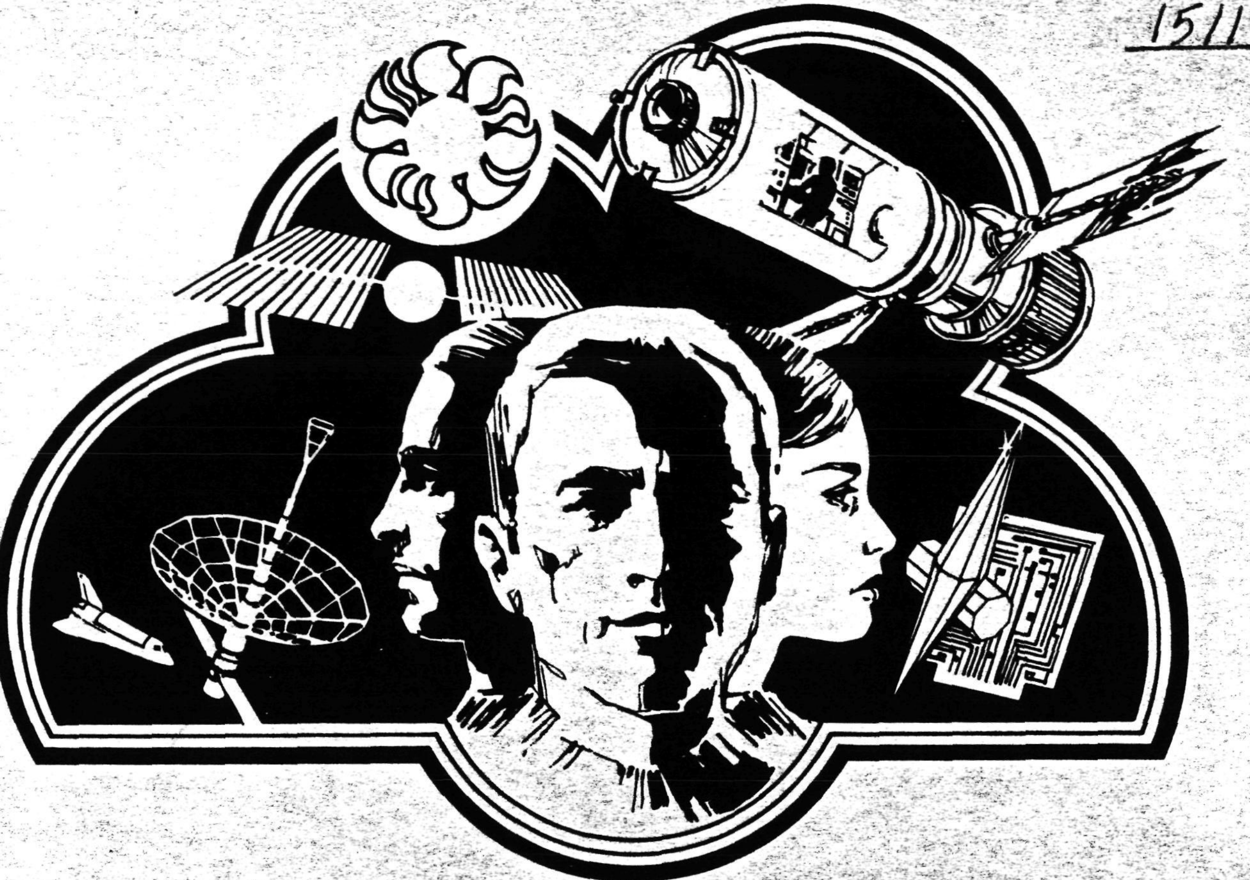
1 SEPTEMBER 1976

MDC G6508

NASA CR-
151102



SPACE STATION SYSTEMS ANALYSIS STUDY

PART 1 FINAL REPORT
VOLUME 1
Executive Summary

(NASA-CR-151102) SPACE STATION SYSTEMS ANALYSIS STUDY. PART 1, VOLUME 1: EXECUTIVE STUDY (McDonnell-Douglas Astronautics Co.) 41 p HC A03/MF A01 CSCL 22B G3/15

N77-11084

Unclas 54603

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

CONTRACT NO. NAS 9-14958
DPD NO. 524
DR NO. MA-04

MCDONNELL DOUGLAS CORPORATION

MCDONNELL DOUGLAS

SPACE STATION SYSTEMS ANALYSIS STUDY

PART 1 FINAL REPORT

VOLUME 1

Executive Summary

1 SEPTEMBER 1976

MDC G6508

CONTRACT NO. NAS 9-14958
DPD NO. 524
DR NO. MA-04

APPROVED BY:

R. J. GUNKEL
STUDY MANAGER, SPACE STATION STUDY

G. V. BUTLER
PROGRAM MANAGER, SPACE STATION

J. W. CRAIG
MANAGER
SPACE STATION SYSTEMS ANALYSIS STUDY

PREPARED FOR: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TEXAS

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY-WEST

5301 Bolsa Avenue, Huntington Beach, CA 92647

Page
Intentionally
Left Blank

PREFACE

The Space Station Systems Analysis Study is a 15-month effort (April 1976 to June 1977) to identify cost-effective Space Station systems options for a permanent manned space facility capable of orderly growth with regard to both function and orbit location. The study activity is organized into three parts. Part 1 is a five-month effort to define and evaluate program options; Part 2 is a five-month effort to define and evaluate system options within the selected program options; and Part 3 is a five-month effort to define selected program and system options.

The purpose of this report is to document the results of Part 1 of the study with specific reference to the Space Station objective selection and the rationale for this selection, and to describe potentially feasible program options for the development of future Space Station systems.

This volume is submitted as part of DR-MA-04, which consists of the following items:

Volume 1 – Executive Summary
Volume 2 – Technical Report
Volume 3 – Appendices
Book 1 – Objective Data
Book 2 – Option Data and Costing

During Part 1 of the study, subcontract support was provided by TRW Systems, Aeronutronic Ford Corporation, and the Raytheon Company.

Questions regarding this study activity should be directed to:

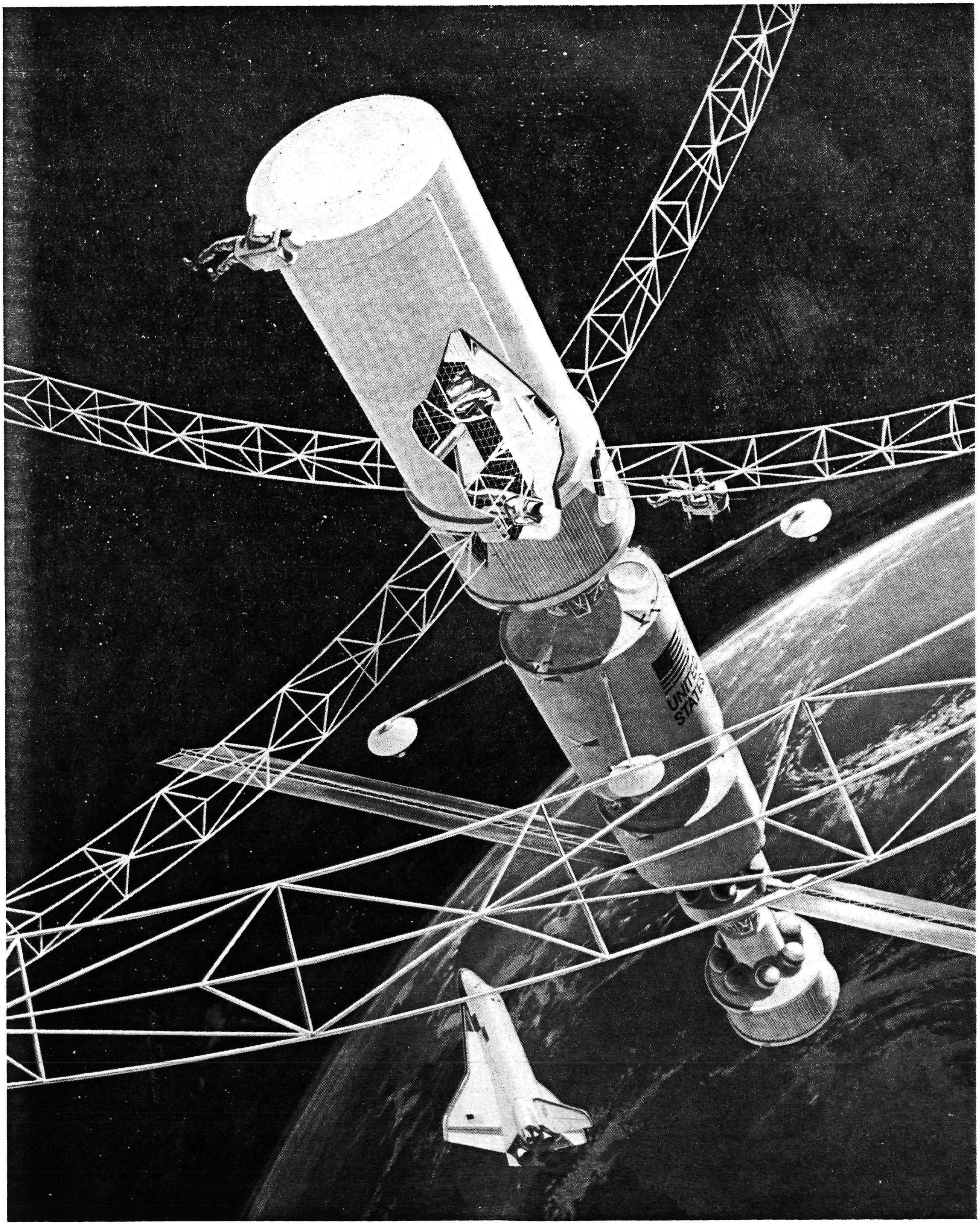
Jerry W. Craig, Code EA4
Manager, Space Station Systems Analysis Study
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058
Telephone (713) 483-4073
OR
R. J. Gunkel
Study Manager, Space Station Systems Analysis Study
McDonnell Douglas Astronautics Company – West
Huntington Beach, California
Telephone (714) 896-3958

