 10's	4. Malaria control ~80
Meteorology		~1000	(Not quantified)	
Geology (mined resources)	100-600	~2000	(Not quantified)	
Oceanography (marine resources)	500-900	100's	Many times greater than cost (no dollar estimate)	5. Fish: albacore tuna ~150

[a]Annual.

[b]Computed over 20-year period discounted to 1970. Annual benefits less early in period; greater late in period.

increased signal receiving and transmitting capabilities compared to systems like Intelsat which rely on large ground facilities. To make this system economically feasible a large number of small users must be identified for a single satellite. The satellite system must therefore be capable of handling a large number of signals simultaneously.

Space broadcasting.–Broadcasting from space is a possibility that should be considered. The various options include direct home radio, television to community receivers for commercial and private distribution, and television to conventional or modified home receivers.

Satellite aids to data relay.–As future unmanned satellites in Earth orbit increase their rate of data acquisition, satellite relay stations may prove to be the economical way to transmit data from any part of the orbit to ground terminals which are frequently out of line of sight. Other applications include the relay of voice, data, and possibly television from manned Earth-orbital stations to ground control centers.

NAVIGATION, TRAFFIC CONTROL, AND DATA COLLECTION

Present electronic navigation techniques are not adequate to cope with expanding air traffic and rising speeds. By 1970, the air traffic system is expected to be saturated in the North Atlantic area. A prime contributor to this situation is the fact that present poor navigation techniques, coupled with safety standards, have led to an ineffective use of airspace. Present separation requirements are 120 nautical miles laterally, 20 minutes flying time, and 2000 feet vertically. In the case of commercial or civilian ships, there is no presently available system that can provide navigational data at any time, in any kind of weather, in any part of the world.

The need here is for a satellite system that can provide rapid navigational fixes (to meet the demands of supersonic aircraft) at all times and include the small user who has inexpensive equipment that is relatively simple to operate. A single system should be capable of handling a large number of users at any one time with a minimum waiting period. It should also be capable of relaying the users' position to a control center that keeps track of all relevant traffic in a given area and of communicating the controller's instructions to the user.

In the data-collection area, the need is for an orbital system that can locate mobile stations (e.g., balloons in the atmosphere), interrogate them for stored data, and relay this information to ground receiving stations. Fixed stations such as anchored ocean buoys and remote surface sites should also be included in the interrogation network. The capability for tens to hundreds of thousands of stations might be required.

GEODESY

Goals of the Geodetic Satellite program of the Office of Space Science and Applications (OSSA) (ref. 18) which extend beyond those cited in Space Accomplishments "as of 1968" (p. 86) include:

1. Mapping the geometry of the ocean surfaces with an accuracy of ±5 meters or better.
2. Locating certain widely separated NASA tracking stations and geophysical observation stations with an accuracy of ±1 meter or better.
3. Improving on existing measurements of Earth tides, polar motion, Chandler wobble, and the Earth's rotation rate.

Geodetic satellites may ultimately provide data on such phenomena as continental drift, vertical uplift of landmasses, and land motion along fault zones.

POST-1968 EARTH-ORBITAL SYSTEMS FOR EARTH SCIENCES AND APPLICATIONS

Having reviewed some of the future needs in the Earth Sciences and Applications program, we now wish to examine how these needs might be satisfied by an Earth-orbital program. In particular, the unmanned program projection of OSSA into the 1970's is reasonably clear in the early stages. The mid- to late 1970's projections should probably be viewed as representative of the planned level of technological effort, rather than as a specific program plan. For the manned program a preliminary payload of Earth sensors has been selected for one of the AAP workshop flights in the early 1970's. However, Earth sensing is far from a major objective and the possibility of a second flight with Earth science/applications as one of its objectives is uncertain. It seems likely that the needs as stated will require instrumentation in Earth orbit that exceeds both the OSSA and AAP plans.

PROSPECTS FOR THE UNMANNED PROGRAM

Terrestrial Environment

As in the pre-1968 programs in this area, the emphasis is on meteorology, but data of interest to geology, oceanography, and hydrology will also be obtained. Early extensions of the basic Tiros system will incorporate the APT and AVCS camera systems (for day-side imagery) and the HRIR (for night-side imagery) on the same satellite as a prototype of a second-generation operational system. This satellite, Tiros M, should be capable of accepting additional advanced sensors in the future.

Nimbus will continue to carry developmental instruments designed to extend our knowledge of the atmosphere. Nimbus B-2 will attempt a more quantitative determination of the atmospheric structure on a global basis. The payload will include an infrared (IR) interferometer, IR spectrometer, and a solar ultraviolet (UV) experiment. In addition, an advanced television camera system will be used for the first time.

Experiments on later Nimbus flights are planned which will extend the remote sensing of the atmosphere (and the surface, except in UV) from the ultraviolet through the visible and IR on into the microwave region of the spectrum. Passive microwave radiometer and spectrometer measurements could provide key data on vertical temperature and water vapor profiles. IR sensors with improved spatial and spectral resolution would provide day and night imagery of clouds and surface features, and yield improved information on atmospheric structure. These high resolutions would require cryogenically cooled IR detectors. Microwave occultation experiments (as on Mariner IV and V) can determine atmospheric density profiles. Polarimeters in the visible spectrum might detect atmospheric pollutants.

A number of new spacecraft systems are possible here. A Synchronous Meteorology System Test Satellite has been proposed for the early 1970's to function as a precursor of an operational system. World weather-watch satellites have been proposed for the mid-1970's for polar orbit in support of the Global Atmospheric Research Program. Finally, advanced ATS satellites in the mid- to late 1970's could provide a platform in geostationary orbit which would have a large payload capacity, long life, and be precisely oriented ($\pm 0.001^\circ$), for experiments such as detailed imagery of small-scale weather phenomena.

Earth Resources

For the near term, flights in the aircraft program will continue to test specific instruments and establish the so-called "ground truth" necessary for data interpretation. Specific sensors now being flown include metric and multispectral cameras, infrared imagers, microwave radiometers, side-looking radar, and radar scatterometers. There is the possibility of an Earth Resources Technology satellite in the early to mid-1970's to test some of these sensors at orbital altitudes. In the meantime, some useful data will be provided by the Tiros, Nimbus, and ATS programs.

Communications

Most of the plans here are for research on experimental systems on ATS satellites, at least through the mid-1970's. Millimeter-wave experiments are planned for ATS-E (1969). Small-user/multiple-access experiments will be extended to take advantage of large erectable antennas and precision pointing. Experiments in data relay could provide the basis for an envisioned data relay satellite system in synchronous orbit during the mid- to late 1970's.

Navigation, Traffic Control, and Data Collection

Further development of technology in this area is planned for future ATS flights. A satellite data-collection system that also locates the source data station (called Interrogation, Recording, and Location System, IRLS) was planned for Nimbus B and is currently scheduled for the Nimbus D flight. A cooperative program with the French is planned in which the positions of meteorological balloons will be determined by Doppler sounding from an orbiting satellite.

Geodesy

Follow-on flights in the Geodetic Earth-Orbiting Satellite Program, carrying accurate laser or radar altimeters, might be used for measurements of the shape of the ocean surface. Such measurements might also be done from advanced ATS satellites in the mid-1970's.

PROSPECTS FOR THE MANNED PROGRAM

Aside from Apollo test flights, the only scheduled program of manned Earth-orbital missions is AAP. A number of Earth resources/meteorology experiments have been reviewed by NASA as part of the payload on one of these flights. These experiments include cameras, IR spectrometers and interferometers, and a microwave radiometer. As currently planned, only one experiment–a multispectral camera–has much chance of being flown. This would be on a workshop flight with an orbital inclination possibly as high as 35°. There will probably also be more Apollo photography with handheld cameras.

Most of the Earth-sensing experiments proposed for the AAP time period are similar to experiments proposed for the unmanned satellite program. However, in the post-1975 era there may be the need for very large and complex systems in Earth orbit which go beyond those discussed in the earlier part of this section. For example, in the communications area, direct television transmission to homes at UHF frequencies should be done with a system in synchronous orbit and requiring a kilowatt of power and a 100-meter diameter parabolic antenna. While a smaller satellite system could be used in conjunction with community receiving and distribution stations, this may not be cost effective in areas of sparse population where the number of television sets per distribution station is small.

For navigation and traffic control systems, a large space-radio interferometer using phase comparison between microwave signals received at two antennas located tens of meters or more apart on an accurately known baseline might prove desirable. Pulsed laser radars (ref. 19) operating at suitable wavelengths have the potential for measuring a wide cross section of atmospheric parameters, including the distribution of key constituents–O_2, H_2O, CO_2–as well as particulate matter. This fact is especially important for the heat-budget problem.

The merits of putting any of these instruments on a manned station are discussed in the following section.

MAN'S INTERACTION WITH THE INSTRUMENTS IN EARTH ORBIT

Man in an Earth-orbital station could have two fundamental types of interaction with the Earth sciences and applications instrumentation. In the first case discussed below, he acts as a technician and observer to check out, maintain, and operate instruments that were developed and tested on the ground. In the second case, also discussed below, he functions as a development engineer on the space station. His intent here is to carry out the design and performance evaluation, at various stages in the development of a new instrument, by testing it at the task for which it is designed. Once this development phase ends, the new instrument proceeds to manufacturing. Subsequent to this, the man in the space station again becomes technician and observer during the operation phase of the instrument.

INSTRUMENT CHECKOUT, MAINTENANCE, AND OPERATION

Basically, the Earth sciences and applications payload consists of instrumentation through which information flows. Even if he has very little or no personal contact with this information, man might still act as a useful technician. If he has contact with the information, he can be an observer and, no doubt, a better technician.

As a technician only, possible functions include assembling and positioning of instruments. One class of assembly might involve large structures such as antennas requiring EVA. Smaller instruments might be moved from launch storage areas and placed in proper position for operation. Calibration and alinement of equipment are functions that could be carried out at regular intervals during a mission. This could be done by having a calibration source on the spacecraft or elsewhere, as long as the source properties were known. Alinement, such as focusing a camera, could be done entirely on the spacecraft or with supporting instructions from the ground, after an observer there had reviewed some information on equipment operation. Carrying out these functions in space would relax the requirement that such adjustments survive launch.

Once the equipment is set into operation (i.e., following assembly, alinement, and calibration), there will ultimately be a need for maintenance and repair. If he is not in personal contact with the information flow, the man onboard will have to be instructed from a ground base as to what the symptoms of the malfunction were. Exactly what types of repair operations could be performed would depend on factors such as basic equipment design and the ability of man to manipulate objects in the spacecraft environment.

For the man onboard to intercept the information flow, proper data displays are required. This applies equally to an infrared imagery experiment or to a broadcast system (although in the latter case the sensor that actually measures equipment performance is likely to be on the ground).

If, in addition to displays, the man onboard has both the time and ability to react, he can perform some function as a scientific observer, responding to objects of opportunity. The apparent rate of motion of the Earth's surface from a 200-mile orbit is comparable to that from a 600-mph jet plane at 35 000 feet; so that even in the lower orbits there is a reasonable reaction time. The ability to react is a function of the man-machine interface. For example, if the man should be observing a real-time display of radar scatterometer data, and he noticed something unusual, he must have the ability to train another sensor on the same area to take additional data.

Another function of the observer is to alter the mode of operation of a given instrument, either because incorrect operating conditions were initially assumed, or because it was found during the flight that productive data could be acquired in several different modes. These alterations might include changing filters and resetting gain levels, exposure times, scan rates, or transmitted power level.

EXPLORATORY INSTRUMENT DEVELOPMENT

As experience is gained in the use of sensors and other instruments in Earth orbit, we can obtain a better understanding of what the most desirable instrument parameters would be, at least conceptually. Some of these ideas will be developed into new, second- or third-generation instruments. If man is reasonably adept in the maintenance, repair, and operation of instruments on an orbital station, he may also have a role in the development and engineering shakedown phases of new instrumentation for orbital use. For example, in the early development stages when many design choices are available, a working breadboard could be installed on the station. The cognizant engineer could accompany it, perform manual functions, analyze and discuss the data with his cohorts on the ground, and make modifications in situ.

In the advanced phases of development, there may be very real advantages in performing qualification tests and engineering shakedown in space. Thermal vacuum chambers and solar simulators are expensive and imperfect. Direct tests in space are less controlled (e.g., because of Earth occultation), but more realistic.

Shakedown involves operation of the final device. On Earth it is customary to have a continuing capability for tuning and last-minute changes. If difficulties arise that the man in the space station cannot handle, the device can be returned to Earth for further work.

CRITICAL ISSUES

The concept of a large space station capable of placing man in contact with a substantial payload, possibly involving a mix of instruments from each of the five categories selected for discussion (Terrestrial Environment; Earth Resources; Communications; Navigation, Traffic Control, and Data Collection; and Geodesy), raises two critical issues.

One issue is the question of interference. This could be instrument/instrument interference, where the requirements for operation of one instrument are mutually incompatible with the requirements for operation of another. This could mean that such instruments would have to be flown separately, detracting from some of the advantages of the space station "bus" concept. There is also a class of man/instrument interference in which either man himself or the subsystems necessary to support him create an environment that is incompatible with the requirements for operation of certain instruments. Examples of these are given below.

INSTRUMENT/INSTRUMENT INTERFERENCE

Electromagnetic Interference

Two categories in the Earth applications area–(1) communications and (2) navigation, traffic control, and data collection–will involve electronic systems on the spacecraft which use extremely large amounts of power, some of which will be radiated throughout the spacecraft environment as electromagnetic noise. These systems will probably be operating full time if they are to perform a useful service. Many of the sensors will be sensitive to such a high electrical-noise background. They must either be shielded, if possible, or carried on another spacecraft.