Page Intentionally Left Blank

CONTENTS

1.	INTRODUCTION	1
2.	SELECTION OF OBJECTIVES	3
2.1	Satellite Power System (SPS)	3
2.2	Nuclear Energy	4
2.3	Earth Services	5
2.4	Space Cosmological Research and Development	7
2.5	Space Processing	8
2.6	Cluster Support System	10
2.7	Depot	11
2.8	Multidiscipline Science Laboratory (MDSL)	13
2.9	Sensor Development	14
2.10	Living and Working in Space	15
2.11	Considerations in Combining Objectives into Program Options	17
2.12	Results of the Analysis of the Objectives	18
3.	DEVELOPMENT OF PROGRAM OPTIONS	19
3.1	Selection of Candidate Options	19
3.2	Candidate Option Descriptions	20
4.	CONFIGURATION DEVELOPMENT AND TRANSPORTATION REQUIREMENTS	27
4.1	Configuration Development	28
4.2	Transportation Requirements Analysis	29
5.	SUMMARY AND CONCLUSIONS	37

PRECEDING PAGE BLANK NOT FILMED



ORIGINAL PAGE IS
OF POOR QUALITY

1. INTRODUCTION

The purpose of the study documented in this report is to examine potential Space Station system options for a permanent, manned, orbital space facility and to provide data to NASA program planners and decision makers for their use in future program planning. It is not the intent to justify specific space program objectives, per se, but rather to identify the range and extent of potential requirements that might reasonably be imposed on a Space Station system. To accomplish this goal it has been necessary to identify and examine a number of specific potential objectives. While the objectives described in this report do not represent approved NASA programs, they were found to be most useful by the design engineers and program analysts in bounding and investigating viable alternatives for the implementation and orderly growth of a permanent Space Station system.

Key inputs to this analysis were the *Outlook for Space* (NASA SP-386), the JSC and MSFC 1975 *Geosynchronous Space Station Study* reports, the JSC *Six-Week Study on a Space Solar Power Development Laboratory*, and the Aerospace *Study* of the *Commonality of Space Vehicle Applications to Future National Needs* (NASw-2727).

The objectives derived from the *Outlook for Space* and the supplemental sources were evaluated as to their importance as determinants in deriving requirements for future Space Station system elements. Criteria used in this ranking were Need (degree of satisfaction of basic needs), Benefits (potential for providing significant economic benefits), Space Station Applicability, Time Frame for implementation, Cost Confidence, Technical Confidence, and the available Data Base.

With this information, JSC and MDAC personnel then identified 10 key Space Station system objectives. These were categorized into five major objectives and five supporting objectives. The major objectives were to support the development of (1) Satellite Power Systems, (2) Nuclear Energy Plants in Space, (3) Space Processing, (4) Earth Services, and (5) Space Cosmological Research and Development. The five supporting objectives, to define space facilities which would be basic building blocks for future systems, were: (1) a Multidiscipline Science Laboratory (general-purpose facility), (2) an Orbital Depot to maintain, fuel, and service orbital transfer vehicles, (3) Cluster Support Systems to provide power and data processing for multiple orbital elements, (4) a Sensor Development Facility, and (5) the facilities necessary to enhance man's Living and Working in Space.

The requirements stemming from each of these objectives were then examined in the context of their suitability in defining Space Station system program options.

The overall approach to establishing an initial set of program options was based on developing a spectrum of Space Station programs which represented a reasonable range of feasible approaches for accomplishing the objectives. The options were varied with respect to: (1) orbits, (2) the type of Space Station involved, (3) the transportation concepts used, (4) the number of Space Station complexes involved in different orbits, (5) the schedule (and sequence) for realizing objectives, and (6) the depth to which objectives were met (e.g., one option might involve only doing the basic R&D for a set of objectives while another might develop pilot plants for the same set). Options in some cases emphasized one major objective or excluded some objectives where there was a rationale for doing so. Forty-five program options were created and were compared with respect to each other to determine the ones which warranted further analysis. Nine selected options were then analyzed in greater detail to provide data to NASA which could be used to select a limited number of options. The options could be used as the basis for the analyses to be conducted in Part 2 of the study.

During the performance of Part 1 of the study, the concept of a basic Space Station Construction Base (described in Section 4) evolved as the baseline system from which the program options were developed. This initial orbital facility was visualized as including a power module, crew module, control center, core (berthing) module, fabrication and assembly module, and cargo module. As will be described in the discussion of program options (Section 3), specific mission hardware such as a laboratory module or laboratory support module can be added to the baseline system, as determined by the requirements identified for each program option, to provide growth versions of the basic facility.

In developing the program options, currently proposed NASA mission models and other related mission planning materials were reviewed to determine the preliminary studies which will most likely be accomplished during STS/Spacelab missions programmed for the 1980 to 1983 time period. These missions can be expected to include activities in the areas of space processing, life sciences, physics and astronomy, earth sciences, and space technology. These background data provided the point of departure for establishing the functional requirements defined in the present study and implemented in the program options considered for the time period beyond 1983.

In the following pages of this report, the procedure followed in the selection of the objectives for the Space Station system is summarized, the creation of the program options is described, and the critical configuration and transportation requirements are identified.

The key terms used in this report and their definitions are as follows:

Objective
Space activity areas or goals which appear to be key determinants in identifying future Space Station systems requirements.
Example: "Provide a permanent space test capability for evaluation of the technical and economic feasibility of a satellite power system."

Functional Requirement
One of a subset of activities or steps necessary to achieve an objective.
Example: "Evaluate RFI effects produced by large scale microwave power transmission systems."

Objective (Program) Element
Physical facilities, equipment, test apparatus, etc, necessary to perform each functional requirement.
Example: 1.7 megawatt RF antenna, 2.2 megawatt solar array.

Program Option
A set of multiple objective elements supporting a selected group of objectives, which permit the development of programmatic schedule and costing data.
Example: "Space Station and mission hardware (elements)
Orbit location(s)
Transportation requirements
Schedule
Cost."

2. SELECTION OF OBJECTIVES

At the outset of the study, it was determined that the *Outlook for Space* Report (NASA SP-386, January 1976), supplemented by data available through the *Study of the Commonality of Space Vehicle Applications to Future National Needs* (Aerospace Contract NASw-2727), provided an excellent descriptive data base of key goals and objectives. The initial step, therefore, was to use this material to identify 61 program objectives for consideration for Space Station systems support. All 61 objectives were entered into the MDAC computer system, together with key descriptive information on each, to facilitate the analysis, ordering, and selection of the key areas to be investigated in the remainder of the study.

The most important support feature that a Space Station can offer toward the accomplishment of any future space program goal is the availability of man as an observer, decision-maker, and operator on a long-term basis. Experience on Skylab offers substantial evidence that the presence of scientists and astronauts can add significantly to mission success and enhance the productivity of spaceflight activities with respect to modification and improvisation. Accordingly, in the initial study effort, concentration was placed upon those potential areas where manned space programs might be expected to make a significant contribution. Forty-seven objectives from SP-386 were identified that required the support of man in space.

In our analysis, the 47 objectives were collated into 10 Space Station system objectives in which manned Space Station systems appeared to have the potential of contributing significant support.

These Space Station system objectives were:

Construction Related
- Satellite Power System
- Nuclear Energy
- Earth Services
- Space Cosmological R&D

Space Manufacturing
- Space Processing

Support Objectives
- Cluster Support System
- Depot
- Multidiscipline Science Lab
- Sensor Development
- Living and Working in Space

They covered a spectrum of potential applications from commercial operations to pure science: four involved space construction of large antennas and solar arrays; five provided a supporting research and development base for other objectives; one represented an early step in the development of the area of space manufacturing. Each objective was studied independently in some detail to determine the implication for the Space Station and to establish design requirements. In cases where the time frame of individual requirements lay beyond the period of interest for Space Station program options (approximately through 1995), they were not included. As a result of this effort, nine objectives were recommended for inclusion in the development of Space Station program options; the objective involving nuclear energy in space was not recommended for early Space Station implementation.

For the surviving functional requirements from each objective, companion hardware concepts were postulated. These data were the basis for the establishment of program options to be described later in this document. Each of the 10 Space Station system objectives is described briefly in the following pages.

2.1 SATELLITE POWER SYSTEM (SPS)

Several issues must be resolved before an SPS system development decision can be made:

1. Projected power-collection systems are enormous in size, so the capability to economically fabricate, assemble, and check out large structures on orbit must be established. Consequently, it must be determined exactly how a full-scale SPS should be built and what the related man-machine

productivity would be. This is fundamental to establishing future SPS production costs.

2. Various methods and design approaches for energy collection and distribution must be evaluated. These solutions will be impacted by the need for avoidance of high-voltage arcing due to plasma interactions during periods of high solar activity.

3. RFI issues must be resolved, including potential interference with radio astronomy, the Shuttle/Space Station, and other communications systems.

4. Environmental concerns must be resolved with respect as to whether the interaction of the radiated power beam with the ionsphere could affect such things as radio communications, and the potential long-term effects of microwave radiation in the vicinity of the rectenna.

In order to resolve the above issues, major space structures are required in orbit. The Space Station can act as the factory to produce these structures on orbit and support their testing. The SPS functional requirements are supported by three objective elements (Figure 1). The first of these (component development) is a laboratory-scale platform for the investigation of components, subsystem technology, and man-machine investigations of elementary fabrication and assembly tasks. It features a pallet-mounted, 86m, tapered, linear-array antenna used for orbit-to-orbit testing to evaluate phase control, beam quality, and RFI aspects of microwave power transmission. Because of the setup and tear-down time required, these tests would appear to be most efficiently performed on a Space Station. Concurrent component development tests will also produce sections of solar collector structure.

The second objective element is designated as Pilot Plant I and is intended to act as the basis for deciding in 1987 on future SPS development. It involves (1) fabrication and assembly of a 2.2-MW solar array, (2) fabrication and assembly of a 1.7-MW_{RF} microwave antenna, and (3) orbit-to-orbit and orbit-to-ground testing. Pilot Plant I is intended to provide an early demonstration of

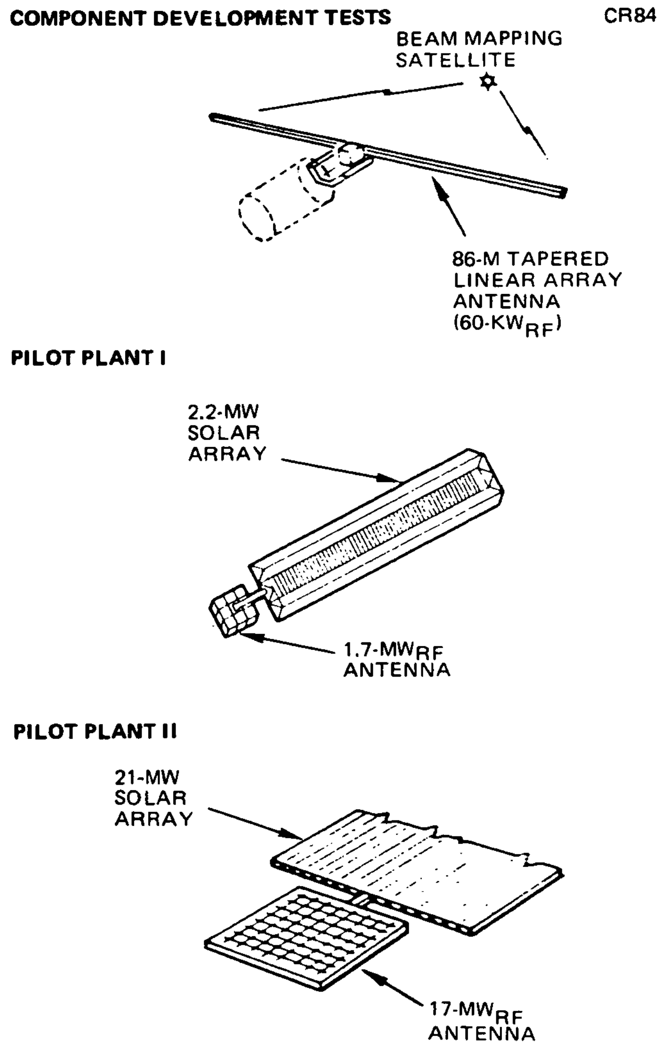


Figure 1. Satellite Power System Objective Elements

concept feasibility and engineering data for the SPS prototype design upon which future design and cost estimates can be firmly based.

The third objective element, Pilot Plant II, would be a first step in development of an operational system and involves the fabrication, construction, and test of a 17-MW_{RF} pilot plant. Pilot Plant II is a "partial prototype" of the SPS and is constructed using a construction base that demonstrates prototype production methods and processes and develops construction, operation, and repair procedures by experience under realistic conditions.

2.2 NUCLEAR ENERGY

Implementing an orbiting nuclear power station involves extremely large structures; thus, a long-term manned presence, such as a Space Station System provides, appears to be mandatory to construct such a facility.

Of necessity, siting a nuclear plant in orbit will require the generation of at least twice the power of an equivalent ground-based plant. This results from the inefficiencies of the microwave transmission to ground and the added losses from widely distributing the large blocks of power.

Comparisons using Boeing estimates and American Nuclear Society data indicate that costs of delivered power, taking into account the larger power plant noted above and the high costs of space transportation and operations, will be much higher than could be obtained from an equivalent ground-based plant. Table 1 presents comparative data on power plant costs. In addition, the weight on orbit of a breeder reactor plant will probably be on the order of three to four times that of an equivalent solar photovoltaic plant.

Table 1. Plant Cost Comparison (1985)

Plant Type		1985 Cost ($/kW)
Space-Based Nuclear Plant*		8,169
Power Satellite	4,713	
Transportation	2,925	
Rectennas	289	
Miscellaneous	242	
Coal-Fired Plant**		
High-Sulfur Coal		650
Low-Sulfur Coal		910
Ground-Based Nuclear Plant** (Nonbreeder)		1,005

*Data from Boeing/MSFC Study escalated from 1976 to 1985 dollars at 4% per year – 62 unit program (includes 2% DDT&E)
**Data from Americal Nuclear Society Publication, "Q&A Nuclear Power and the Environment"

Although several foreign countries have operational breeder reactors, progress on developing a commercial plant of this type in the USA is lagging, and a decision on commercialization from the Energy Research and Development Administration is not expected before the late 1980's.

Adequate ground demonstration of the breeder concept selected for space and resolution of the issues raised by space siting seem certain to delay construction of a pilot plant until the 1990's. Fortunately, the bulk of the work devoted to an SPS will apply directly or supportively (e.g., large-scale construction techniques) to nuclear energy as well. It is believed that those specific component and technology tests suitable for an earlier time frame can be accommodated by minimal modular addition to an SPS-oriented Space Station option.

Thus a Space Station program that does not explicitly include nuclear energy can still be expected to have sufficient flexibility to allow redirection to nuclear energy when and if a rational decision to include it is made. Therefore, nuclear energy is not recommended as an early candidate objective.

2.3 EARTH SERVICES

Radiometry (primarily from aircraft) and communication and navigation aids from space are current state-of-the-art achievements. It appears, however, that capabilities in these areas can be greatly enhanced in an economic manner through use of large, high-gain antennas.

However, as antennas increase in size, allowable structural tolerances and distortions diminish, and on-orbit fabrication of these antennas appears to be necessary. The Space Station will provide this capability and can support subsequent testing. Thus, in the broad field of earth services (from space), the Space Station can play an important role.

An analysis was made to determine the limiting size (diameter) of antennas that are unfurled. The primary problem in deploying large antennas is maintaining structural tolerances or distortion; accordingly, this parameter was investigated. Using available data on two deployable antennas (Figure 2), distortion vs diameter was plotted with the two sets of data being such that a smooth transition from one set of data to the other is possible. Assuming these curves to be representative of the accuracy that can be realized in deployable antennas, achievable gain was calculated and an S-band example plotted. As can be seen, the effect of distortion is to lower gain significantly at large apertures indicat-

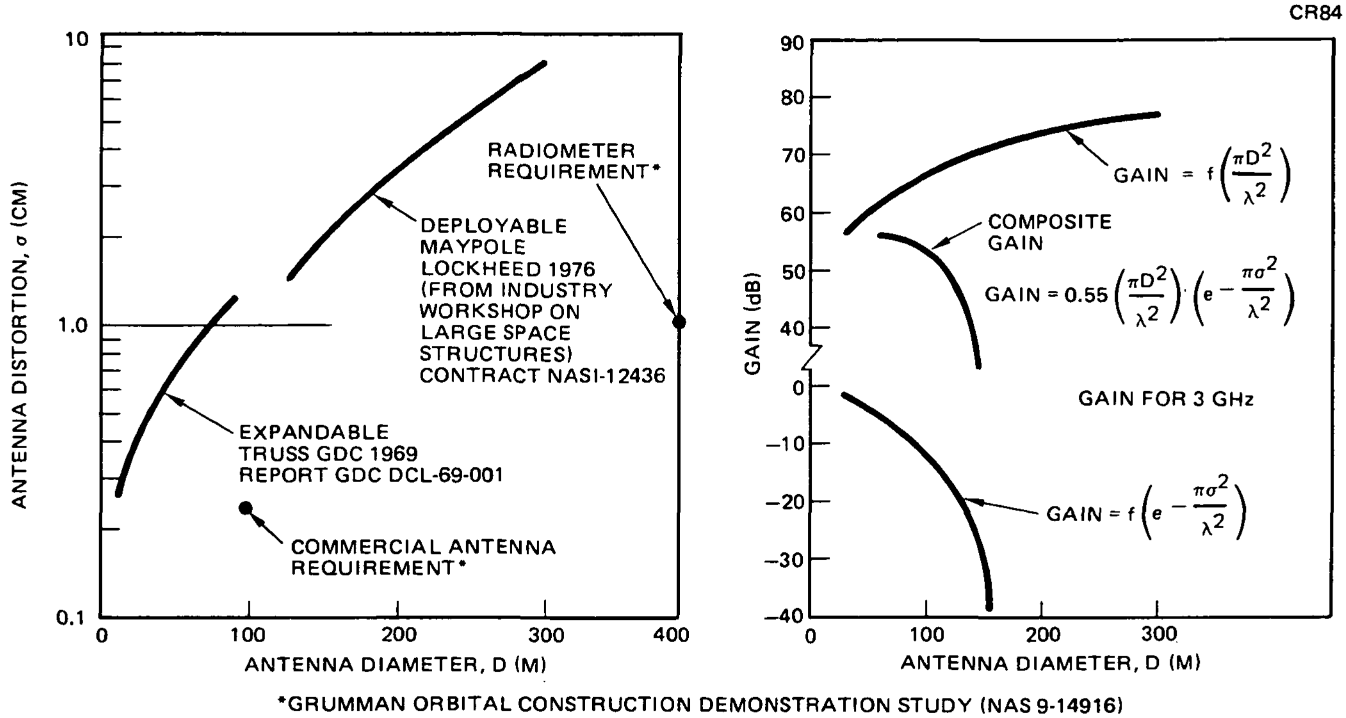


Figure 2. Earth Services Impact of Distortion on Gain of Unfurled Antennas

ing (in the example) that, for antennas greater than about 60m in diameter, new approaches (such as on-orbit construction coupled with use of materials with very low coefficients of expansion) are required. To provide a "distortion margin" of 2, antennas 30m in diameter and larger probably should be assembled on orbit rather than unfurled.