Radiation Interference

For instruments that require large amounts of power, nuclear power supply may be the most efficient source. Heat and nuclear radiation may interfere with remote-sensor detection equipment.

Mechanical Coupling

Some instruments require a very stable mechanical configuration; these include interferometers and camera optics. Any excessive motion on the spacecraft will interfere with their performance. Other instruments require mechanical motion that could be a source of interference; these include scanning radiometers and cameras. In addition, mechanical motion that changes the attitude of the spacecraft would interfere with navigation systems that depended on precisely maintained spacecraft attitude.

Orbital Parameters

Different instruments require different orbits. Geodesy is probably an extreme example in which the orbital parameters are essentially tuned to the characteristics of the gravitational field one wishes to measure. In general, these orbits will be elliptic, with low-periapsis altitude and a variety of inclinations. In most other categories of measurements and operations, medium altitude, circular polar orbits, or synchronous orbits are preferred.

MAN/INSTRUMENT INTERFERENCE

Orbital Position Perturbation

Man plus his life-support system produce an active spacecraft with certain uncontrollable motions. This essentially rules out man's presence on a gravimetric geodesy satellite, as it would be virtually impossible to separate the spacecraft motion caused by onboard effects from that caused by gravitational effects. While geodesy is probably the most sensitive case, orbital position is also quite important for navigational purposes.

Mechanical Coupling

Onboard motion of man and mechanical disturbances caused by his support systems (leaking cryogenic supplies, rotating machinery) will interfere with instruments requiring a precise mechanical configuration, as pointed out above. These disturbances and subsequent motions may also be incompatible with systems requiring stable and accurate attitude control, such as for navigation.

Orbit Selection

Placing man in the spacecraft may constrain the possible orbits, for example, to avoid the radiation belts. Daily coverage of all points on Earth can be achieved from polar orbit at altitudes of 1000 to 1500 kilometers where the radiation hazard is quite severe. This hazard is reduced to levels that are tolerable with present shielding arrangements at altitudes of 300 to 500 kilometers, but here the coverage is less frequent, averaging only once every several days. The degree of hazard at synchronous altitudes is comparable to that at 500 kilometers.

ECONOMICS

The second critical issue is basically one of economics. The interference constraints can be offset by dividing all the instruments one wishes to fly into a set of individually compatible payloads.

Some of these could have a man onboard to perform the functions outlined in the previous section, and others could not. Man could have essentially four classes of interaction with the payload. The first two require manned space flight and include permanent occupancy of the station or occasional visits at times when maintenance, repair, etc. are required. The visit type of interaction would be the only possibility for those payloads where man's presence during operational periods would cause interference. The second two classes do not require manned flight. One option would be to return the payload to Earth for manned repair and relaunch. The other option would be to have no manned interaction with the payload at all; this would mean either terminating the particular function of the malfunctioning payload or replacing the payload altogether.

Economic tradeoffs are certainly an important factor in determining which of the four options to pursue. The 1967 President's Science Advisory Committee report (ref. 20) made the following comment on scientific observation of the Earth from Earth orbit: ". . . we recommend that in the comparison of manned versus unmanned modes of carrying out research in this field the criterion of relative total cost effectiveness be applied to the extent possible." Their recommendation on Earth applications was somewhat more definitive, probably reflecting the difficulty of attaching a price tag to science–"we recommend: That, whether the proposed space applications systems are manned or unmanned, a reasonably clear case of potential utility must be made, which includes an assessment of potential economic benefit, before significant development costs are assumed."

Evaluating the economic benefits of having a working facility in orbit is probably the easier problem. Attaching economic significance to the role of man is more difficult. What makes this difficult is not having a real understanding of the man/machine interface in the spacecraft environment. When we use words like calibrate, maintain, and repair in the context of an Earth laboratory, this might imply either a rather rudimentary or a very sophisticated result. At this stage in our space-flight experience, it is extremely difficult to describe quantitatively what man's contribution to the success of the Earth sciences/applications mission would be.

RECOMMENDATIONS

The needs in the Earth Sciences and Applications program call for a vigorous program of Earth-oriented space activities in the 1975 to 1985 time period. It is likely that the best strategy for pursuing these needs will involve a mix of both manned and unmanned space activities. Of the various criteria that should be used to determine this mix, economics is certainly a key factor. Further experiments and study to determine just what contribution man would make to the operation of an instrumented station in Earth orbit are required before the larger question of the manned/unmanned mix can be successfully considered.

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APPENDIX G
Life Sciences

INTRODUCTION

Evidence has been accumulating which indicates that man can survive and perform useful work in space. Consequently it can be assumed that man in space is capable of conducting many of the activities that he accomplishes on Earth. His efficiency and effectiveness, however, are directly dependent upon appropriate training, man-machine interfaces, and supporting technology. If these are inadequate, his proficiency will be lessened.

The roles of man in an Earth-orbital and lunar life sciences program can be divided, at least theoretically, into two categories—passive and active. In his passive role, man is the subject of experimental study, the object of which is to obtain a basic understanding of his ability to function both as an adaptive system and as an integral part of the total space system. In the actual flight situation, the role of man is never purely passive.

In his active role, man is the researcher and experimenter. He possesses a versatile, all-purpose, sensing and responding intelligence capable of processing information, evaluating situations, and making decisions. More specifically, he acts as a sensor, manipulator, controller, and analyst. For example, his presence in space is invaluable, inasmuch as many of the biological processes to be studied there are too complex, subtle, and time dependent for handling and interpretation by fully automated techniques. For certain experiments, highly qualified, on-the-spot judgments would extend experimental capabilities.

A discussion of man's roles in the life-sciences aspect of space flight is the topic of this paper. A section of extracts, "Goals and Research Activities in the Life Sciences" (see p. 121) summarizes specific program objectives and tasks.

PASSIVE ROLE OF MAN

An in-flight study of man is required, because additional medical, physiological, and behavioral data are necessary before prolonged manned missions can be undertaken. This study must include two parts:

1. Medical measurements during prolonged manned space flight and on the lunar surface, to determine—

a. The nature, time-course, and limits of human physiological and psychological adaptation to the space-flight environment.

b. The specific causes and mechanisms by which these adaptations are mediated.

c. The means of predicting the onset and severity of undesirable effects.

d. The means for preventing or ameliorating any undesirable effects.

2. Task-performance measurements to determine the capabilities and limitations of man to perform useful work in space and on the lunar surface, either as a scientist or as an operator. These can be assessed by such measures as task time-line, performance accuracy, and metabolic cost in both nominal and contingency situations. Returned information can be used to optimize man's contribution. Environmental factors believed to affect performance parameters are identified in table G-I.

The knowledge gained from both types of measurements must be of sufficient depth to provide the data upon which future operational and design decisions relating to manned space flight can be based. The effects of weightlessness are the primary unknown here.

The null or subgravity state offers a new dimension of inquiry into human physiology which can be used to supplement ground-based medical research and provide scientific information of value to conventional clinical science and practice.

ACTIVE ROLE OF MAN

In trying to define the potentially active roles of specialists/astronauts, in the life sciences, this study can be divided into five areas of discipline-oriented activity. These are: (1) aerospace medicine, (2) biotechnology, (3) space biology, (4) exobiology, and (5) back-contamination containment and quarantine.

Table G-I.–The Effects of Environmental Factors on Performance Parameters

Performance parameters		Nominal											
		Intravehicular								Extravehicular			
	Environmental factors	Weightlessness	Relative physical restriction	Altered periodicites	Reduced barometric pressure	Enriched oxygen atmosphere	Presence of diluent gas	Lack of diluent gas	Artificial gravity	Subgravity state	Lack of light dispersion medium	Presence of spacesuit	Need for transient decompression
Afferent function	Vision					P					P	P	
	Audition												
	Somesthesis											P	
	Smell												
	Taste												
Efferent Function	Orientation	P							P				
	Positionkeeping	D											
	Translation	D							P	P			
	Psychomotor Response								P			P	
	Verbal communication						P						
	Work capacity	D						P		P		D	
Efferent Quality	Accuracy		P								P		
	Speed		P								P	P	

Performance parameters		Off-nominal											
		Mechanical				Ambient				Physiological			
	Environmental factors	Noise	Vibration	Linear acceleration	Rotation	Oxygen starvation	Contaminants accumulation	Low or high temperature	Low barometric pressure	Inadequate accommodation to 0-g state	Exposure to radiation	Disease	Injury
Afferent function	Vision		X	X		X	X	X	X	X			
	Audition	X				X	X	X	X	X			
	Somesthesis		X			X	X	X	X	X			
	Smell												
	Taste												
Efferent Function	Orientation				X		X	X	X	X	X	X	
	Positionkeeping												
	Translation				X								
	Psychomotor Response		X	X	X	X	X	X	X	X	X	X	X
	Verbal communication	X	X	X									
	Work capacity					X	X	X	X	X	X	X	X
Efferent Quality	Accuracy	X	X	X	X	X	X	X	X	X	X	X	X
	Speed	X	X	X	X	X	X	X	X	X	X	X	X

Performance parameters		Off-nominal														
		Human engineering					Motivational–emotional				Social					
	Environmental factors	Inefficient work-rest cycles	Inadequate training	Low-volume per man ratio	Inadequate man/machine interface	Sensory overload or underload	Loss of accustomed patterns	Low interest in work	High cost (e.g., excessive discomfort)	Low reward expectation	Limited social roles	Inappropriate crew structure	Lack of central authority	Lack of privacy	Limited interpersonal interaction
Afferent function	Vision														
	Audition														
	Somesthesis														
	Smell														
	Taste														
Efferent Function	Orientation														
	Positionkeeping														
	Translation														
	Psychomotor Response	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Verbal communication														
	Work capacity	X	X												
Efferent Quality	Accuracy	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Speed	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Legend: P = Possible interference or degradation. D = Definite interefence or degradation.
X = Effect whose severity depends on the amplitude of imposed stress.
Where there is no entry, the effect is considered to be comparatively minor or irrelevant.

Possible contributions of man in these areas include:

1. Sensory capabilities, especially in discerning fine detail and slight deviations in patterns.
2. Wide range of manipulative abilities.
3. Highly selective, flexible, and extensive memory.
4. Ability to perceive, interpret, and analyze new situations as they develop in flight. This involves informational discrimination and filtering, establishment and evaluation of alternatives, and real-time decisionmaking.

AEROSPACE MEDICINE

Prior to space flight, untested but plausible theories had been proposed which predicted calamitous failures of various vital functions in an organism suddenly exposed to and maintained in an environment lacking gravitational stimulus. Orbital space-flight experience refuted these theories, and by the end of the Gemini program positive evidence was available to indicate that significant physiological responses were occurring. In considering these flight observations, it is important to realize that the available data are insufficient to permit confident extrapolation to major extensions in mission duration. In addition, the tasks of determining the precise nature, ultimate severity, and fundamental etiology of all changes in man's functional capabilities during and following prolonged space flight are still ahead. Three circumstances, however, make such determination difficult. First, basic knowledge of the "normal" or "reference" functional capabilities of the human organism is relatively limited despite rapid advances in medicine and physiology. For example, individuals of the same build, sex, and age (i.e., matched as well as possible) have different physiological responses to the same treatment. Again, the same individual may respond differently to an identical stress imposed at different times. Second, in-flight stressors act collectively, affect more than one physiological system, and are difficult to evaluate singly. Our present understanding is also inadequate to allow meaningful extrapolations from single to multiple stressors and from one specific composite situation to another. Third, powerful compensatory mechanisms can mask physiological disturbances until conditions become critical.

Although pertinent experiments with varying degrees of human involvement are possible, crew activities are generally reducible to relatively few tasks. These, for example, include, in order of increasing complexity: (1) equipment manipulation (deployment, adjustment, calibration, etc.), (2) specimen removal and preservation, (3) subjective on-the-spot observations and evaluations, and (4) changes in experiment protocol. In a fully operating space station laboratory, all levels of involvement would be required.

The possibility of illness or injury among astronauts increases with larger crew size, longer flight duration, and more complex missions. Rapid determination of pathological states and on-the-spot effective medical assistance will necessitate the onboard presence of experienced and adequately trained medical personnel.

Finally, it is of scientific interest to explore whether or not the unique qualities of the space environment offer an advantage over conventional medical practice for the treatment of certain pathological conditions occurring on Earth.

BIOTECHNOLOGY

As mission duration and crew size increase, it becomes necessary to recover useful materials from onboard waste to reduce launch weight, volume of stored resources, and resupply requirements. Concurrently, as programs become more ambitious, additional demands are placed on the astronauts, necessitating improvement of living and working conditions. Attention must be given to the design of equipment for more effective man-machine interaction, and to spacecraft architecture for more satisfying habitation. It follows that an in-flight testing and validation program is required to:

1. Determine the adequacy of crew life-support equipment, work and decision aids, and crew protective systems to preserve and enhance astronaut work proficiency and performance effectiveness, both inside and outside the spacecraft.
2. Optimize astronaut habitation in terms of volume utilization, color and decor, clothing, personal hygiene, waste management, thermal/humidity limits, levels of illumination, recreation, social interactions, duty-rest scheduling, and food preparation.

Although approximate mean metabolic rates have been derived from the measurement of carbon dioxide removed by the cabin life-support system, little is known of actual metabolic rates in extravehicular activity, during which rapid breathing and sweating during task performance have consistently occurred. No detailed evaluations have been made of patterns of muscular activity and motor coordination in the skilled movements of the unrestrained individual in space flight. Although the evidence suggests that brief, heavy overloads can be met adequately, the findings are equally suggestive of impaired capability in prolonged effort, both during and after flight. Rapid heart rates during the physical effort in EVA require careful evaluation of factors in the spacesuit, restraining systems, and working aids design, as well as an assessment of maximum tolerable workloads. From a habitability standpoint, there is a need for careful consideration of the relation between spacecraft architecture and human engineering; i.e., motivational, emotional, and social factors, optimal work-rest cycles, and modes of recreation.