The initial development of antennas and verification of construction and assembly techniques on the Space Station center about a low-resolution radiometer 30m in diameter, a size considered the minimum which requires on-orbit construction. Development continues on increasing sizes of antennas up to a 300m antenna which provides a high-resolution capability for radiometry.

Other types of antennas need to be evaluated. Accordingly, an active antenna, the multibeam lens antenna, and an extremely large, 3.25 km-communication antenna were included in the MDAC analysis of this objective area. Antenna configuration analysis and definition studies were performed to establish a firm basis for Space Station requirements.

The multiple-beam lens antenna system provides high gain for point-to-point communications. The beams are focused through 1,000 cylinders of 4.6 cm diameter, assembled in a structure of 27m diameter. The antenna was sized to service 100,000 post offices, sending 10 pages of data per second, and had the capability of 1,000 simultaneous beams.

The cross-phased array navigation antenna was conceived to provide navigational fixes with a relative accuracy of ±90m. The antenna would produce two extremely narrow beams swept orthogonally, which could indicate location, heading, and speed on very small portable ground devices. The cross-phased array consists of an extremely long series of modules. Radio-frequency energy is distributed to each module by use of a low-loss beam waveguide having a succession of shaped reflectors. Energy is extracted through a slot in the reflectors. The phase of the radiation elements would be controlled by hardwire from a central control unit.

The parabolic antennas used for radiometry would focus small signal emissions in the lower frequency spectrum. The parabolic antenna will consist of a built-up truss structure, to give the necessary stiffness, and an appropriate reflector such as a wire mesh. Graphite epoxy is used as the structural material to meet the extremely small structural distortion limits which must be maintained at the frequencies of interest.

2.4 SPACE COSMOLOGICAL RESEARCH AND DEVELOPMENT

Answers to basic questions regarding the galactic processes, the nature of quasars, the nature of stellar explosions, the composition and dynamics of interstellar matter, the search for other planets and solar systems, and the search for extraterrestrial life requires access to the full electromagnetic spectrum. While certain regions of the spectrum are accessible to earth-based systems, space platforms offer observational advantages in the x-ray, UV, parts of the IR (see sensor development discussion), and in the low-RF portions of the spectrum. In the RF regions in particular, the need for very large antenna structures requires space assembly and construction.

By using an antenna system in space, for example, water absorption bands can be eliminated and the detailed study of planetary surfaces – especially surface compositional studies complementing measurements made in the visible and near-IR regions of the spectrum – can be carried out to a greater degree of resolution. Geochemical mapping of the planets and their satellites might also be carried out.

The Space System objective identified for consideration in this study was to produce a highly useful radiotelescope while developing the technology for space-based astronomy at the longer (RF) wave lengths. This objective has three elements.

The first phase deals with the Component Development and Test activity and involves system analysis and prototype construction of advanced electronic instruments, such as receivers and data processors for use on the ground.

In the intermediate phase, activities are planned which will use space systems as well as earth-based radiotelescopes. The Mark II system identified in the Ames *Search of Extraterrestrial Intelligence Study* (SETI) activity was selected as the model for the Space Station system requirements analysis for the intermediate phase activities. During this phase, the R&D emphasis will be directed toward solution of the electronic problems (i.e., low-noise amplifiers, scanning feeds, pattern recognition data processors) which will be directly applicable to very large-scale and ultraprecision electromagnetic collectors (300 to 3,000m in diameter with surface accuracies of 1 mm overall). Work will concentrate on thermal stabilization, lightweight materials, construction techniques, assembly methods, pointing and control methods, active figure of merit correction schemes, etc. A primary problem to be solved is control of surface accuracy. On-orbit construction should help eliminate distortion problems associated with unfurling antennas. However, complementary techniques such as electronic scanning will be required to enhance effective surface accuracy.

The third step is testing the telescope at geosynchronous orbit (GEO). An unmanned Orbiter transfer vehicle (OTV) is required to transport the telescope to GEO for these operations. The ultimate goal of this objective is to develop the technology for even larger radiotelescopes in space; thus, of equal importance is the requirement to demonstrate that such hardware can be successfully constructed and operated in orbit.

Figure 3 shows several projected systems on a wavelength/aperture plot, indicating probable space-based requirements. The radioastronomy window wavelengths (from 10 cm to 10m) are generally lacking as requirements on the chart because these observations are currently being made from ground observatories. The Outlook for Space System 1055 is the one exception in this window. However, this system is the space component of a ground-based interferometer of very long wavelength. In this case, a 10m microwave telescope is carried in a highly eccentric orbit to extend the baseline to several earth radii; the purpose is to obtain milli-arcsec resolution of radio sources.

The SETI Mark II radiotelescope is a slightly smaller version of OFS System 1073. It operates in the 300 GHz region of the spectrum and re-

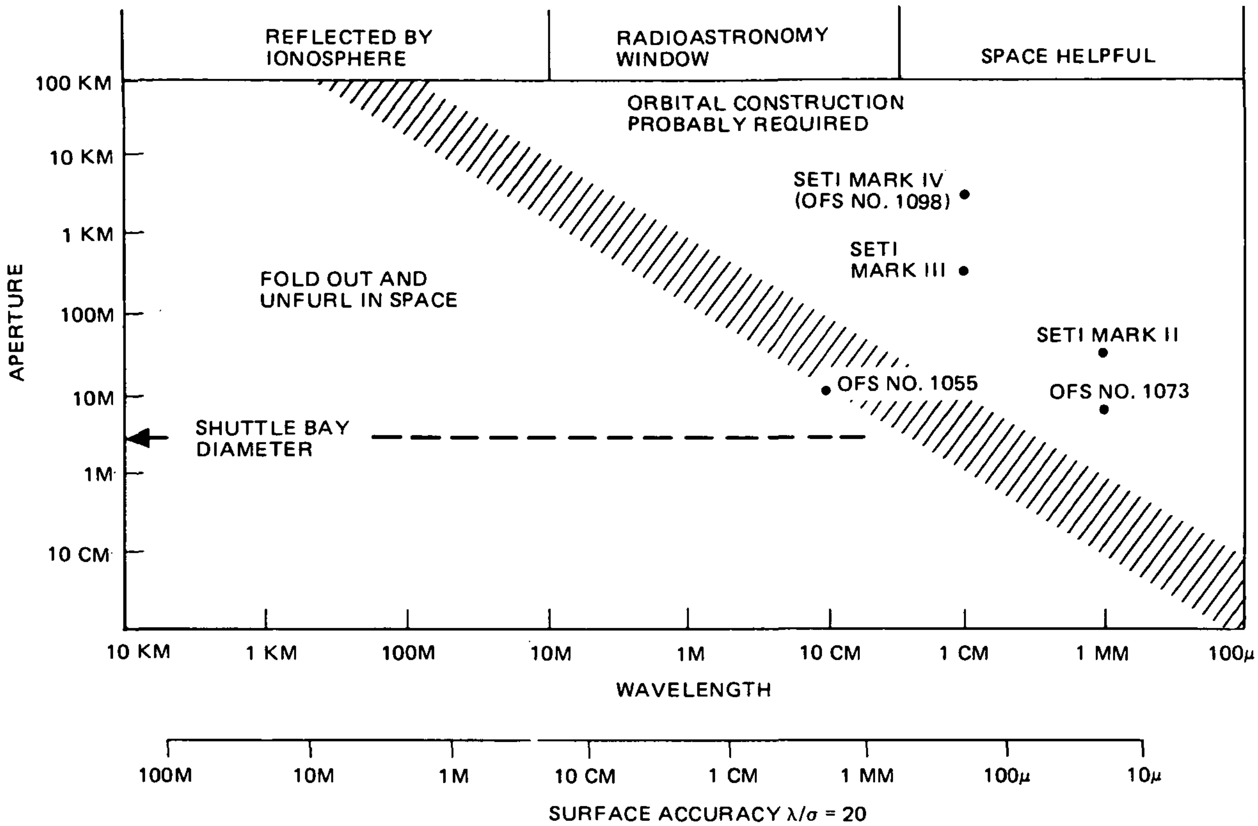


Figure 3. Radio-Frequency Antennas in Space

quires a primary collector surface accuracy of 50 microns. To achieve this degree of precision, advanced techniques for on-orbit construction must be employed, including in-space adjustment of the primary and secondary optical figure.

The Mark IV system is taken as being representative of the general intent of Outlook for Space System 1098. The two smaller-scale instruments are considered in present SETI planning to be essential R&D building blocks to advance to the state-of-the-art required by the Mark IV system. The steps in this advance are indicated on the chart.

2.5 SPACE PROCESSING

The long-term, reduced-gravity environment experienced on a space platform minimizes or eliminates gravity-induced phenomena (e.g., convection) that hamper or preclude specific processes from taking place on earth. Likewise, containerless processes, such as levitated melting and heat treating, can eliminate contamination introduced by the crucible on earth. There are no other viable alternatives using ground-based facilities.

The potential market for new products of commercial interest such as silicon ribbon, ultrapure glasses, and pharmaceutical and biological materials (e.g., the enzyme urokinase) is significant. When potential products of commercial value are identified during fundamental science investigations they can be introduced and the Space Station system can support their development as commercial products. The objectives elements associated with this objective are intended to result in the Space Station having an industrial-oriented capability.

The initial space processing objective element (a Process Development and Testing phase) is an early activity (1984) to demonstrate the economic feasibility of the basic processes involved in biologicals, inorganics, and silicon ribbon manufacture. A portion of a laboratory module is used to accomplish this activity with the specialized equipment as noted.

The next phase of activity (the Process Optimization for Production), circa 1987, is aimed at refining the biological and inorganic processes for volume (continuous) production. Separate dedicated modules are provided for biologicals and inorganics for this level of activity.

The Commercial Process Pilot Plant is a continuous, high-production rate facility that produces material for commercial markets. A separate dedicated facility may be required for each product line.

Note that commercial inorganic processing refers to single crystals, metal oxides, and matrix and composite materials where essentially the basic elements and inorganic compounds are the raw materials. Biological materials refer to working with living matter. Organic materials, i.e., carbon compounds, have not been prominent in space processing proposals to date although this important class of substances could be the subject of future space activities.

Requirements for space processing differ by the type of product facility. Biological requirements are characterized by maintenance of an ambient environment necessary to support various forms of living materials and live processing. This environment is in contrast to the second class of processing which requires elevated temperatures and pressures necessary to effect phase changes in materials such as glasses, metals, and ceramics. Temperatures in these processes typically range from 1,000° to as high as 3,000°C. The third class of processing requirements is characterized by dedicated facilities where the procedures are automated to the extent that routine operations are maintained on a continuous basis. Figure 4 summarizes pertinent data on these processes. The early Space Station R&D role is predominantly associated with the first two classes of requirements.

An orderly progression of development activity (e.g., biological processing) is envisioned. Early R&D activities include design verification of the central processor by experiments aboard Shuttle and Spacelab flights, and human support in the

CR 84

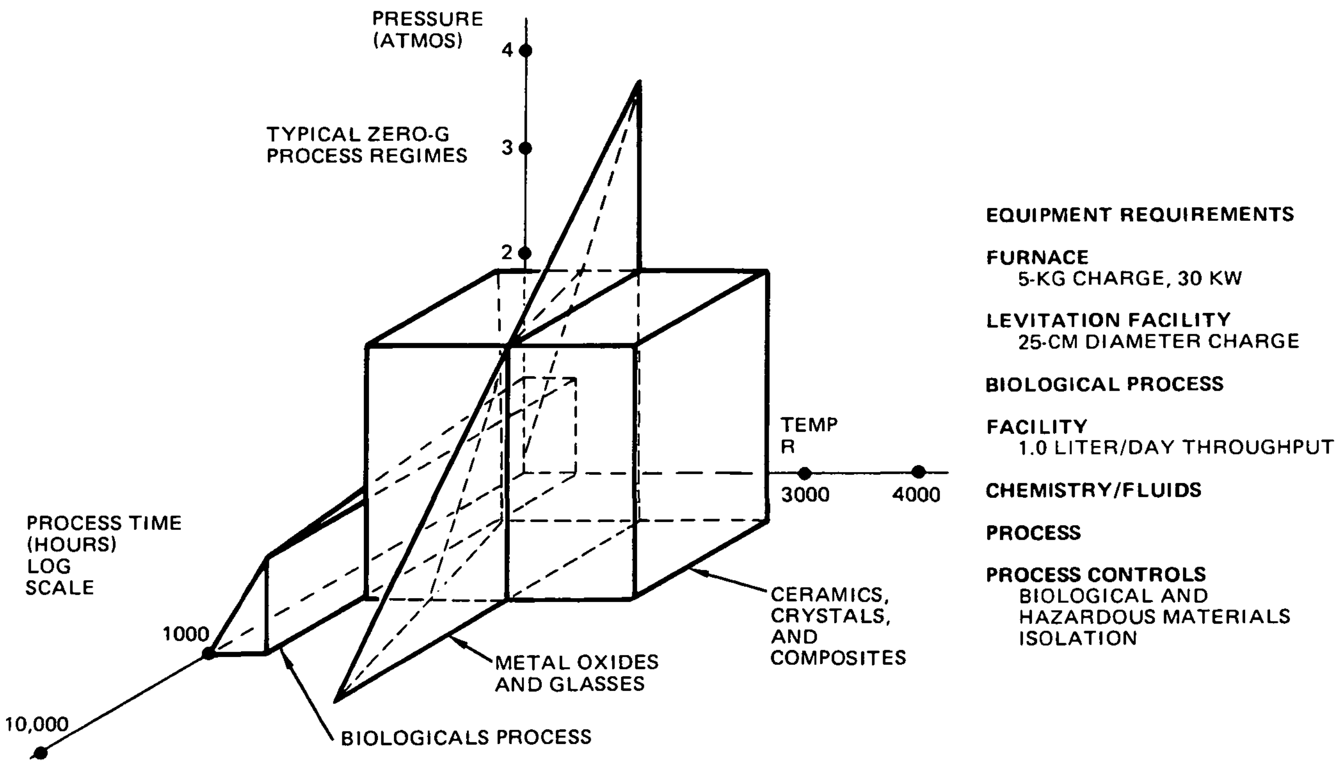


Figure 4. Space Processing Pressure, Temperature, and Process Time Envelopes for Different Classes of Materials

process. Procedures that cannot be accommodated in an early automated facility deal primarily with preprocessing and postprocessing of experimental materials to assure maximum postflight utility. For example, it may be desirable to use specific cells collected from ground-based experimental animals immediately preceding the experiment; however, these cells cannot easily be maintained in a viable condition during delays normally encountered in prelaunch, launch, and preoperational activities. A manned laboratory could use an animal-holding facility in space. The evolution of a biological space processing capability from a Spacelab to a Space Station, then, will be one of scale – a quantitative increase in complexity rather than a qualitative change.

Types of equipment needed for space processing work on the Space Station include a furnace facility, containerless process facility, biological process facility, chem/fluid process facility and control, and data acquisition services.

The major facilities should be designed for modular replacement of apparatus within a facility as the research or production emphasis changes. With the prospect of 100-day mission times, the five major facilities indicated will require some in-flight apparatus changeout and some recalibration. Human engineering of the equipment and crew skills should take this into account.

2.6 CLUSTER SUPPORT SYSTEM

The cluster concept is one in which a large space platform can supply power (and other utility services) to a variety of users. As an example, the role of the Space Station is one of constructing the platform (primarily the power system) and then supporting subsequent test activities and operations. For a satellite cluster, appropriate sensors, RF transmitters, and antennas are attached to form the cluster. In the test mode, these will be operated with ground transmit/receive stations, truth sites, etc, to verify operation. Other utility services could also be provided (i.e., thermal control, data processing, attitude control, etc) by the space platform.

An analysis of the satellite traffic projected in the *Outlook for Space* revealed an average of approximately 100 satellites on orbit in the period of interest (assuming a 7-year lifetime). Considerations of pointing, interference, location, etc indicated 10 satellites per cluster to be an upward limit. Analysis of existing satellite power requirements suggested that the space platform should provide 30 kW of power to the cluster. Analysis indicated that this could best be provided by a Multiple-Purpose Space Power Platform (MSPP) consisting of a separate stabilization and control system and a gimballed, photovoltaic solar array. The 30 kW figure also is compatible with early Space Station needs, and thus the MSPP design could act as the early Space Station power module. It also could be used as an auxiliary power source for sortie missions.

The concept of providing electrical power to satellites via electromagnetic (microwave or laser) transmission was evaluated. For antenna sizes of less than 100m a transmission range of 1 km or less is required. Clearly the antenna size is too large (much larger than the solar panels that would be mounted on the satellite to produce the required power) and the range capability too short to be effective. Using a laser transmission system, the antenna size is more reasonable (<3m diameter for up to 100-km range). However, the system efficiency is very low (1/13 to 1/33 that of the satellite-mounted solar panel system) and the energy-conversion system (laser-to-electrical) needed on the satellite is at least equal in weight to the system it is intended to replace. Therefore, the concept of transmitting power to orbiting satellites was discarded as a cluster capability.

Another facet of the cluster concept is to supply power to an on-orbit OTV via laser transmission of energy. The development of this system requires operation in a low-g environment, so palletized tests are necessary. The ultimate demonstration of the laser-powered OTV requires a large power source and a vehicle with a laser-operated propulsion system. The energy would be transmitted from the pilot plant by means of a 30m-diameter laser antenna system to an OTV. The OTV would have a collector lens which would focus the laser beam through a laser-transparent window such that the propellant (e.g., cesium) is heated to high temperatures, resulting in a high specific impulse.

The space-based cluster concept is predicated on economic saving accrued by using a central facility to provide power service to a number of potential users. Using the satellite traffic from the *Outlook for Space* and detailed information available on similar satellites, the weight and cost associated with satellite power supply were estimated (see Figure 5). The results indicated that for the traffic model, approximately $600M would be required to be invested in power system recurring costs (nonrecurring would be three to five times recurring). Costs associated with delivering the power supply portion of the satellites (weight to orbit) were estimated to be $578M. Thus, significant budget for development and deployment of cluster hardware should be available. However, it should be noted that the development cost of the 30-kW cluster is estimated to be $300M, with unit recurring costs of $200M. The cluster module also can serve as Space Station power module, supporting performance of the needed R&D tests for cluster concept growth and for activities of other objectives.

2.7 DEPOT

The depot objective is to demonstrate the value of a manned depot function by implementing such a system for delivery of small satellites to geosynchronous orbit.