Man's role, in order of increasing complexity, can be envisaged as reducible to: (1) systems operation and research, (2) systems performance evaluation, and (3) systems maintenance and repair.

SPACE BIOLOGY

As our knowledge increases, measurement protocol requirements and experiment operation tasks become so sophisticated that for certain experiments the presence of biologically trained astronauts is necessary. Two distinct goal-oriented classes of activities are envisaged:

1. Experiments using cells and animals to generate the support data required for advanced manned missions. While all data from in-flight experiments with organisms other than man are not applicable to manned flight, they could be of material assistance to this program. Studies in cellular biology will provide unique information on the effects of prolonged exposure to space-flight conditions on basic biological processes. Observation of animals could produce useful information on central nervous, cardiovascular, and metabolic functions. However, to assure the validity of in-flight results, species should be selected that will minimize the problem of extrapolating the animal data to man. In addition, research activities must be planned to supplement medical research in case any problem areas are discovered.

2. Experiments using cells, plants, and animals to increase basic biological knowledge. The unique features of the space environment can be utilized here to analyze basic organism-environment relationships. For example, the attainment of near weightlessness and the

availability of an environment unequivocally disconnected from the Earth's rotation, are environmental factors of obvious biological importance. In both instances, there exist theoretical bases for predicting effects in growth, development, circadian rhythms, and physiological functioning.

Astronaut involvement, in order of increasing complexity, is the same as in the section, "Aerospace Medicine" (p. 114).

EXOBIOLOGY

The search for extraterrestrial life has been recognized as a scientifically valid goal. Three types of relevant activities are possible during Earth-orbital and lunar missions.

1. Multispectral sensing of the planets in search of emission or absorption patterns characteristic of life-associated molecules. Earth sensing will serve as a control for better interpretation of the spectra received from the planets. This activity will also provide valuable information applicable to agriculture, forestry, and possibly marine biology. Although this could be done on an unmanned spacecraft, the presence of man will increase the effectiveness of the data return by assuring proper equipment operation. Additionally, astronauts can aid in the development and refinement of equipment and methodologies that could later be automated.
2. Collect and return lunar samples for bio-organic examination in terrestrial laboratories (early during the lunar exploration phase).
3. Search for and conduct analyses of possible organic materials on the Moon (early during the lunar exploration phase).

BACK-CONTAMINATION CONTAINMENT AND QUARANTINE

To protect the terrestrial biosphere from incoming alien contamination, a capability must be provided outside the terrestrial environment so that returned planetary missions may:

1. Quarantine personnel and equipment
2. Sterilize exposed equipment being returned to Earth.
3. Make preliminary safety analyses of returned planetary samples to assess adaptation and growth under terrestrial condi-

Table G-II.—*Orbital Constraints on Radiation Hazard*

Orbit		Amount and type of use
1) Low altitude Low inclination	200 to 300 nautical miles 0° to 25°	Desirable
2) Low altitude High inclination	200 to 300 nautical miles 50° to 90°	Undesirable
3) Earth-synchronous Low inclination	22 500 nautical miles 0° to 25°	Undesirable
4) Other	....	....

NOTE—The preferred orbit is low altitude and low inclination. High-inclination and synchronous orbits are undesirable because of the danger of high radiation flux in the particle fields and exposure to more radiation accompanying solar flare. Additionally, synchronous orbits could interfere with biorhythm studies, because the geophysical periodicities would remain identical to those on Earth. Finally, radiation hazards would make EVA feasible only in low-altitude, low-inclination orbits.

tions, as well as the toxicity and pathogenicity potential before sealing and sending to Earth.

Sterilization of returning planetary probes in Earth orbit does not preclude the possibility of back-contamination, because planetary particles adhering to the probes might be dislodged during orbital capture operations and might drift later to Earth. A base on the Moon, if established for other reasons, could also be used for back-contamination control purposes.

CRITICAL ISSUES

Common to all future manned program alternatives is the necessity for man to function normally in space, tolerate reentry stresses, and readapt successfully to normal Earth conditions.

A decision regarding the necessity of artificial gravity must be made on the basis of whether or not bodily functions are maintained within certain prescribed limits. If artificial gravity is necessary, a further decision must be made concerning the optimal mode for its provision. It is important, however, to confirm first whether or not the physiological processes observed in both Mercury and Gemini flights are caused by natural acclimatization rather than by gradual and progressive deterioration of bodily functions.

Uncertainties exist regarding both the radiation environment in space and the physiological effect of this environment on man. Evaluation of the radiation hazard in synchronous or high-inclination orbits is limited by the particular model chosen for predicting solar flare activity. Dose-effect relationships are likewise uncertain. Orbital constraints imposed by such considerations are summarized in table G-II.

Engineering constraints limit crew size. Interpersonal-social requirements that must also be satisfied are not easily quantifiable, but do indicate the need for a large crew. Stress can also be caused by limiting both the range of social roles available to the individual and the degree of interpersonal interaction to which each crewmember is exposed.

Experimental data indicate that volume per man is an important factor in reducing behavioral aberrations and that highly habitable environments help in reducing performance decrements and personal stress. However, the relationship between the acceptable minimum volume per man as a function of mission duration (for extended space flight) has yet to be determined, and habitability requirements remain uncertain.

Very little is presently known about the relative duration and type of ground-based simulation necessary to validate a given mission. Extrapolations from simulated to actual events may not have fidelity, if only because crew motivation is expected to vary. Techniques for drawing meaningful inferences from ground-based simulations need to be developed.

The standards for acceptable space-cabin atmospheres should assure maintenance of maximum physiological comfort, physical efficiency, and safety during the flight. These factors include barometric pressure, the nature and abundance of constituent gases, temperature, humidity, and the rate of circulation. Further research to optimize space-cabin atmospheres must continue.

Sources of cabin contamination are of both human and material origin. Atmospheric contaminants that are normally nontoxic may cause adverse physiological effects (ranging from nonspecific functional shifts to incapacitation) under prolonged and continuous exposure. Therefore, it is necessary to determine tolerance limits, identify means of detection, and establish methods of control to acceptable levels. Operational tolerance limits should be determined through simulations and validated during long-duration flights in Earth orbit. Spacecraft materials must also be studied to identify the extent of toxic and fire hazards they present.

Present life-support systems appear to compromise man's work performance. While this compromise can be tolerated by short-duration missions, it may become increasingly expensive with longer ones. Most tradeoffs between engineering and physiological requirements have been made on the basis of man's very considerable ability to adapt to adverse circumstances, rather than on the basis of clearly defined optimal conditions for effective performance of his role in space. Testing and validation in space of advanced life-support systems is presently considered a pacing item in support of future missions.

CONCLUSIONS

All advanced concepts for the future of manned space flight are structured on either one of two basic assumptions:

1. Man is able to remain in space for long periods of time without physiological aberrations, performance decrements, and permanent injurious effects after returning to Earth; or

2. Physiological or performance degradation can be avoided, through the use of preventive medical measures. These will result from increased space-flight experience and physiological knowledge.

It follows that crew safety, mission success, and optimal use of the astronauts necessitate the establishment of a broad program with two main objectives. The first objective is to understand man's physiological and behavioral response to space flight. The second is to develop the technology required to preserve his physical integrity and enhance his performance capability. The attainment of these two objectives is a prerequisite for achieving all other manned space-flight objectives.

The effort to "space-rate" man will initially demand a large percentage of crew time to conduct experiments in the biomedical and behavioral areas. By about the mid or late 1970's, however, if no major problem areas are revealed, crew time expenditure in these areas could be expected to diminish progressively.

Parts of this section were extracted from the "Space Medicine and Biotechnology" and "Space Biology" program memoranda. Other parts were extracted from working documents generated by the Aerospace Medicine and Biotechnology Subgroup.

Goals and Research Activities in the Life Sciences

SPACE MEDICINE AND BIOTECHNOLOGY PROGRAMS

GOALS

The goals of the space medicine and biotechnology program are: (1) to develop an understanding of man's physiological, psychological, and behavioral reactions as an operator in and of space systems; and (2) to develop a technology for the systems that will provide for man's support and enhance his operational capability. This understanding must be of sufficient depth to provide the data upon which future space-flight program decisions may be based and allow for subsequent design and development of appropriate operational manned space-flight and exploration systems. It must progress at a rate commensurate with the development of the other systems required to achieve the broad goals and specific objectives of the national space program.

OBJECTIVES

The space medicine and biotechnology program is directed to provide critical information with respect to:

1. Man's physiological, psychological, and behavioral reactions to weightlessness and other space stresses for extended periods of time.
2. The requirement for and techniques of providing artificial gravity.
3. Man's capabilities for performing useful tasks in both space vehicles and the extravehicular environment, with and without pressure suits and assistant devices.

4. The environmental requirements and the design criteria for life-support and protective systems, and the technology that will allow and assist man to do useful work in space for extended periods of time.

5. The design criteria for equipment maintenance and reliability and for escape and rescue systems.

The program is divided into three discipline-oriented activities—biomedical and behavioral research (human and animal), man/systems integration, and life-support and protective systems.

Biomedical and Behavioral Research (Human and Animal)

The objectives of this biomedical and behavioral research are:

1. To preserve and extend man's physiological, psychological, and behavioral capabilities during prolonged space flight and on the lunar surface, by determining:
    a. The nature, time-course, and limits of human adaptation to the space-flight environment.
    b. The specific mechanisms through which these adaptations are mediated.
    c. The means of predicting the onset and severity of undesirable effects.
    d. The means for preventing or ameliorating the undesirable effects.
    e. An understanding of the effects of the space-flight environment on human behavior.

2. To utilize the unique qualities of the space environment to obtain scientific information of value to medical science and practice.

Man/Systems Integration

The objective of man/systems integration research is to optimize man's ability to work in space and on the lunar and planetary surfaces by determining, preserving, and extending his performance capability through:

1. The identification of inflight tasks that can best be performed by man.

2. The determination of the optimal measurement techniques required to assess performance.

3. The identification of crew skills and the training needed to insure optimal performance.

4. The development of equipment, design requirements, and techniques for critical operations such as command, control, rescue, transfer, assembly, maintenance, and repair inside and outside the space vehicle.
5. The continued development of methods and design criteria to produce habitable living areas in space and on the lunar surface.
6. The extension of extravehicular performance design information and the continued development of effective work aids.

Life-Support and Protective Systems

The objective of life-support and protective systems technology is to provide a controlled and physiologically acceptable environment for flight crews during all phases of a space mission. The life-support system must, therefore, provide a pressurized shirt-sleeve environment that also allows for pressure-suit operation during normal or emergency conditions. It must supply food, water, and oxygen; provide for personal hygiene; and remove waste and contaminants. Lastly, the system must provide a thermal balance through utilization of available energy and dispersion of any excess heat.

The following parameters necessitate additional life-support system design requirements:

1. As mission duration and crew size increase, it becomes necessary to recover useful materials from onboard wastes to reduce launch weight, volume of stored supplies, and resupply requirements.
2. Prolonged space missions increase the probability of in-flight malfunctions, while more ambitious crew activities impose additional requirements in work performance, especially under suited conditions. Both underline the need for advanced crew protective systems.

RESEARCH ACTIVITIES

For the immediate period ahead, we must attempt to increase our understanding of man's capabilities in and adaptiveness to a weightless space environment for extended periods of time, and pursue those long lead time technological developments of reliably reclaimable life-support and crew protective systems that are essential for long-term, manned space missions.

To accomplish these objectives, research is programed in the three major areas as follows:

1. In biomedical and behavioral research (human and animal)—
   a. Cardiovascular function
   b. Hematology
   c. Respiration
   d. Neurophysiology
   e. Metabolism and nutrition
   f. Microbiology and immunology
   g. Endocrine function
   h. Behavioral effects
   i. Integrated medical and behavioral laboratory measurement system and associated bioinstrumentation
   j. Space pharmacology
   k. Radiobiology
   l. Clinical medicine in space
2. In man/systems integration—
   a. Behavior
   b. Work performance
   c. Habitability
   d. Extravehicular technology
   e. Maintenance and maintainability
   f. Information display and processing
   g. Visual skills
   h. Manipulators and remote controls
   i. Lunar and planetary human factors
3. In life-support and protective systems—
   a. Water management
   b. Waste management
   c. Thermal control
   d. Personal hygiene and sanitation
   e. Atmosphere supply, control, and oxygen regeneration
   f. Carbon dioxide removal
   g. Trace-contaminants control
   h. Astronaut protective systems
   i. Subsystems integration
   j. Closed-spacecraft systems problems
   k. Sensors and instrumentation
   l. Food management

Biomedical Behavioral Research (Human and Animal)

Cardiovascular Function

Statement of the problem.–Space flight has been shown to disturb the homeostasis of the cardiovascular system of man. Decremental changes have been documented in compartmental fluid volumes (plasma volume, red-cell mass, blood volume), hydrostatic pressure (orthostatic hypotension), and related parameters. The extent to which these changes may be exaggerated by prolonged space flights and the extent to which they may adversely affect the performance of man remain to be determined.

Scientific objectives.–To define our understanding of the effects of space environmental factors on the cardiovascular system and determine the effectiveness of preventive and/or remedial techniques. Present assessment indicates that the following need detailed study: (1) central circulation, (2) peripheral circulation, (3) prophylactic and remedial measures, and (4) systems interactions.

Hematology

Statement of the problem.–Detailed hematologic investigations were performed on selected Gemini flights, yielding data from missions of 3 to 14 days in duration. Although a paucity of conclusive data have been obtained thus far, red-cell mass deficits have been consistently observed. More information is needed to determine the cause of this space-flight-related hemolysis. In addition, man's ability to combat infection and repair traumatized tissues under space-flight conditions has not been established.