There are three R&D areas where on-orbit activities are needed. The first is demonstration of long-term propellant storage and transfer. Techniques are in an advanced stage of R&D and no major technology problems are envisioned; on-orbit test is needed, however, to develop engineering data for design. The same holds true for the other two

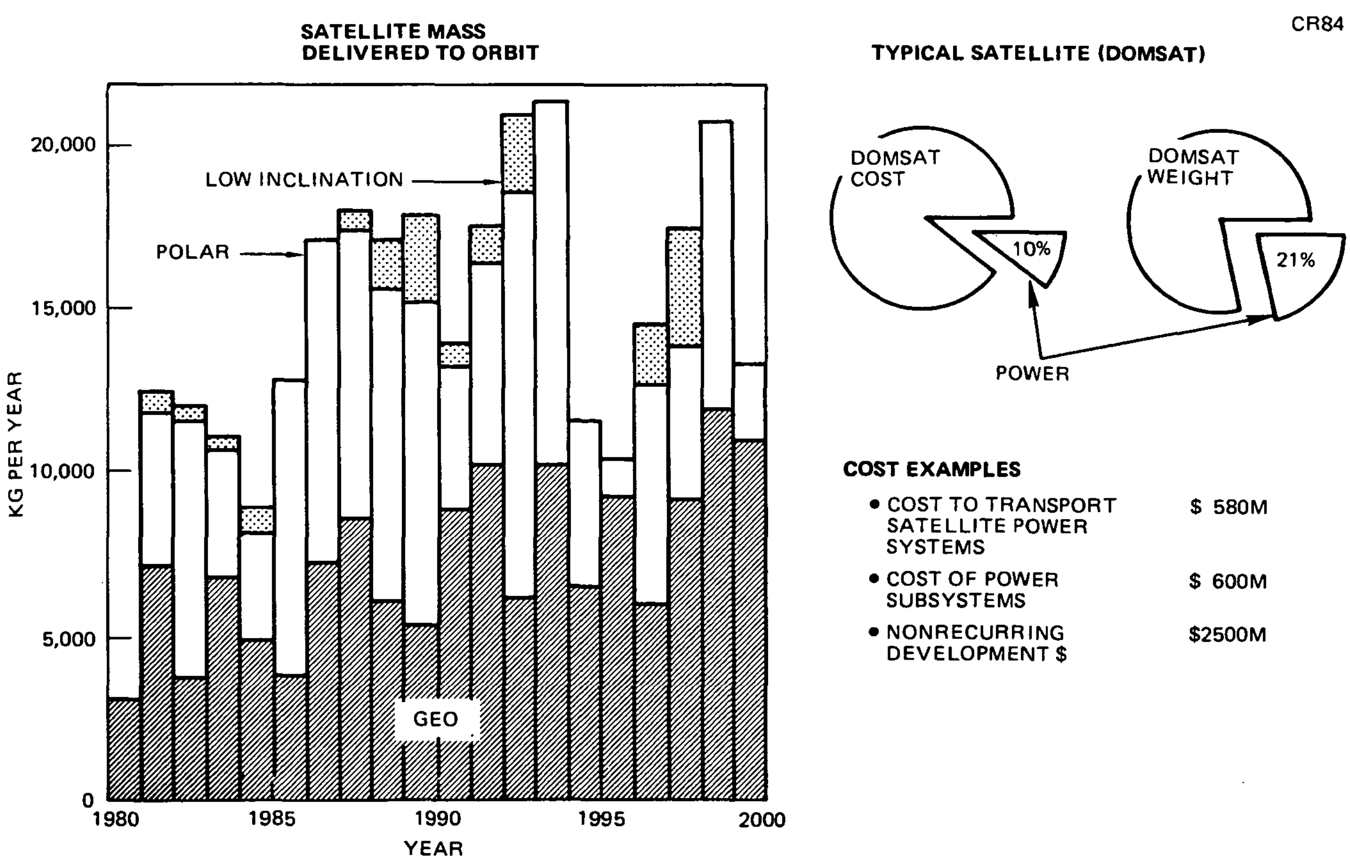


Figure 5. Cost Considerations for the MSPP

areas requiring on-orbit testing, orbital maintenance and repair operations, and precise handling of payloads and the OTV.

Development of engineering data for the depot concept requires a palletized test setup in which one-tenth scale (2,250 kg propellant storage capability) tanks can be added or removed on orbit to test tank changeout systems and techniques. The test setup should also have provisions for pressurization of the tanks and periodic transfer of fuel from one to another. Several transfer tests are needed with the tanks allowed to reach equilibrium between each transfer. Each tank should be changed out at least once. Development of maintenance and repair techniques will require partial mockups of OTV systems and will use a laboratory or a laboratory support module for conduct of operations such as development of engine changeout procedures.

The demonstration of the depot concept requires an on-orbit capability to receive and store payloads and propellant. An OTV is needed with appropriate capability to mate payloads (probably two at a time) to the OTV, fuel the OTV, and check out and launch the combination. Recovery of the OTV also is required. Since a number of other objectives require a large OTV, the capability to handle large-payload vehicles also is needed.

Eventually it can be anticipated that the depot concept will evolve into a facility supporting the assembly, launch, and recovery of interplanetary vehicles. Scientific payloads such as the Mars sample-return mission are quite complex and the depot concept offers considerable potential to support this type of mission.

The potential savings of a depot are reflected in the reduced operational costs that would accrue. For a program consisting of placing ten 1,800-kg satellites at GEO per year, the relative yearly operational costs for a cryogenic tug, storable interim upper stage (IUS), and a depot-serviced cryogenic OTV* are shown in Figure 6.

The costs for the cryogenic Tug were taken from the *Space Tug Systems Study (Cryogenic)* which MDAC did for the Marshall Space Flight Center in

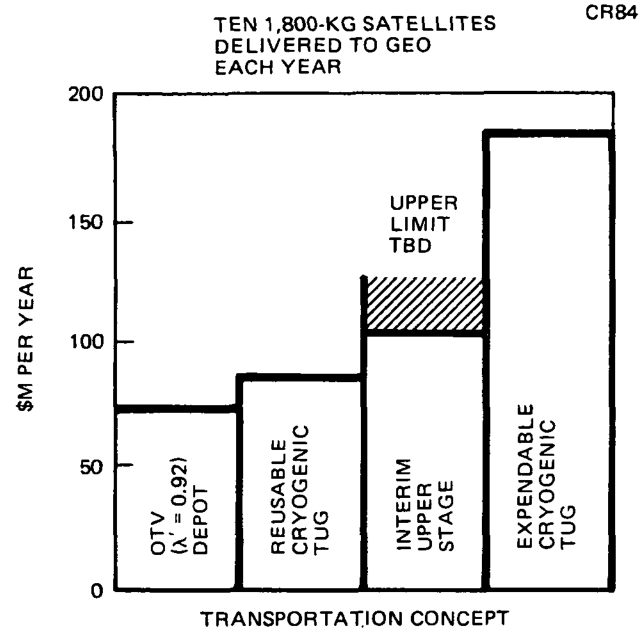


Figure 6. Operational Costs

1974. The IUS costs were assumed to be a minimum of $1.5M per flight, based on current design goals and the Boeing IUS study. The depot costs were developed from a determination of on-orbit crew requirements and the costs of training and maintaining them, the cost of the supporting ground crew, crew transportation and supporting ground crew, crew transportation and supplies, crew wages, and propellant delivery costs. The depot-supported OTV would result in a 13% savings in yearly operating cost over the Shuttle-delivered reusable tug, its closest competitor.

The depot implementation cost is in the range of $558M to $667M. The cost of developing and building two small OTV's is in the range of $250M to $300M. Assuming the depot would replace the IUS, the time needed to recoup this investment for a rate of 15 flights per year, is from nine to eleven years. These potential savings are marginal in justifying a depot. Higher traffic rates, commensurate with the implementation of a major objective

*In developing these data, a lightweight OTV concept was used. This concept was based on the cryogenic tug design modified to take advantage of the reduced design loads resulting from not having to withstand the Shuttle launch (and abort) environment. A zero-NPSH propulsion system allowed reduction in tank structural weight. Thrust was limited so that no accelerations over 0.1g would be experienced; stage weight dropped accordingly. Also, new lightweight composites were used. Trends in electronic system weight were extrapolated for further weight reduction.

such as SPS, however, clearly justify the development of the depot concept.

2.8 MULTIDISCIPLINE SCIENCE LABORATORY (MDSL)

There are two objective elements that support the Multidiscipline Science Laboratory (MDSL) objective. Since this objective is aimed at conducting research in space relating to the basic sciences, the two objective elements were simply defined at two different manpower levels. The lower level was considered reasonable as a minimum to get useful information; at the higher level, the prime consideration was keeping the total crew to a realistic number.

The initial capability for the above is provided by Spacelab modules adapted to the Space Station early in the program, with a later inclusion of an MDSL module tailored specifically to Space Station uses. Pallets are Spacelab types modified as necessary.

The basic concept of the MDSL is that it should provide general laboratory services; objective-peculiar or experiment-peculiar equipment is included as necessary and is charged to the program in question. Equipment items in the MDSL inventory might include the following:

Hard-Data Processing Facility. Film processors and storage, video data display and control console, microfilmer, light table, spectrophotometer, densitometer, and operations console.

Electronic/Electrical Laboratory. Instrumented test bench, battery charger, high-voltage source, high-energy-counter calibration equipment, and glove box.

Experiment and Test Isolation Laboratory. Hazard detection system; electrical and vacuum power center/hydraulic/pneumatic work station; cryogenic, fluid, and high-pressure gas storage; airlock; chemistry and physics glove box; and analysis and storage unit.

Optical Sciences Laboratory. Optical work station, microdensitometer, monochromatic spectrometer, modulation transfer-function measurement system, optical spectrum analyzer, airlock, and optical window.

Mechanical Laboratory. X-ray diffraction unit, experiment and isolation test panel, laminar-flow glove box, specimen tester, metallographic tester and microscope, thermostructural test equipment, and X-ray generator.

Biomedical/Bioscience Laboratory. Biochemical and biophysical analysis unit, bicycle ergometer, lower body negative-pressure device, and body mass measuring device.

Data Evaluation Facility. Multiformat viewer editor, microfilm retrieval system, film reader, copy machine, stereo viewer, image processing and data management control station, working image, permanent video and digital storage, time reference unit, TV camera control, video tape, printer, and scientific computer.

Figure 7 compares the effectiveness in accomplishing identical missions with alternative space platforms. In deriving the data, a typical multidiscipline research program used in the Phase B Space Station Study served as the model. The product of man-hours and equipment pounds required in orbit was used as the basic index of productivity. The reference program required a productivity index of 1,392 x 10^6 man-hour pounds

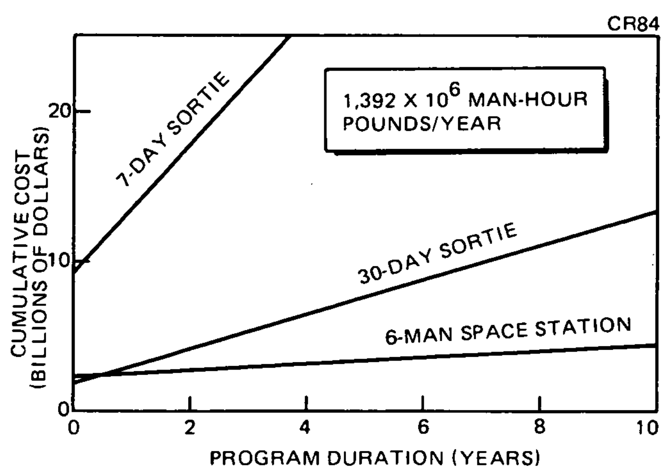


Figure 7. MDSL Cumulative Program Costs

(mhp) for its accomplishment (typical of a six-man Space Station).

To compare costs between sortie missions and Space Station operation, we assumed that a six-man Space Station was employed to maximum capacity (estimated to be 696 x 10^6 mhp per year) and compared its cost to that of sortie missions working to the same level. Sortie missions of seven days and longer were included. As sortie mission time extends, available manpower increases; however, the payload available decreases (more weight must go into consumables). The product of sortie manpower and available payload weight peaks at a 30-day mission; thus this duration was also considered. Space Station costs were taken from the Phase B study with an inflation factor to produce an estimate in 1976 dollars. A three-Orbiter fleet, capable of 15-day turnarounds, was assumed. Additional Orbiters and Spacelabs were assumed to cost \$300M and \$42M each, respectively. Operationally, it was assumed that Orbiter flights cost \$17.25M each and no additional facilities were required for the maximum use (229 flights per year). Since each program was assumed to accomplish the same orbital research program, no research equipment costs were included.

The most significant conclusion that can be reached from data of this type is that justification of the Space Station does not depend upon a unique mission capability (long duration, large electrical power capacity, etc). Rather, its fundamental efficiency allows considerable cost advantage even when the missions could be accomplished by a series of Orbiter or Spacelab sorties.

2.9 SENSOR DEVELOPMENT

Optical sensors provide essential data for both earth-oriented observations and astronomical research. When coupled with the viewing vantage point of a space platform, vast improvements in observational programs can be realized. The attenuation of the earth's atmosphere limits outward viewing primarily to the visible portion of the spectrum (4000 to 8000Å) and to portions of the radio region of the spectrum (1 cm to 10m). The infrared is transmitted through the atmosphere only in fragmented bands. For advancement in astronomy, and to further our understanding of cosmological processes, it is essential that observational opportunities be expanded by placing optical instruments, covering the IR to extreme UV portions of the spectrum, above the earth's atmosphere. Figure 8 summarizes data on observations as function of contamination.

There are a number of sensors used for earth-oriented observations and used for astronomical observations in the IR, visible, and UV portions of the spectrum that would profit from orbit-based support. As an example, long-wavelength infrared (LWIR) sensors are extremely difficult to test and calibrate on earth. Such sensors must be mounted in a cold chamber, simulating the space environment to reduce background photon flux. In such a chamber, it is difficult to mount a gimbal and simulate scanning and tracking against a calibrated blackbody source. Such testing and calibration usually requires months in ground simulation facilities and are costly.

It is potentially feasible to test and calibrate these sensors on a Space Station under ideal dynamic conditions that duplicate the final operational and environmental conditions. IR sensors for earth-oriented as well as for astronomical use could be tested in this fashion.

In space, many natural targets (stars, galaxies, etc) emit radiations over large spectral regions. These radiations can be calibrated and separated spectrally to be monitored and used as radiation standards for calibration instruments involving spectrographic measurements. Using natural standards would greatly simplify calibration and would decrease considerably the calibration equipment and sources required.

Other functions that might be performed in space include the following:

A. Assembly of and servicing sensors for:
- Remote sensing and earth resource satellites
- Atmospheric sounding satellites
- Astronomical telescopes

ORBITER EFFLUENTS

SOURCE	AVERAGE RATE	PRINCIPAL CONSTITUENTS
VERNIER CONTROL SYSTEM	1.06 KG/HR (1)	H_2O, N_2, CO, CO_2, H_2, NO
REACTION CONTROL SYSTEM	16.6/STAR SIGHT (2)	SAME AS VCS
FLASH EVAPORATOR	10.9 KG/HR (3)	H_2O
TRASH H_2O	0.02 KG/HR (4)	H_2O
CABIN ATMOS LEAKAGE	0.16 KG/HR (3)	N_2, O_2, CO_2
OUTGASSING	0.004 KG/HR (3)	POLYMETHYL SILOXANES

(1) NASA JSC PROGRAM H4R RSC

(2) MDC G6367 DOD STS PAYLOAD INTERFACE SUPPORT STUDY

(3) MARTIN MARIETTA ORBITER CONTAMINATION CONTROL STUDY MCR-76-12

(4) RI (INFORMAL DATA)

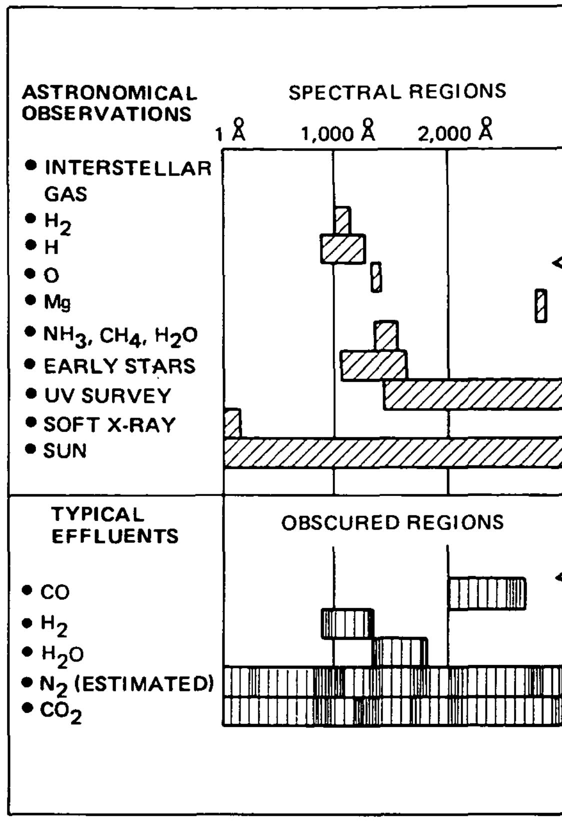


Figure 8. Considerations for Sensor Operation

B. Testing of LWIR sensors where cryogenic backgrounds and remote sources are available.

C. Manufacture of sensor or telescope mirrors, crystal growth, filter coatings, deposition phototubes, detectors, and arrays where high vacuum is needed.

The initial element in a sensor development program would be to provide a facility for the development and test of optical sensors.

In a second-generation or growth station the potential for the actual production of sensors on orbit might evolve. A production facility might include an optical fabrication shop; a clean, pressurized manned laboratory; a clean vacuum laboratory; and a pallet for final assembly or mounting of sensors and instrumentation.

The vacuum laboratory might include facilities for vacuum deposition, preparation of optical coatings, detector assembly, etc. It has been suggested that melting glass and forming glass lenses and mirrors with greatly improved optical characteristics are possible in the zero-g environment. If this proves feasible and if electrical energy supply is limited, melting of glass might require the installation of a large solar collector and the construction of a solar furnace.

2.10 LIVING AND WORKING IN SPACE

Three primary goals are associated with this objective:

A. To better understand physiological problems which degrade performance and/or physical health and processes, and to develop methods of controlling or counteracting them.

B. To establish the capability for long-duration space flight of up to 720 days. This would be done in increments on many subjects and would require 5 to 10 years to complete.

C. To optimize man's on-orbit productivity through determining his capabilities and then providing the environment, tools, work cycles, etc, that allow maximum exploitation of man's capabilities.

The functional requirements imposed on the Space Station are geared to address these goals. In addition, a continuing goal of the living and working in space objective is to support all manned activities to assure continued high levels of performance. This goal includes basic health care and health maintenance procedures.

The Living and Working in Space Objective provides for sequential, progressively more sophisticated, collection of data on the ability of man to tolerate prolonged space flight and on his productive capability in support of other Space Station objectives.

The initial element in a program of long duration would represent an early minimodule approach to the conduct of life sciences research. Its purpose would be to verify and extend the research on biological systems previously performed during Spacelab missions.

The second element in a long-duration program would include a Space Station module dedicated to more extensive research necessary to biomedically qualify man for prolonged orbital tours of duty, to the development of medically indicated countermeasures (conditioning devices), and to the orbital qualification of IVA/EVA tools and the restraints necessary to enhance man's productivity during later fabrication and assembly operations.

To permit EVA tool demonstrations, an airlock will be required which will also serve as a recompression chamber.

The final element would include the orbital examination of manned fabrication and assembly techniques and assumes that man has essentially been qualified for prolonged stays in space. This objective element will investigate sophisticated tools for IVA/EVA, as well as the orbital demonstration of manned maneuvering devices oriented toward augmenting large construction base operations. Studies will be addressed to the efficiency of proposed operational techniques to be employed during later operational phases of manned space activity.