Scientific objectives.–To describe the qualitative and quantitative changes evoked by space flight in reference to the immunohematologic systems. The significance of hemolysis is of obvious importance to the Manned Space Flight program, for only complete elucidation of its extent, cause, and consequences will permit confidence in committing men to long-duration space missions.

Respiration

Statement of the Problem.—Weightlessness, increased acceleration forces, and artificial atmospheres have major effects on the respiratory gas-exchange function of the body. These effects not only impose health hazards and limitations on man's performance capabilities, but also impose severe design constraints on the spacecraft.

Scientific objectives.—To define the optimal atmosphere for long-duration space missions, establish the mission constraints imposed by this atmosphere, determine any of its adverse effects on man, and determine what mission constraints would be imposed by the choice of a less-than-optimal atmosphere.

Areas that require continued and increased study are:

1. Effects of a gaseous environment
   a. Composition
   b. Dysbarism
   c. Contaminants
   d. Oxygen toxicity
   e. Carbon dioxide
2. Effects of weightlessness
3. Systems analysis

Neurophysiology

Statement of the problem.—To date, the neurological evaluation of space-flight crews has been limited to preflight and postflight clinical medical examinations, the recording of two leads of electroencephalogram of one astronaut for the first 2 days of his flight, and a vestibular experiment that assessed the otolith function of four flight crewmembers during the 8- and 14-day Gemini missions. Although no significant changes were detected, these neurophysiological observations were meager. For extended manned space flight, a thorough investigation of neurological function becomes increasingly important, because this information will have a direct bearing on the determination of what man can do in space and on the development of means to protect his functional integrity during extended flight.

Scientific objectives.—To investigate and evaluate the effects of the space-flight environment and the relative roles of component environmental factors on flightcrew neurophysiological function.

Embodied in this effort are the assessment of the occurrence of adverse effects, the establishment of trend curves, the determination of specific causative factors and mechanisms by which undesired effects become manifest. In addition, the means of prediction and prevention or correction of ill effects must be discovered. To implement these objectives, the following will require special attention: (1) central nervous system function (including sleep, alertness, speech, biorhythms, and emotional reactivity); (2) functioning of the special senses; and (3) peripheral nervous system function.

Metabolism and Nutrition

Statement of the problem.–Some changes related to metabolism and nutrition have been noted in astronauts exposed to 14 days of orbital flight. These changes include reduction in body weight and loss of mineral material in the bones. Such effects may become progressively more serious to the extent of impairing the tolerance of bone structure against torque and shearing, weakening of muscle mass, and possible formation of kidney stones.

Scientific objectives.–To investigate human metabolism and digestion, develop nonsurgical techniques for appraising the human metabolic state, study the control mechanisms that regulate metabolism and energy requirements, and evaluate the effects of the space environment and of drugs on the mobility, digestion, and absorption in the gastrointestinal tract. Detailed study is needed in (1) general metabolism (energy), (2) cellular metabolism, (3) muscle and bone metabolism, and (4) nutrition and gastrointestinal function.

Microbiology and Immunology

Statement of the problem.–The microbiological aspects of manned space flight and the ability of crews to cope with potential infectious agents on extended flights are presently undefined.

The delicate balance between host animal (crew) and its microbial environment in closed and semiclosed ecological systems is precarious, and even minor alterations in diet, physiological or immune state, or the genetic constitution of cohabitant microorganisms may result in the shift of equilibrium to a new balance of microflora. The dominant species in this new balance may or may not be compatible with the host.

Scientific objectives.—This complex program has as its objective the definition of potential problem areas in long-term host/microflora relationships pertinent to closed or semiclosed ecological systems and the development of optimal methods of control to assure crew resistance to all potentially infectious or pathogenic microorganisms.

The important program study tasks may be reasonably grouped under (1) ecology, (2) host resistance, (3) control measures, and (4) general hygiene.

Endocrine Function

Statement of the problem.—Space flight subjects man to a composite of increased and decreased stresses and, as such, could be expected to affect the endocrine system. Observations from past flights are too sketchy to give a precise picture of how the endocrine system responds to these stresses and, consequently, to those imposed by prolonged space flight. Minimal information gained thus far indicates decreased endocrine activity during flight and increased activity after reentry.

Scientific objectives.—To define the effect of space-flight stresses (both simulated and actual) on the response of the endocrine system. Emphasis should be placed on:

1. Stress indices and tests of endocrine function
2. Methodology (measurement techniques)
3. Endocrine systems: physiological function and mechanisms of each of the systems
4. Remedial and prophylactic measures
5. Systems analysis

Behavioral Effects

Statement of the problem.—The assessment of operational or experimental behavior with objective data under conditions of prolonged stress and confinement, as represented by extended space flight, has not yet been achieved. Returned information will aid in providing baseline data for optimizing the design of the astronaut/spacecraft/crew equipment interfaces.

Scientific objectives.–To (1) assess man's functional ability in completing necessary operational and useful scientific work during long-duration space-flight conditions, (2) assess the spacecraft and equipment design from a human habitability point of view, (3) provide functional ground and in-flight behavioral measurements of sensory-motor performance, and (4) implement experimental and clinical methods for evaluating complex in-flight behavioral changes associated with extended missions.

Integrated Medical and Behavioral Laboratory Measurement System and Associated Bioinstrumentation

Statement of the problem.–Presently available flight biomedical instrumentation consists of little more than vital-sign measurements and as such is inadequate to meet the requirements of mission-rating man for extended flights.

Scientific objectives.–To provide a compact unit in modular form to allow simple exchange of measuring equipment. This will give versatility to the system by enabling the replacement of old with new techniques, and of gross observations with finer measurements and discriminations in the implicated investigative areas. It also allows rapid and less expensive integration of approved in-flight medical experiments and optimization of equipment commonality and crew tasks.

Space Pharmacology

Statement of the problem.–No unfavorable effects to date have been reported in the limited use of drugs during space flights. The use of any drugs on longer missions will require a systematic exploration of the effects of drugs in the space environment and the effects of the space environment on the drugs that may be used. Such a study should include the mode of action, side effects, contamination effects, effects on performance, and drug compatibility. These studies should be carried out in both animals and man under simulated (bedrest) and actual space-flight conditions.

Scientific objectives.–To use pharmacology as a major means of applying protective measures to maintain and restore the mental and physical integrity of man in the space environment. The studies that will be described will be an aid in delineating the physiological effects of the space environment and in designing onboard diagnostic or prognostic tests. Special attention should be given to: (1) drug metabolism; (2) drug stability; (3) pharmacological manipulation of sleep, behavior, and biorhythms; and (4) dose levels (including determination of chronic toxicity and drug-atmosphere interaction).

Radiobiology

Statement of the problem.– There is significant measurable radiation in the space environment. Exposure of biological materials, including man, to ionizing radiation may produce undesirable effects. The radiation in space is due to particulate radiation such as protons, alpha particles, and electrons. There has been little information available on the biological effects of particular ionizing radiation. The hazards of this type of radiation are presently being determined.

Scientific objectives.–To determine human tolerance levels to space radiation by means of fundamental and applied radiobiology research. The effects of acute and protracted doses of radiation relative to the production of nausea and to injury of critical organs such as the eyes, hematopoietic system, skin, and intestines will be determined in animals and humans, where possible. The following require investigation: (1) molecular and cellular changes, (2) effects on mammalian systems, (3) combined effects of radiation and other stresses, and (4) dosimetry.

Clinical Medicine in Space

Statement of the problem.–The relatively short manned flights to date have posed no medical problems of the sort that would require on-hand clinical diagnostic and/or therapeutic capabilities more elaborate than simple medications and dressings. Extended missions, particularly those that may be physician attended, will require a considerable diagnostic and therapeutic capability that must provide for minor surgical procedures.

Scientific objectives.–To define and develop the diagnostic and therapeutic procedures, medications, and equipment that will be required to maintain the health and well being of the crew. Needed are (1) clinical medicine definition studies, and (2) clinical medicine equipment development.

Man/Systems Integration

There is a need for extensive ground-based research on problems of man/machine integration, habitability, and small-group dynamics. A fruitful medium for studying such effects is in operations that resemble space missions; for example, Antarctic scientific bases and underwater operations such as Sealab and Project Tektite.

These operational simulations, which provide stress and reward conditions that cannot be duplicated in the laboratory, are useful in both: (1) providing many solutions to human engineering problems that occur in space, but are not unique to space, thus enabling in-space research to focus on those problems that are unique to space; and (2) supplying baseline data for comparison with long-term space data, thus clarifying the probable causes of observed in-space effects.

Behavior

Statement of the problem.—From an operational viewpoint, all astronauts to date were capable of carrying out their functions and assigned duties satisfactorily, even under demanding situations in isolated cases (e.g., Gemini 8). However, actual performance was never measured, and it is entirely possible that some degradation actually occurred. Factors that are believed to affect performance include habitability and vehicle design, small-group dynamics, man-systems coupling, physiological status, and motivational or emotional states. For extended manned space flight, the assessment of man's capabilities and limitations in space is warranted. Return information will help optimize the role of the flightcrew and establish the support measures or devices required to preserve and extend human performance in space.

Scientific objectives.—To maximize the effective utilization of man in space, extensive participation by the crew in all activities of the flight program will be required. The astronauts must learn to evaluate the human-factors design features of most onboard systems, report problems and recommend measures to deal with them, and document the evolution of their working methods and other interactions with the machines around them.

1. Small-group dynamics
   a. Crew composition

   b. Dominance problems
2. Individual characteristics
   a. Off-duty time
   b. Isolation effects
   c. Social restrictions
3. Mission effects
   a. Stress
   b. Duties

Work Performance

Statement of the problem.–Because it is planned that man will work in the space environment for extended periods of time on longer missions, we must determine what effects the space environment will have on his ability to perform effectively.

Scientific objectives.–It is necessary to investigate human work capabilities in stress environments typical of space. This includes measurement and development of individual performance, psychological adjustment, effective tools and work relationships, and changes in these adjustments and relationships as a function of time and stress. This information will provide crew, job, and equipment design data to minimize individual and crew performance degradation in space. Work performance measures which are meaningful to the astronauts and survey techniques that can be assessed by the crew commander and ground-support personnel are both needed. Ground-based simulation studies must be followed by studies of typical populations under stress in space.

1. Performance measures
   a. Extravehicular activity
   b. Intravehicular activity
2. Work-area physical parameters
   a. Lighting and color environment
   b. Shape and volume
   c. Flexible airlock
   d. Worksite design/packaging
   e. Restraints/work platforms/handholds
   f. Transfer aids/man-translation
   g. Egress/ingress
   h. Tools
   i. Controls and displays

3. Skill proficiency
   a. Dexterity
   b. Reasoning/information processing
   c. Visual/audio; Ames vision test–component
   d. Auditory function
   e. Muscle brain coordination; Ames human transfer function experiment (T-007)
   f. Force generation–fine
   g. Force generation–gross
   h. Assembly tasks
   i. Monitoring and observation
   j. Communication and recording
   k. Physical change
4. Stress effects on work performance
   a. Psychological Adjustment
   b. Interpersonal relationships
   c. Task performance under stress
   d. Work-rest cycles

Habitability

Statement of the problem.–For extended orbital flights, attention must be given to the design of a vehicle and the procedures that will provide for long-term living and work needs.

Scientific objectives.–Individuals and crews will be confined to relatively small habitats in space for extended periods of time. These habitats must be designed to provide optimum comfort, workspace and layout, recreation and relaxation areas, and shape consistent with vehicle size and mission duration.

High-priority efforts that are needed to determine the most habitable design for small crews in long-duration space flight include:

1. Volume, configuration, and layout of crew areas for facilitating work performance and mobility inside the vehicle. This is a function of work tasks, crew size, flight duration, and vehicle size.
2. Basic illumination and special lighting for work, recreation, and sleep activities in various areas in the space station.
3. Effects of modifying interior physical arrangements during the space flight (changeable room sizes and shapes, removable panels, etc.).

4. Basic decor and changes in space stations and in various crew areas during the space flight.
5. Methods for facilitating crew mobility inside the space vehicle; both traffic-flow patterns and handhold and restraints configuration and placement.
6. Methods for achieving individual privacy by physical arrangements or by providing the illusion of privacy.
7. Requirements for simulated day-night cycles for long-duration staytimes (acoustically isolated sleep and rest areas).
8. Various food-management and eating-facility concepts.
9. Protective devices for astronaut safety during free-movement in the space vehicle under zero-g conditions.
10. Off-duty and recreational facilities.
11. Suit don/doff, drying, and storage facilities.

Extravehicular Technology

Statement of the problem.—To achieve the future scientific and technical goals of Earth-orbital manned space flight, it is absolutely essential that man perform useful work. Most of the tasks will be performed from inside the spacecraft, but some may require man's excursion into actual space. Astronauts performing work outside the space vehicle will have to work within the limitations imposed by spacesuits and reduced gravity. They will also have to move themselves and their equipment to the worksite, where they must maintain body position and exert leverage. Maximum safety and minimum EVA time require development of effective mobility systems, design of appropriate worksites, and validation of restraint and anchor devices.

Scientific objectives.—To develop the supporting equipment and techniques for counteracting the difficulties inherent in working in the weightless state under suited conditions. The following extravehicular technology study areas are considered essential:

1. Work-performance capability
   a. Evaluate and develop the capability to control astronaut mobility and attitude in the space-component
   b. Assembly/erection techniques
2. Translation aids (e.g., foot-controlled maneuvering unit)
3. Rescue and retrieval

Maintenance and Maintainability

Statement of the problem.–The probability of a systems failure increases with increasing mission duration. Capability for in-flight maintenance is essential to provide the reliability needed by future space systems. Flight equipment must be designed according to maintainability criteria, and techniques must be established and tools developed to enhance the ability of the astronaut to maintain, repair, and assemble systems in space.

Scientific objectives.–To permit effective repair and/or maintenance of spacecraft systems, base systems, or other equipment crucial to either mission success or crew safety. Study areas requiring attention include:

1. Human performance capabilities and limitations
2. Design of maintainable and repairable systems
   a. Checkout and fault isolation
   b. Accessible packaging
   c. Nonmaintainable versus maintainable tradeoffs
3. Crew assistance systems
   a. Tools
   b. Tethers
   c. Worksite aids

Information Display and Processing

Statement of the problem.–A human information-processing error of any magnitude in space-systems operations could prove disastrous. To insure against this eventuality, we must examine information-processing requirements during actual space-systems operations and develop techniques that will lead to a minimum of error in human information processing.

Scientific objectives.–A satisfactory approach to the problems in this area can be found by developing techniques for displaying all necessary information promptly and unambiguously, and by discovering the principles that govern how information from various sources is effectively combined, how it is retrieved from memory storage and how unnecessary information can be eliminated.

Visual Skills

Statement of the problem.–The environment of space both inside and outside the space vehicle poses unique visual problems.

Man's capabilities and limitations for receiving information through the visual-sense modality in this environment must be determined, and methods developed for optimizing his capabilities in those areas where limitations are discovered.

Scientific objectives.—The specific objectives of visual skills research are to:

1. Develop techniques allowing compression of bandwidth in visual displays.
2. Develop information regarding target characteristics necessary for reliable detection and identification.
3. Develop methods (computer aided) for precise calculation of the probability of target detection and identification.
4. Determine visual capabilities under adverse conditions (e.g., glare in the visual field) and develop techniques for eliminating such adverse conditions when necessary to mission success.
5. Develop visual aids to assist the astronaut.

Manipulators and Remote Controls

Statement of the problem.—In many situations, it will be either unsafe, unfeasible, or impossible for an astronaut to perform his tasks personally. For example, radiation levels might be hazardous, or portable life-support during extravehicular activity might be inadequate, or perhaps the task might be beyond the physical strength of the individual. For these instances, manipulators and remote controls must be developed.

Scientific objectives.—To develop techniques and equipment that can be used in IVA or EVA to supplement man's personal capabilities.

Lunar and Planetary Human Factors

Statement of the problem.—Extensive exploration of the surfaces of the Moon and accessible planets and intensive study of their properties will require parties of men to be present and active for relatively long periods. The human factors involved in such activities will have a few characteristics in common with those encountered in orbital operations, but most of these factors will be new. Lunar surface exploration, for example, will involve extensive activity in a "dusty-vacuum" environment, at an unfamiliar gravity level, and in the presence of hazards very different from those encountered in extravehicular activity in space. Similarly, life and work in a lunar laboratory, where communications with Earth have low information rates and where there is no quick Earth return capability, will probably differ considerably from human activity in an orbiting laboratory. Extensive study of the human factors involved in such situations is needed if we are to make effective use of men to explore the surfaces of extraterrestrial bodies.

Scientific objectives.–To determine the most effective techniques for manned lunar and planetary exploration. The following areas must be investigated to attain this goal:

1. Shelter and vehicle habitability

   a. Define shelter and vehicle requirements for volume, configuration, expendables management, waste and hygiene, food, and radiation and thermal protection.

   b. Determine airlock design and dimensional requirements.

   c. Establish communications requirements for operations beyond line-of-sight contact.

   d. Define configurations and functions for stations that will recharge life-support systems.

   e. Determine requirements for stability-augmentation devices for mobility within shelters.

2. Lunar mobility

   a. Determine the optimum techniques and devices to aid in walking in 1/6 g.

   b. Determine the types of locomotion aids needed for various exploration activities.

   c. Devise criteria to assure man-machine compatibility in surface and flying vehicles.

   d. Establish communication and navigation requirements.

3. Exploration, maintenance, and repair

   a. Define maintenance requirements for habitats and vehicles.

   b. Design tools appropriate for use in the 1/6-g environment.

   c. Develop procedures and aids for maintenance and repair tasks in 1/6 g.

4. Lunar surface visibility

   a. Determine the effects of the lunar (and planetary) visual environment on man's ability to guide himself by visual references.

   b. Establish requirements for vision aids needed for manned exploration activities in vehicles or on foot, and for necessary maintenance and repair work.

Life-Support and Protective Systems

Water Management

Statement of the problem.—Current spacecraft life-support requirements, as established by Apollo, do not require water-reclamation systems because of the low weight penalty for storing water for these time periods and because potentially potable water is available from the fuel-cell power system. However, for future mission classes now under consideration, the availability of sufficient water from fuel cells is doubtful, and the weight of stored water is prohibitive. Therefore, water-reclamation systems utilizing the several waste sources available are necessary. These sources are, in order of their ease of purification: humidity condensate, wash water, urine, and feces.

The extent to which these sources of water are utilized will depend greatly on mission class (e.g., oxygen reclamation requires water electrolysis for a closure of the oxygen cycle and, therefore, a greater utilization of waste water for reclamation to balance the water cycle). In all of these mission classes, attention must be given to efficient, reliable systems, using a minimum of expendables, that are capable of providing water for consumption which meets both chemical and biological quality standards.

Scientific objectives.—To advance the technology and develop prototype subsystems to provide for the purification and sterilization of spacecraft waters.

For early missions, only the purification of humidity condensate and urine will be required, with the possible addition of sponge wash water. Chemical purification must be accomplished with minimum power consumption and vehicle interfaces and with a system that has an advanced development status. Sterilization will be required to eliminate bacteriological contamination.

For the intermediate-duration missions, full-body washing water and automatic water flush-fecal collection and processing will also be included. Because the vehicle power source will constrain the desirability of several subsystem concepts for water reclamation and sterilization (i.e., availability of waste heat), multiple subsystem developments will be pursued for both purification functions until a power source is selected. However, even then, because of the different contaminant levels (both chemical and biological), use of a single concept is not likely.

For extended missions, water from fecal matter, food wastes, etc., also will be reclaimed. Both thermal and oxidation techniques will be followed.

1. Water reclamation
   a. Water recovery
   b. Recovery-system pretreatment
2. Potability monitor–potability verification
3. Thermal control–condensing heat transfer and rate

Waste Management

Statement of the problem.–A system for the management of biological waste material must be developed that will meet medical and vehicle integration requirements.

Scientific objectives.–To design and develop an integrated waste-management system that will: (1) provide an inoffensive means of waste collection, mass measurement, and sampling (if required); (2) process biological and other solid waste materials; (3) prevent contamination of the environment with waste material, odors, and micro-organisms; (4) provide for sample preservation and storage; and (5) provide an interface with water-reclamation systems.

1. Collection
   a. Gas transport of solids
   b. Gas transport of liquids
   c. Manual transport of solids
   d. Collector tests
2. Processing
3. Sampling

Thermal Control

Statement of the problem.–Thermal control devices must be developed for maintenance of optimum temperatures during both IVA and EVA. Low-temperature waste heat must be collected and ejected into space, while high-temperature thermal energy must be conserved for use in CO_2/water desorption, water reclamation, etc.

Scientific objectives.–To assure thermal comfort during prolonged space flight.

1. Heat transfer–cooling
   a. Advanced cooling methods

   b. Gas to solid heat transfer
2. Heat transfer—heating
   a. Radioisotope thermal heat
   b. Heat-source comparisons
   c. Solid to gas heat transfer
   d. Thermal insulation and surface coatings
   e. Convective heat transfer at zero-g
   f. Material solar absorptivity and thermal emissivity
   g. Nucleate boiling mechanism
   h. Parameters affecting comfort level
3. Atmosphere circulation—cabin air distribution and control
4. Thermal storage systems

Personal Hygiene and Sanitation

Statement of the problem.—Because of the short duration of the Gemini and Apollo missions, personal hygiene and sanitation did not, and were not expected to, pose major health problems. With the advent of extended missions, however, it becomes essential to consider personal hygiene and sanitation as a major problem area from both the medical and crew social requirement aspects.

Scientific objectives.—To develop personal hygiene and sanitation subsystems that will meet crew requirements during extended missions: These subsystems include (1) body-cleansing—evaluation of equipment, (2) whole-body washing, (3) technology for clothing maintenance and cleaning, (4) oral hygiene, and (5) hair removal.

Atmosphere Supply, Control, and Oxygen Regeneration

Statement of the problem.—Oxygen regeneration was not required on short-duration missions (Mercury, Gemini, and Apollo), because the penalty of storing in tanks all the breathing oxygen required was relatively small. As mission durations increase, however, a saving in weight must be effected by breaking down the metabolic carbon dioxide and water given off by man and recovering the oxygen for rebreathing.

Concepts must be evaluated and systems developed to provide oxygen and nitrogen for atmospheric supply, and oxygen for metabolic consumption, with the least weight and volume penalty that is commensurate with the incurrence of reliability loss.

Adequate development status at the time of the mission must also be insured.

Scientific objectives.–To evaluate concepts and develop systems to provide oxygen and nitrogen for atmospheric supply and oxygen for metabolic consumption by (1) developing cryogenic tankage, (2) progressively closing the regenerative cycle and reclaiming oxygen from carbon dioxide and water, and (3) determining a chemically inert, dense source of nitrogen.

For early missions, cryogenic storage systems with their attendant expulsion techniques must be provided. For intermediate-duration missions, storage-system improvements may be required; however, the emphasis must be on development of reclamation systems for obtaining oxygen from metabolic by-products. Existing (or quickly achieved) advanced development status is a requirement. For extended missions, the emphasis should shift to improved recovery efficiency, operational simplicity, and long life in oxygen reclamation. Another source of atmospheric diluent, rather than cryogenic tankage, is also required.

1. Nitrogen and oxygen supply and recovery
   a. Test of storage technology
   b. Oxygen generation from water
   c. Oxygen recovery from CO_2
   d. Airlock gas conservation
   e. Density profile of cryogenic fluid
   f. Capillary studies
   g. Kinetics and dynamics of gas bubbles
   h. Gas-free liquid maintenance
   i. Interface phenomena in liquid gas separation
   h. Supply gaging
2. Trace-Contaminant Control
   a. Absorption of gases by liquids
   b. Humidity control
   c. Water condenser-separator
3. Two-gas control
4. Carbon dioxide control
5. Microbiological control and monitoring

Carbon Dioxide Removal

Statement of the problem.—In any manned-flight situation, the need exists to remove metabolically produced carbon dioxide from the gaseous environment. In longer missions, the requirement exists for concentrating the carbon dioxide for subsequent reduction to minimize or help eliminate the requirement for stored oxygen.

Scientific objectives.—To develop, through extension of the technology now available, subsystems of carbon dioxide removal and concentration with improved reliability and maintenance characteristics. Efforts are also underway to extend adsorption technology and develop water-tolerant adsorption media, while reducing system weight and power requirements. Long-term mission systems are being sought which will have inherently longer life and higher reliability than current adsorption systems. Areas of study are (1) collection methods and components, and (2) atmosphere purification.

Trace-Contaminant Control

Statement of the problem.—Odors and trace contaminants, both physical and biological, must be removed to provide habitable, semiclosed and closed environments.

Scientific objectives.—To provide technology for the control and/or elimination of trace contaminants in spacecraft atmospheres. This includes chemical oxidation techniques, regenerable charcoal sorption of contaminants, and advanced processing techniques.

Astronaut Protective Systems

Statement of the problem.—Present and future manned-space-flight orbital and surface missions require astronaut protective systems that will maintain and support an environmental condition in which useful work may be performed in any operational mode. These systems will protect man from harsh thermal radiation, micrometeoroids, and the vacuum conditions of the extravehicular environment. They also will provide optimum personal environmental conditions within the spacecraft in both normal and emergency situations.

Scientific objectives.—To protect, sustain, and support man against environmental extremes that may occur in orbit or on an extraterrestrial surface, during all phases of extravehicular and intravehicular manned space-flight missions. This will be accomplished by utilization of spacesuit systems and space life-support systems, which will have high reliability and will be designed for ease of maintenance. Specific weight, volume, power, and overall systems-impact objectives will vary according to the specific class of missions. Research and development in this area will therefore be devoted to (1) intravehicular spacesuit/clothing, (2) extravehicular spacesuit–advanced spacesuit, and (3) portable life-support system–bio-pack evaluation.

Subsystems Integration

Statement of the problem.–Long-term manned missions will require life-support and environmental-control systems of proven performance and with demonstrated reliability, maintainability, vehicle integration, and control automation at the total-system level.

Scientific objectives.–First, to accomplish research and development on individual subsystems to prove the technical feasibility of processes and hardware designs. Subsequently, total systems efforts are needed to identify and solve the problems of scale-up, integration, and control automation. It then is necessary to develop integrated flight-prototype systems that will be used to establish design verification through a long-term ground-test program.

Closed-Spacecraft Systems Problems

Statement of the problem.–In addition to the identified technology problems, there are some systems problems that involve more than one area.

Scientific objectives.–(1) Life support, (2) solid and liquid control, and (3) fire prevention.

Sensors and Instrumentation

Statement of the problem.–For manned spacecraft, a variety of sensors and instruments is required to: (1) measure atmospheric constituents for monitoring and control purposes; (2) detect and identify trace contaminants, including chemical and biological contaminants, to demonstrate the suitability of the atmosphere and proper operation of the contaminant control system; (3) assess water potability; (4) show proper operation of the entire life-support system; and (5) provide the capability for manual override.

Scientific objectives.—To perform research and development in the area of sensors and instruments to assure that instrumentation will be available to solve adequately the problems that are either currently recognized or anticipated for future space missions—especially intermediate and extended-duration missions. Currently, the sensing and potential control outputs of the atmospheric constituent pO_2 and pH_2 are provided by both polarographic and total-pressure sensors and by a recently developed mass spectrometer two-gas atmosphere sensor. This latter development includes the capability of measuring pCO_2 and pH_2O, in addition to oxygen and nitrogen (or another inert gas).

In the area of contaminant sensing, limited development of flight-qualifiable sensors for early space missions is being undertaken by modification of the two-gas atmosphere sensor and the Apollo gas chromatograph. The development of microwave spectrometers and other types of sensors is essential to: (1) monitor ground simulator atmospheres, (2) evaluate contaminant control systems, (3) establish threshold limit values, (4) perform materials outgassing measurements, and (5) demonstrate candidate flight sensor techniques for intermediate and extended-duration manned missions. Biological sensors for spacecraft atmospheres, and chemical and biological sensors to assure potability of water on manned spacecraft, have not yet received adequate attention. The techniques and associated sensors to accomplish potability assessment of reclaimed water will be developed and tested.

In addition, the development to flight-qualified status of a variety of sensors, such as flowmeters and oxygen and carbon dioxide suit sensors, must be accomplished to verify the proper operation of these systems and provide control functions where necessary.

1. Cabin
    a. Leak defection
    b. Aerosol particle analyzer (T-003)
2. Fire prevention—fire-sensing

Food Management

Statement of the problem.–For future missions food must be tasty, nutritious, simple to prepare, and must store for long periods. Current space foods only partly meet these requirements.

Scientific objectives.–To find ways to prepare and package food for space flight so that it retains its flavor and appeal and serves as a positive morale factor in space missions. In addition, it must be lightweight and small in volume and be easily prepared for consumption in flight.

BIOSCIENCE PROGRAM

BIOSCIENCE GOALS

The goals of bioscience include: (1) the study of the effects of the space environment on living Earth organisms, (2) the use of space flight as a research tool to obtain both new fundamental knowledge and new biomedical applications, and (3) the search for extraterrestrial life.

Space Biology Goals

The goals of space biology are to: (1) study the effects of space environmental factors on living Earth organisms, especially the factors of weightlessness and effective dissociation from factors related to the Earth's rotation; (2) exploit the unique space environment to analyze organism-environment relationships, especially the role of environment in establishing and maintaining normal organization in living systems; and (3) study the physiological, behavioral, and genetic responses and adaptations of living organisms to the space environment.

There is need for a new and better understanding of life processes. The urgency of this need is evident from national and world preoccupation with biological problems, such as food supply, overpopulation, disease, and pollution. The space biology program offers unique and heretofore unavailable opportunities to obtain increased understanding and knowledge that are required in attempting to alleviate these problems.

The most significant characteristics of life are the capacities of living organisms either to maintain a uniform internal environment in the face of altered external conditions, or to modify the environment to the advantage of the organism and adapt genetically to improve the probability of survival. There is a complicated interrelationship between basic biological functions and environment. The space biology program is now exploiting the use of space as a research tool for new environmental studies. These include studies on the biological effects of weightlessness for prolonged periods, weightlessness combined with radiation, and removal of organisms from geophysical periodicities associated with the Earth's rotation.

Biology's emergence from a descriptive to a quantitative science has been comparatively recent, and it still lacks the establishment of a general theory that is so characteristic of the physical sciences. The ability to conduct studies in unique environmental situations removed from terrestrial influence will significantly aid our approach to such a general theory by increasing our understanding of processes that are universally applicable to all forms of life.

Exobiology Goals

The goals of exobiology are: to obtain knowledge of the origin, nature, levels of development, and distribution of life in the universe, and to develop fundamental theories and models based on this knowledge. These goals require (1) a search for extraterrestrial life and life-related chemicals on the Moon and other planets, (2) study of the early chemical and biological history of the Earth, and (3) prevention of planetary contamination from Earth by effective spacecraft sterilization.

The principal goal in the search for life on another celestial body is to determine the nature of the biota and the state of biological evolution, if life is present, or the presence and nature of organic compounds, if there is no life.

The universality of chemical and physical laws has been demonstrated repeatedly by direct, instrumental observation of various bodies in the universe. No comparable universality of biological laws can be deduced in such a manner, nor can we extrapolate the universality of chemical and physical laws to life as we know it as being the inevitable result of the operation of these laws. Thus, we have unequivocal empirical evidence for biology on only one planet—the Earth. This very fact, however, has caused men to wonder and speculate not only about possible life on other planets, but also about the very origin of life.

The subject of the possibility of life on other planets has been given the name "exobiology." Indeed, the advent of the space age has even imbued the term exobiology with an attainable goal–that of obtaining data relevant to the origin, nature, and distribution of life in the universe.

To our knowledge, no reasonable concept of life, other than as we know it on Earth, has ever been formulated. Thus, in preparing for the study of exobiology, we are operationally restricted to terrestrial life as a model system. Nevertheless, it is necessary to bear in mind the possibility of life forms that are completely alien to our own planet.

The subject of exobiology is an integral part of any planetary study. The origin, nature, and distribution of life on any given planet is considered to be inextricably interwoven with the origin and evolution of the planet itself and must be studied in that light.

BIOSCIENCE OBJECTIVES

Space Biology Objectives

The main objective is to study the effects of the space environment on living Earth organisms. Carefully selected and controlled experiments are being flown to provide a broad survey of biological effects, preliminary to more detailed studies, to determine the mechanisms of response and adaptation of organisms. Other major objectives are to:

1. Survey the biological effects of weightlessness in Earth orbit on the physiology, morphology, and behavior of various organisms, including primates, rats, invertebrate animals, plants, and single-cell organisms.
2. Survey the effects on the biorhythms of organisms, including rodents, insects, plants, and single-cell organisms, in removing them from Earth's periodicities by Earth- and solar-orbital space flight.
3. Survey the effects of weightlessness combined with controlled radiation in Earth-orbital flight on various organisms.
4. Survey the biological effects of high-energy, heavy-particle, cosmic radiation on selected biological organisms.
5. Initiate studies in space flight on the mechanisms of, and the basis for, response and adaptation of organisms to weightlessness,

space radiation, and removal from Earth periodicities. The achievement of the initial studies will assist the direction of follow-on studies.

Exobiology Objectives

Earth

1. To determine the chemical composition of earliest Earth life, and distinguish between the biological and nonbiological origins of organic matter; to understand the abiogenic synthesis of organic molecules.
2. To determine the extreme parameters of environmental factors that limit biological activity and the influence these factors have on evolution.

Planets

1. To study the physical and chemical characteristics of planetary environments that may be compatible with biological activity.
2. To search for life or life-associated molecules.

Moon

1. To analyze returned samples for biological and/or organic material.
2. To analyze, in situ, life forms or organic material.

Meteorites and Comets

1. To determine the source of the organic matter found in carbonaceous chondrites and its significance with respect to extraterrestrial life.
2. To analyze spectroscopically cometary matter in space, with respect to its organic composition.

Ground-based and extraterrestrial studies required to achieve exobiology goals and objectives can be categorized as: (1) life detection and characterization, (2) chemical evolution and organic geochemistry, (3) environmental parameters affecting life and its evolution, and (4) development of theories for the origin and evolution of life.

Studies in Life Detection

1. To select those parameters of life that can be determined by remote instrumentation and that will provide data permitting unequivocal interpretation as to the presence or absence of living organisms on the planet being examined. Evidence of metabolic activity, growth, and/or reproduction is considered of primary importance, at least in early missions.

2. To detect and identify organic molecules as evidence for past or present life on a planet.

Studies in Organic Geochemistry

1. To determine the organochemical and/or biochemical history of the Earth.

2. To apply the developed techniques and interpretations to other planets and the Moon.

3. To establish criteria for the differentiation of organic compounds with respect to their biogenic or abiogenic formation.

Studies of chemical evolution have the primary objectives of supplying experimental evidence for the possible origin of life and providing a basis for the recognition of such a process on another planet.

Studies in Environmental Parameters

1. To measure the physical characteristics that constitute the environment for life on the planets.

2. To increase our understanding of the mechanisms by which organisms interact with and adapt to their environment. The environment interacts profoundly with living organisms. When environmental pressure is maintained over a period of many generations, an organism has the opportunity to adapt, through mutation and natural selection in the population. Likewise, the environment may be changed by the biological activity within it. A notable example is the biological production of oxygen in our terrestrial atmosphere.

Theories on the Origin and Evolution of Life

1. To develop general theories based on an understanding of the nature and processes of extraterrestrial life and its distribution in the universe.

2. To describe the line of organochemical-biochemical-biological development within the framework of planetary evolution.

Contamination Control and Biological Constraints

For a manned or unmanned exobiology program in which planetary samples will be acquired; and returned to Earth, consideration must be given to contamination quarantine, the feasibility of sample return, and sample preservation.

Contamination and quarantine constraints.—Control of outbound Earth contamination of the spacecraft is based on the need to protect the validity of life-detection experiments on target planets and on the probability that terrestrial life may grow and spread to change the planetary biota, geochemistry, and atmosphere before scientific exploration is achieved. The probability of growth and spread can be determined experimentally, within reasonable confidence limits, on Earth, after detailed information has become available on the characteristics of the atmosphere, surface, and subsurface environment of the target planet.

Return samples.—Although there is current questioning about the feasibility of returning to Earth even small samples from the surface of Mars, the importance of such samples is sufficiently great to warrant continued study of methods for accomplishing it. Conversely, the potential hazard of contamination of the Earth by extraterrestrial organisms from returned Martian samples is considerably greater than the hazard from samples returned from the Moon, so that the precautions taken should be appropriately greater. It is conceivable that quarantine of returned Martian samples could be conducted on the Moon or in Earth orbit, or that in situ experiments on Mars might resolve the question of hazard.

Sample preservation.—It has been frequently suggested that, to guarantee that extraterrestrial surface material will be preserved from contamination by early spacecraft for future analysis, studies be made to determine a method for preservation, or encapsulation, and to determine the longevity of chemical and biological material under extraterrestrial conditions. Unless complete analyses are made very early in the program, such preservation should be considered.

MANNED SPACE-FLIGHT PROGRAM

The Advanced Biosatellite should be considered as an alternative to the Biotechnology Laboratory (or comparable manned laboratory), since the manned laboratory is not an economical vehicle for conducting small, automated, nonrecoverable payloads, nor for those experiments requiring short times in orbit. However, if we assume an increase in the overall capacities of space stations and increasing experience in space biology experimentation, there will be a corresponding need for scientist-astronauts.

The experiments planned for a wet workshop will be largely automated, but they will also begin to test man's ability to perform simple laboratory tasks, such as verifying the integrity of living systems in flight, recording physiological variables, and focusing a microscope. Experiments in the intermediate period (1973-1975) will involve more elaborate measurements and manipulative skills. Some of them may also provide for simultaneous automated and astronaut-conducted experiments to allow comparison and evaluation of the effectiveness of the astronaut.

In the post-1974 program, most of the manned space-biology experiments will be carried on in the Biotechnology Laboratory, which may be thought of as a life-sciences laboratory occupying all or part of a manned space station, or perhaps several space stations. It will provide a coordinated space laboratory facility for all of the life-sciences activities of NASA, including bioscience, biotechnology, and space medicine. It is difficult to elaborate on this only in terms of bioscience, because the purpose then will be to achieve maximum common use of skills and equipment for all of the life-sciences work. In general, the trend will be toward greater use of scientist-astronauts trained in the life sciences and toward more general-purpose laboratory facilities. Special experiment packages will be required with some degree of automation as determined by the limited astronaut time, the peculiarities of the experiments, and the nature of the spacecraft environment. It is in this laboratory and during this time period that much of the "intensive" (as distinguished from "survey") experiments will be accomplished. Reusable adaptive equipment is contemplated which will permit repetition and variation of experiments without laborious development and integration work. Observations and procedures performed by the astronaut will be especially important for simplifying equipment, enhancing the flexibility of the experimental work, and maximizing the scientific output.

BIOSCIENCE PROGRAM PACKAGES

Primates (Bio A)

Scientific objectives.—To extend the study of primate physiology in weightless orbit beyond that accomplished in the biosatellite.

Justification.—

1. To gain a basic knowledge and theoretical understanding of physiological processes in the unique space environment; particularly, to study the mechanisms of response to gravity and Earth periodicities and determine the effects of long-term confinement and the absence of sensory cues on the psychology and physiology of higher order primates. This is a search for fundamental knowledge which will ultimately find use in biomedical research and applications.

2. To learn more about the time course and extent of physiological and psychological changes and adaptation processes in higher order primates subjected to the space-flight environment. This basic research will provide a good empirical comparison with the physiological responses and adaptations observed in astronauts which may be encountered during future space flights. It will provide the analytical basis for evaluating untoward physiological effects that may occur later and for devising appropriate preventive measures.

3. To develop the techniques and technologies necessary to conduct analytical research on large animals in space. This will have particular value in the event that future manned experience indicates a need for more fundamental knowledge.

Component experiments.—(1) The physiology of chimpanzees in orbit, and (2) the hemodynamic and metabolic effects of weightlessness in monkeys.

Microbiology (Bio C)

Scientific objectives.—To extend the survey and in-depth study of the responses of micro-organisms, cells, tissues, and semimicroscopic animals or plants to weightlessness, evolving from results gained in the Biosatellite program toward plans for research in the Biotechnology Laboratory.

Justification.–

1. The biological scientific community has identified a need for these data arising from both survey and in-depth experimentation.
2. The manned space-flight and bioscience communities have endorsed this activity as a means for evolving a flexible, responsive, and powerful mode of carrying out research on the above test subjects in the Biotechnology Laboratory.
3. The capability of long-term space systems to meet the environmental needs and the spacecraft support requirements must be evaluated in the operational environment (e.g., provision of a very low acceleration environment, and isolation of microbiological experiments from rhythmic or cyclic phenomena).
4. The ability of man to monitor, maintain, and repair experiments and equipment must be demonstrated operationally. The capability of the scientist/crewman must also be tested to determine whether he can:
   a. Receive microbiological or other culture material.
   b. Prepare reusable or adaptable equipment inflight for inflight setup of experiments.
   c. Initiate new experiments.
   d. Remove, manipulate, and preserve samples.
   e. Modify experiment protocol and conditions as required by the price incentive.
   f. Terminate experiments, preparing appropriate material for logistics return.

   The requirement for, and role of, the microbiology specialist in a space station must be determined in operational tests.
5. Technological requirements must be satisfied for:
   a. The evolution of microbiological (and other) research equipment for incorporation in the Biotechnology Laboratory.
   b. Providing a low-g research environment free of rhythmic "cue" phenomena.

Component experiments.–

1. Influence of zero gravity on isolated human cells (further development of S015).
2. Behavior and reproduction of paramecia in the weightless state.
3. Effect of zero gravity on the growth rate of yeast and *E. coli.*
4. Growth of a plant tissue culture in the gravity-free state.
5. Effect of the space environment and weightlessness on

periodicity of growth and conidial formation in *Neurospora* "clock-mutants."

6. Effect of subgravity on frog egg development.
7. Automatic analysis of cytogenic material.
8. Kinetics of DNA replication and recombination under weightless conditions.

Small Vertebrates (Bio D)

Scientific objectives.—To extend the survey and in-depth study of the responses of small vertebrate animals to weightlessness, evolving from results gained in the Biosatellite program toward plans for research in the Biotechnology Laboratory.

Justification.—

1. The biological scientific community has identified a need for these data arising from both survey and in-depth experimentation.
2. The manned space-flight and bioscience communities have endorsed this activity as a means for evolving a flexible, responsive, and powerful mode of carrying out research on the above test subjects in the Biotechnology Laboratory.
3. The capability of long-term space systems to meet the environmental needs and the spacecraft support requirements must be evaluated in the operational environment (e.g., provision of a very low acceleration environment, and isolation of vertebrate animal experiments from rhythmic or cyclic phenomena).
4. The ability of man to monitor, maintain, and repair experiments and equipment must be demonstrated operationally. The capability of the scientist/crewman must also be tested to determine whether he can:
    a. Receive test animals.
    b. Perform in-flight experimental preparation of animals for installation in onboard experiment modules.
    c. Make direct observations of recordings on the test subjects.
    d. Perform various specimen collection and preservation techniques, including biopsy, body-fluid sampling, sacrifice, and necropsy.
    e. Make serendipitous or *ad hoc* demand observations.
    f. Modify experiment protocol and conditions.
    g. Terminate animal experiments, preparing both life specimens and preserved material for logistics return.

The requirement for, and role of, an animal physiology specialist in a space station must be determined in operational tests.

5. Technological requirements must be satisfied for:

a. The evolution of small-animal research equipment for incorporation in the Biotechnology Laboratory.

b. Providing a low-g research environment free of rhythmic "cue" phenomena.

Component experiments.–The experiments comprising Bio D are grouped in eight areas, characterized either by (1) potential for common use of the same test individuals by a number of principal investigators, (2) the unique importance of the biological area of interest, or (3) the unique environmental conditions required by the test subjects.

1. The role of gravity in cardiovascular function (one experiment).
2. The role of gravity in embryogenesis, parturition, growth, development, metabolism; and again in rodents (11 experiments).
3. The role of gravity in immune responses of mammals (two experiments).
4. The role of gravity in embryogenesis and development in amphibia (one experiment).
5. The role of gravity in growth and metabolism in reptiles (one experiment).
6. The influence of gravity on behavior in mammals (one experiment).
7. The influence of geophysical factors on biorhythms in vertebrates (two experiments).
8. The role of gravity in hibernation (one experiment).

Plant Specimens (Bio E)

Scientific objectives.–To extend the survey and in-depth study of the responses of a variety of plant species, evolving from results gained in the Biosatellite program toward plans for research in the Biotechnology Laboratory.

Justification.–

1. The biological scientific community has identified a need for these data arising from both survey and in-depth experimentation.
2. The manned space-flight and bioscience communities have endorsed this activity as a means for evolving a flexible, responsive, and powerful mode of carrying out research on the above test subjects in the Biotechnology Laboratory.

3. The capability of long-term space systems to meet the environmental needs and the spacecraft support requirements must be evaluated in the operational environment (e.g., provision of a very low acceleration environment, and isolation of plant experiments from rhythmic or cyclic phenomena).

4. The ability of man to monitor, maintain, and repair experiments and equipment must be demonstrated operationally. The capability of the scientist/crewman must also be tested to determine whether he can:

a. Receive plant seeds, tissues, or other material.

b. Perform in-flight experimental preparation of plant materials for installation in onboard experiment modules.

c. Make direct observations of recordings on the test material.

d. Perform various specimen collection and preservation techniques, including macro-dissection for particular organs or tissues.

e. Make serendipitous or *ad hoc* demand observations.

f. Modify experiment protocol and conditions.

g. Terminate plant experiments, preparing both live specimens and preserved material for logistics return.

The requirement for, and role of, a plant physiology/morphology specialist in a space station must be determined in operational tests.

5. Technological requirements must be satisfied for:

a. The evolution of plant research equipment for incorporation in the Biotechnology Laboratory.

b. Providing a low-g research environment free of rhythmic "cue" phenomena.

Component experiments.—

1. Plant responses from 0 to 1 g.
2. The role of Auxin mediated reactions in the developing wheat seedling during weightlessness.
3. Pea seedling growth in orbit.
4. The effect of weightlessness on gametogenesis and morphogenesis of Pteris gametophytes.
5. Studies of the circadian leaf movements of pinto beans.
6. Environmental factors regulating circadian rhythms in *Phaseolus* leaves.
7. Plant morphogenesis under weightlessness.

8. The role of gravitational stress in land-plant evolution: the gravitational factor in lignification.

Invertebrates (Bio F)

Scientific objectives.–To extend the survey and in-depth study of the responses of invertebrate animals to weightlessness, evolving from the results gained in the Biosatellite program toward plans for research in the Biotechnology Laboratory.

Justification.–

1. The biological scientific community has identified a need for these data arising from both survey and in-depth experimentation.
2. The manned space flight and bioscience communities have endorsed this activity as a means for evolving a flexible, responsive, and powerful mode of carrying out research on the above test subjects in the Biotechnology Laboratory.
3. The capability of long-term space systems to meet the environmental needs and the spacecraft support requirements must be evaluated in the operational environment (e.g., provision of a very low acceleration environment, and isolation of invertebrate-animal experiments from rhythmic or cyclic phenomena).
4. The ability of man to monitor, maintain, and repair experiments and equipment must be demonstrated operationally. The capability of the scientist/crewman must also be tested to determine whether he can:
    a. Receive invertebrate animals, eggs, larvae, pupae, or other material.
    b. Perform in-flight experimental preparation of animals for installation in onboard experiment modules.
    c. Make direct observations of recordings on the test subjects.
    d. Perform various specimen collection and preservation techniques, including biopsy, body-fluid sampling, sacrifice, and necropsy.
    e. Make serendipitous or *ad hoc* demand observations.
    f. Modify experiment protocol and conditions.
    g. Terminate animal experiments, preparing both live specimens and preserved material for logistics return.

    The requirement for, and role of, an invertebrate physiology/morphology specialist in a space station must be determined in operational tests.
5. Technological requirements must be satisfied for:

a. The evolution of invertebrate-animal research equipment for incorporation in the Biotechnology Laboratory.

b. Providing a low-g research environment free of rhythmic "cue" phenomena.

Component experiments.—

1. The effects of weightlessness, genetic diversity, and life cycle in *Drosophila melanogaster*.
2. Circadian rhythm—Vinegar gnat.
3. The circadian rhythm of the Madura roach in orbit.
4. Cockroach circadian rhythms during prolonged orbital flight.
5. The biorhythmicity of fiddler crab activity and respiration.
6. Discrimination and communication under weightless conditions.

Biotechnology Laboratory

Scientific objectives.—To provide a space-laboratory facility in which a broad spectrum of life-sciences experiments can be performed, making effective use of general-purpose or common equipment and the skills of scientist-astronauts. In particular, for space biology it will continue the investigations of organisms and phenomena indicated by prior survey experiments to be most worthy of intensive further work.

Justification.—

1. The biological community has identified a need for a substantial amount of space-flight research to gain a better fundamental knowledge of life processes, using exploration of the unique space environment as a research tool.
2. The presence of a life-scientist astronaut can greatly enhance the scientific value of biological experiments, substantially reduce the complexity of the equipment, and improve reliability.
3. The relative permanence, and the large volume and power capacity of the Biotechnology Laboratory, in conjunction with the astronaut, will permit the use of the equipment for repetition or variation of experiments without laborious development work. It should permit a lower cost per experiment and shorter time cycle for implementing experiments than are characteristic of the more highly automated facilities.

Future experiments.—Specific future experiments cannot be identified now with any useful accuracy, because they depend upon the results of preceding flights. However, it can be postulated that the elements of the experiment complex will be adaptation of the earlier elements (i.e., Bio A–primates, Bio C–microbiology, Bio D–small vertebrates, Bio E–plants, and Bio F–invertebrates). Future efforts are expected to concentrate on such areas of study as:

1. Cellular life
2. Growth, aging, and longevity
3. Experimental embryology, differentiation, and regulation of morphogenesis
4. Genetics
5. Plant studies–geotropism
6. Basic microbiology and immunology
7. Animal behavior
8. Biorhythms–circadian and others
9. Radiation effects in space
10. Mammalian physiology and adaptation, including the following systems–
    a. Cardiovascular
    b. Renal and urinary
    c. Neurophysiological
    d. Musculoskeletal
    e. Metabolic
    f. Respiratory
    g. Endocrine

Experiment Requirements and Constraints

The bioscience research program requires the lowest possible acceleration environment for the proper conduct of experiments to investigate the effect of weightlessness on life forms. This requirement stems from the lack of baseline knowledge of the g-sensitivity thresholds for biological systems, from cellular and subcellular levels to total organisms. Initial estimates indicate that the maximum nominal g-environment should be no greater than 10^{-4} g for 90 percent of the time. An acceleration environment of 10^{-3} can be accommodated for 10 percent of the time, integrated over the duration of the mission. Pulses up to 1 g can be accepted occasionally, if the pulse duration is less than 1 minute. All pulses above the nominal environment of 10^{-4} g should be predictable, and sufficient advance notice be given to the experimenter to permit him to protect all experiments against the adverse effects of the acceleration pulse. Exact records of the g-levels, weight of onset, and duration must be provided the experimenter to permit him to identify experimental anomalies resulting from the g-pulse.

To permit meaningful research in biorhythms, all pertinent bioscience experiments must be isolated from any 24-hour periodic cues or harmonics thereof which result from acceleration, noise, lighting, thermal changes, crew activity, etc.

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APPENDIX H
Materials Science and Processing in Space

INTRODUCTION

An Earth-orbiting manned space station will provide important new capabilities for the pursuit of research and development activities in the general field of materials technology. The availability of skilled men who can function in the space station allows for radically different designs from those required for unmanned space experiments. It can result in lower experimental costs, broader flexibility in experimental objectives, increased experimental reliability, and longer useful lifetimes for the experiments. In the areas with which this paper is concerned, so little is known about the unique effects of the space environment that many of the experiments must be heuristic in nature, and it is in precisely this milieu that man is most useful.

Despite the great importance of materials technology and the enormous amount of research devoted to the subject, a systematic program for carrying out such research in space has received relatively little study. A number of general qualitative surveys have been presented at meetings devoted to practical space applications (refs. 1 to 3), and proposals have been made for individual experiments in such related fields as physics, advanced technology, and engineering operations. Recently, however, Marshall Space Flight Center has initiated a program to identify and evaluate candidate processes for space manufacturing (refs. 4 to 6). These efforts have been primarily directed toward applications, but extensive research is clearly required before specific products can be developed.

Our objective in the following sections is to discuss the most promising new processes and materials and to make a preliminary evaluation of their future potential. At present, we can only speculate on what the eventual applications will be.

PROPERTIES OF THE SPACE ENVIRONMENT RELEVANT TO MATERIALS AND PROCESSING

We will first consider the properties of the environment that may lead to new processes and applications. In this respect, the one unique characteristic is the phenomenon of weightlessness, usually referred to as zero-g. This is the only factor that cannot be duplicated on Earth, although such features as the large volume of vacuum may remain difficult or costly to produce.

THE GRAVITATIONAL FIELD

It is important to recognize that zero-g does not mean literally zero gravitational force in orbit, but rather an approximate balance between the gravitational and centrifugal forces. All free-floating objects have independent orbits and will generally contact a container wall within one orbit, unless an external force is applied to prevent this. Other sources of disturbance include crew motions, mechanical and acoustical vibrations, attitude-control and orbit-keeping maneuvers, and atmospheric drag.

The required constraining force in all cases is quite small and accelerations of 10^{-5} g or less should be maintainable for extended periods of time. Accelerations during peak station maneuvers and crew activities, however, may increase to 10^{-2} g. A more detailed discussion of the zero-g environment is presented in "Limitations on Zero-G" (p. 170); see also "Requirements for a Space Facility" (p. 169).

THE SPACE VACUUM

The level of vacuum in low Earth orbit is considerably poorer than the 10^{-13} to 10^{-14} torr currently achieved in vacuum chambers. For comparison, mean atmospheric pressures for several representative altitudes are given on the next page (ref. 7).

Altitude, km	*Nautical miles*	*Pressure, torr*
150	81	3.8×10^{-6}
300	162	1.4×10^{-10}
700	378	8.9×10^{-12}
> 2500	1350	$< 10^{-12}$

These values are the lower limits on the attainable vacuum pressure, since spacecraft leakage will contaminate the environment. Calculations on predicted leak rates for the Apollo Command module or lunar module indicate that the effective pressures will be as high as 10^{-5} torr within a few meters of the leak source.*

The unlimited vacuum of space can be of significant value where high mass-flow rates are required. Back contamination resulting from low pumping rates and small volumes is often a limiting factor on vacuum chamber performance. This would not be a constraint in free space, so that much larger flow rates could be achieved. Vacuum technology is advancing rapidly, however, and by the time space processes requiring large vacuums become feasible, Earth capabilities for vacuum pumping may be competitive with Earth orbit, both in pumping rates and cost.

The vacuum in the vicinity of an orbiting laboratory does not appear to offer a sufficiently unique capability to provide a circumstance that would justify space manufacture. In conjunction with other properties of an orbiting laboratory, it might prove a useful adjunct.

RADIATION ENVIRONMENT

The high-energy and particle radiation environment does not appear to provide particularly useful characteristics, because fluxes are too low and are subject to random fluctuations. Temperatures on the order of 5000° K, difficult to obtain using normal heat-transfer methods, can be attained with solar reflectors. Again, this would be a useful adjunct rather than a unique capability (ref. 8).

*F. G. Allen of Bellcomm, Inc., private communication, 1968.

OPPORTUNITIES PROVIDED IN ZERO-G

A number of unique processes have been suggested for possible study and application in the space environment. Lists of these processes have been given by Wuenscher (ref. 5), Frost (ref. 9), and Steurer (ref. 10).

In zero-g, density variations become unimportant and convection currents are suppressed. Variable-density mixing of immiscible liquids and liquid/solid/gas suspensions is achievable. Contact between bodies can be eliminated by selective force-field constraints, avoiding introduction of contact distortions and impurities. Vibrations can also be effectively isolated.

It is difficult to gage the potential impact of specific processes for products which would be otherwise unavailable or impractical to manufacture in the Earth environment. Some applications are immediately recognizable, but others, of perhaps more far-reaching consequences, remain yet to be discovered.

The following sections summarize and review the most promising of the processes proposed. Specific applications are cited only as representative examples of potential use.

IMPROVED CRYSTALLOGRAPHIC OR MICROSCOPIC PROPERTIES OF MATERIALS

Levitation by radiofrequency fields on Earth, the closest long-term simulation of zero-g, has shown great promise, but suffers from the basic limitations of being restricted to conducting materials and to small quantities. Moreover, the supporting forces are concentrated near the periphery, where induced eddy currents are maximum. In zero-g, these processes can be extended to nonmetallic substances as well as high-temperature ceramics, as for example, melting of free-floating refractory materials that are subject to contamination when in contact with any crucible or mold. Production of materials with components added in precisely specified amounts or locations, and of very large crystals or crystals free from imperfections, appears feasible. In Earth orbit, semiconductor materials and ceramics could conceivably be refined in amounts limited only by the stability of the liquid melt under surface tension. Achievements in these areas are of considerable scientific interest, and have the promise of practical applications.

Such processes as materials purification, homogenization of alloys having large density differences between phases, preparation of new alloys, semiconductors, and mixed crystals and glasses are also feasible. Ultrahigh-purity glasses, growth of crystals directly from the levitated mass, and solidification involving extreme supercooling are other possibilities. (A characteristic of supercooled material is the formation of extremely small crystal grains, which appears to be the mechanism by which materials achieve superplasticity. Elongations in metals of greater than 1000 percent have been observed (ref. 11).

Floating-zone melting is another process with great potential. Relaxation of present restrictions on the size of the molten zone should permit application of this technique to materials that are not now feasible on Earth. In addition, crystals of much larger diameter could be grown (ref. 12).

Convection currents have been shown to be a source of dislocations and other inhomogeneities in crystals grown from the melt (ref. 13). Suppression of these currents should reduce the number of imperfections. In fact, it may be possible to grow very large dislocation-free crystals from nonmetallic substances. For crystals grown from solution or vapor, the absence of convection would cause the process to become diffusion controlled. As a result, the growth rate would be reduced, allowing greater precision in control of additive components.

The weightless condition could eliminate the need for supports, another major source of imperfections (refs. 9 and 14). Seed crystals could be suspended in the center of the melt, solution, or vapor. The absence of stresses in crystals grown by pulling could allow much larger perfect crystals to be grown by this technique.

Single crystals of high perfection are in great demand for many applications. The technology of crystal growing is an extensive and rapidly growing field, and predictions of the future value of any particular technique are difficult to make. Nevertheless, the weightless environment of space does offer some possible solutions to currently unsolved problems.

NOVEL STRUCTURAL MATERIALS

Entirely new classes of alloys, colloids, and variable-density solids and solid/gas mixtures, utilizing characteristics of the zero-g environment, can readily be conceived. These include high-strength foams, metallic and nonmetallic mixes, variable-density melts for casting, etc. Other than their utilization as subject materials in basic research, however, it is difficult at this time to assess the benefits derivable from such materials. For example, it may be possible to fabricate high-strength foams and structures by controlled distribution of gas bubbles, but it is not clear that such materials would offer advantages warranting space processing. The problem is not in visualizing new materials, but in establishing justification of their value. The crucial question is whether the quantity returnable to Earth would be worth the cost. The material must be worth a great deal per pound and per cubic foot, and relatively small quantities must satisfy demand. There may be possible uses of such materials *in* space, but at present these do not look as promising as competitive approaches that utilize the assembly of modularized structures.

Particularly promising applications of new structural materials are the high-strength composites, which will now be considered in some detail to illustrate possible benefits derived from zero-g processing.

High strength to weight composite materials are formed by embedding microscopically thin, dislocation-free crystalline whiskers in a matrix or filler material. In practice, bond failure between the whiskers and filler is the governing failure mechanism. Composite material strength can be increased by (1) using longer elements, and (2) achieving optimum whisker spacing and alinement. In the Earth environment, practical problems associated with physical spacing and alinement of whiskers in the matrix material are prohibitive, and are responsible in large measure for the current high costs of composites, which sometimes are thousands of dollars per pound. In zero-g, it may be practical to grow longer whiskers from free-floating droplets and also to alleviate spacing and alinement problems. For example, polarization techniques could be employed to stratify and aline crystals along the desired axes. Matrix material could be vapor-deposited to achieve uniform "wetting" at the bonding interface and maintain uniform spacing and alinement.

FORMING PROCESSES

In the absence of a gravitational field, forces of secondary influence in the Earth environment become of paramount importance. For example, materials in the liquid state rapidly take the form of perfect spheres under the influence of surface tension. Likewise, spun liquid masses form accurate ellipsoidal shapes.

Numerous forming processes that depend on the lack of convection and the absence of gravity separation and distortion have been proposed (refs. 4, 5, 9, and 10). These include thin-wall membranes and castings, forging and extrusion of long, delicate structural components, blow-molding of complex components, and a variety of casting techniques utilizing materials of differing densities. Some of these processes can have significant use in basic research. Whether markets will develop for products utilizing these processes, however, is uncertain.

A case in point, demonstrating the need for further understanding of these processes, is a suggested method of fabricating hollow ball bearings (ref. 5), a very desirable product under active investigation at the present time, with imperfect results so far. In space, formation of a hollow sphere by injecting gas into the center of a molten ball would appear to be a straightforward technique.

Further investigation, however, reveals several significant problems (ref. 15). Some of these, notably the problems of surface facets and dendritic growth during solidification under pure surface tension, are of considerable interest in crystallography. Stresses induced by density changes and uncertainties in centering the gas bubble may also lead to imperfections.

These potential problems might be avoided in various ways. For example, if rapid, homogeneous nucleation of fine crystals in the melt is achievable by supercooling, a smooth surface may result. The point is, that even the simplest appearing processes would require an extensive development program in zero-g.

REQUIREMENTS FOR A SPACE FACILITY

A materials and processes facility required on a manned station to explore some of these ideas can be described in general terms. Early experiments will probably involve levitation melting of refractory materials, crystal growing from the melt, vapor and solution, casting of composites, and studies of surface-tension-controlled shapes and processes. A compartment in a space station will be required to accommodate one or more men and the necessary apparatus. This will include an enclosed chamber, several feet in each dimension, with provision for inert gas flow, viewing ports and cameras, feed-throughs for motion and electrical inputs, and an intense power source that may be supplied by radio-frequency-induction, an electron beam, or possibly focused solar radiation. A simple metallurgical microscope with specimen-treating equipment will also be desirable.

Experiments requiring an absolutely zero-g and vibration-free environment could be done in a chamber allowed to float free of the walls of the station for minutes up to hours. The same facility could accommodate certain experiments on the physical behavior of liquids, gases, and solids in zero-g.

CONCLUSIONS

An analysis of the influence that the space environment could exert on the processing of materials suggests that a materials laboratory would be a useful component of a space laboratory. A number of specialized materials have been identified as having unique properties that can probably be produced only under space conditions. The initial emphasis should be upon research to understand how materials behave during zero-g processing and to identify new materials and fabrication methods to be used later. It does not appear that early emphasis should be placed upon actual fabrication of specific products.

We believe that the materials presently proposed as candidates for study are limited by the abbreviated current state of knowledge. It is our expectation that experience with zero-g processing will markedly expand our horizons and generate a much broader spectrum of possibilities.

Development of new materials and processes puts a particular premium on the presence of man as a modifier and controller of the experimental conditions. The course of experiments will be determined by early results. Only a man on the scene, with apparatus under his control, can react and modify the next experiments as required.

Limitations on Zero-G

Earthbound simulations of zero-g are limited to periods of a few seconds in a drop tower or about 1 minute in an aircraft. Rockets can provide weightless intervals of several minutes, although these are necessarily preceded by periods of very high acceleration. Only in space can longer periods be achieved.

In an orbiting spacecraft, free-floating objects travel in independent trajectories, so that some restraining force will be required to avoid hitting the walls of the container. For example, without the restraining force, an object traveling in the orbital plane and placed 1 foot above and 1 foot in front of the center of gravity of the space station would describe the trajectory shown in figure H-1 (ref. 16), where X and Z refer to tangential and radial axes fixed in the space station. The average distance that such an object drifts along the X axis during one orbit is equal to $-12\pi Z_0$, where Z_0 is the vertical distance from the center of gravity. The minus sign shows that, for positions above the X axis, the object is drifting backwards, while for positions below the X axis, the object moves forward. Note that the average drift distance per orbit is independent of the orbital altitude.

The acceleration required to alter an object's trajectory to maintain its position is very small (on the order of 10^{-7}g), and it is expected that the maximum accelerations will be those

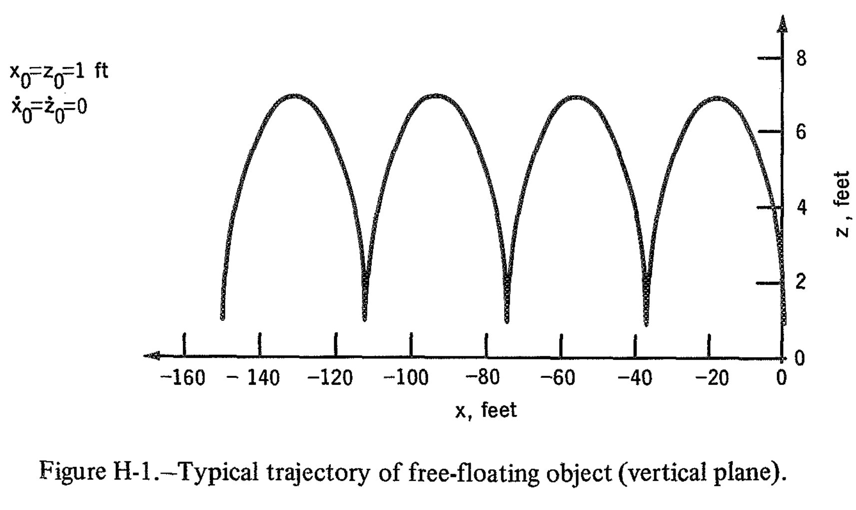

Figure H-1.–Typical trajectory of free-floating object (vertical plane).

caused by astronaut body motions, if thrusting is inhibited during these periods. Assuming that position-control accelerations of 10^{-3} to 10^{-4} g could be allowed during melting and casting operations, "rigid" position of a levitated mass relative to the spacecraft could be maintained despite the influence of astronaut body motions (ref. 9).

The influence of acceleration caused by positioning forces results in a shape distortion of the molten mass. For 10 kilograms of molten metal with a surface tension of 1000 dyne/cm and density of 8 gm/cc, the acceleration that causes its surface curvature to differ by a factor of 2 across the diameter is approximately 10^{-3} g. Rotation also causes distortion and, for the above 10-kilogram sample, a rotational period of a few seconds results in an oblate spheroid having a curvature at the equator twice that at the poles.

Lorentz forces will distort the floating fluid if eddy-current forces are used for position control or if radiofrequency fields are used for heating or stirring the specimen. Although the main limitations in radiofrequency levitation work will be removed, others will eventually be encountered because of potential failure of the integrity of a molten mass, if the processing of too large a batch is attempted.

The main disturbing forces will arise from the requirement for position control within the facility. Application of radiofrequency position-restoring forces will initiate shape oscillations in a molten mass. Because molten metals possess viscosity, such oscillations will diminish with time. The damping time is proportional to the square of the radius of the sphere and inversely proportional to the kinematic viscosity. For a 10-centimeter radius spherical mass of a density of 10 gm/cc and a viscosity of 2 to 4 centipoise, the time constant for damping will lie in the range of thousands of seconds. For spheres with radii near 1 centimeter, the damping times will be tens of seconds.

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NASA-Langley, 1969 —— 34

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