The Space Station's inherent ability to provide a long-duration platform for R&D investigations can produce considerable savings over shorter Spacelab operations. (See Figure 9.) These savings are primarily related to transportation costs due to (1) fewer flights necessary to accomplish a specific amount of research, (2) longer crew times on orbit per duty period, and (3) greater crew career time on orbit. These features of Space Stations must be exploited to obtain maximum benefits to the

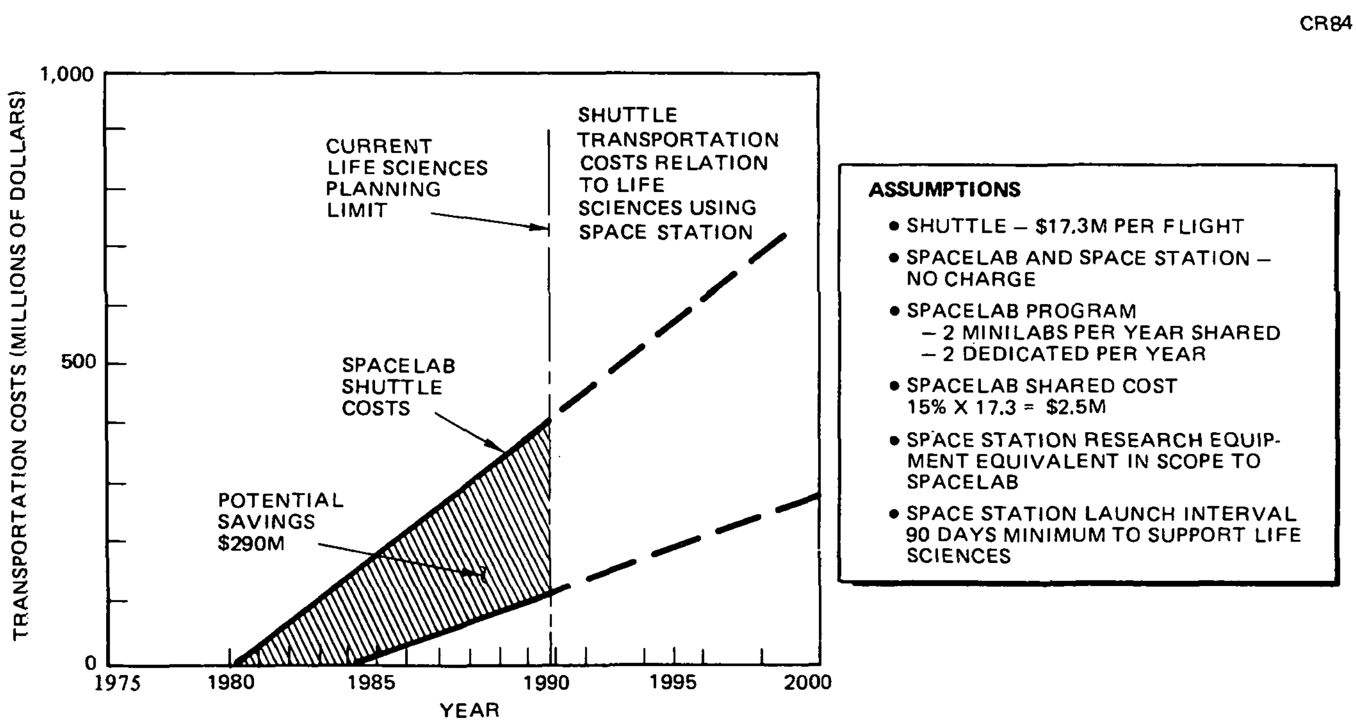


Figure 9. Space Station Versus Spacelab Costs for Life Sciences Research

objectives and should be considered operational requirements for the station.

2.11 CONSIDERATIONS IN COMBINING OBJECTIVES INTO PROGRAM OPTIONS

The objectives considered in program options were all selected because of their potential utilization of a Space Station and their overall value in contributing toward satisfying a basic need or goal of mankind. Each objective was examined individually to derive requirements and to identify the objective elements which should be addressed. An examination of these objectives on a collective basis revealed further information important to the establishment of program options. It was determined that some objective elements are fundamental and should be in all options (e.g., the living and working in space activities). In other cases, requirements clearly conflict. Resolution of these conflicts is possible. However, where activities are to be performed in different orbits, more detailed trade studies are needed before a Space Station system can be derived that can handle them in the optimum fashion.

Another aspect of this examination of objectives on a collective basis revealed areas where objectives could be combined (requirements or required/provided capabilities overlap) to help optimize operations. Also revealed were areas where combined capabilities could, in turn, provide new capabilities. As an example, the Depot and MDSL can combine to support planetary missions.

One of the primary requirements identified in the analysis of the selected objectives was the need for the Space Station to support on-orbit construction. The alternative to on-orbit construction would be deployment from the Shuttle. The determination of what structures should be deployed vs constructed on orbit involves consideration of: allowable tolerances (tolerances on unfurled structures become difficult to control as size increases), total weight (structures weighing more than the Shuttle payload delivery capability require some form of on-orbit assembly or construction), manpower and logistics costs (as structures become larger, the total cost of transporting men and machinery in a sortie mode eventually exceeds that associated with providing a permanent capability on orbit), and type of structure involved (rugged, stiff structures are more difficult to unfurl).

Based on analytical considerations, predictions of achievable levels of distortion and tolerance requirements for such things as communication, radiometry, and radiotelescope antennas, it appears that any antenna above 30m in diameter and any structural array heavier than can be delivered in a single Shuttle flight probably will have to be constructed on orbit.

The Space Station system is intended to support a number of specific objectives and will be designed accordingly. However, because the Space Station will provide a unique environment (zero-g, high-vacuum, no interfering atmosphere for stellar/solar observations, broad coverage of the earth, etc) it is desirable to provide an updating capability in order not to preclude the introduction of new research that might benefit from such an environment. This can be provided by allowing for the addition of laboratory modules and pallets.

An analysis of the crew activities associated with each of the 10 potential space program objectives was performed to identify crew skills and requirements. An initial set of crew skills was derived and these skill requirements are not expected to vary radically with shifts of objective emphasis. Smaller crews must be cross-trained and be able to perform a wide range of operations, particularly in the area of assembly and construction techniques. Cross-training is especially needed for missions of long periods (120 to 180 days) on orbit between crew changes.

Another factor to consider in the accomplishment of the various objectives involves a determination of those activities that should be performed by means of a Shuttle sortie mission and those activities that require the Space Station. Important work can be performed in the sortie mode. However, the fact that a Space Station is required to satisfy each objective and, collectively, could do the work more economically, leads to the conclusion that the majority of the objective efforts should be performed on the Space Station.

In establishing the requirements for each objective, some areas which historically have caused conflict were examined on a preliminary basis. Aspects of environment such as pointing and data rates posed problems similar to that addressed in previous programs and studies. Experience reveals that such conflicts generally can be resolved through design, local protection, careful planning of operations, etc. Processes which require very low gravity (for instance, below the level induced by crew motion, $\sim 10^{-4}$ to 10^{-5} g, and Shuttle docking, $\sim 10^{-3}$g) can be accommodated by a flotation table. Processes requiring other than an ambient atmosphere or easily achieved level of cleanliness can be accommodated by special enclosures, test cells, etc. The high data rates required by earth services must be satisfied if a full test program is to be conducted; as a result, other objectives data requirements can be met easily. Objectives which require conflicting Space Station orientations can be accommodated by timing their operations so that they are not conducted simultaneously. Objectives requiring precision pointing or stability limits beyond that which is practical for the Space Station to provide can be accommodated by mounting them on separate gimbal systems.

One area that resists convenient solution is the requirement for different orbits. Previous Space Station work solved this problem via a compromise orbit which had a reasonably high inclination to give good coverage of the earth without too great a sacrifice of shuttle logistics performance. The current objectives may not be amenable to such a compromise. Satisfying conflicting requirements for different orbits could be solved by such means as having more than one Space Station, use of sortie missions, or use of automated free fliers. An alternative would be to restrict objectives to those which could be handled by a single Space Station. In any event, further trades in this area are warranted.

2.12 RESULTS OF THE ANALYSIS OF THE OBJECTIVES

The results of the objectives substudies verified their selection in all but one case: nuclear power. The studies also revealed that Space Station involvement is necessary to each objective to satisfy the associated functional requirements.

The objectives from which functional requirements were derived and hardware concepts synthesized all exhibit a capability for yielding significant benefits. They also impose a significantly broad spectrum of requirements on the Space Station itself so that, as new requirements evolve, the ability of the Space Station to accommodate them is highly probable.

One last observation on the objectives is appropriate before the discussion on program options. Previous studies have defined the enormous benefits of the Space Station as a laboratory facility. The current analyses reveal its even greater potential in acting as an operations base for supporting development of space systems which will be key stepping stones toward solving many of the problems of mankind.

3. DEVELOPMENT OF PROGRAM OPTIONS

Using the objectives described in Section 2 as the point of departure, potential Space Station system programs were constructed to ascertain parametric effects of programmatics and design and allow comparisons, sensitivity studies, and selections to be made. These potential programs were termed Program Options. Briefly, a Program Option was considered to be a complete program plan for the development of a Space Station, including:

- Definition of the Space Station hardware elements
- Orbit location
- Implementation schedule
- Transportation elements
- Number of flights required
- Cost

Each program option provides the capability to support a selected group of objectives and objective elements within each objective.

In the initial phase of the study, 45 program options were developed. The emphasis was to develop options that covered all reasonable combinations of objective elements, represented a broad range of program costs, covered the various orbit regimes of interest, and included some reasonable growth contingencies such as the heavy-lift logistics vehicle (HLLV). In short, the intent was to bound the possiblities and present a wide range of choice.

The results achieved are indicated by the following:

- The level of achievement, defined as the total number of objective elements included within a particular option, covers a range of 45 to 100% over the entire population of options.
- The option complexity varied from LEO only, through LEO plus unmanned GEO, to LEO plus manned GEO operations.
- Transportation requirements varied from Shuttle only to Shuttle plus unmanned OTV, Shuttle plus unmanned OTV plus solar electric propulsion system, and finally, added a manned OTV to support GEO operations.
- Total program costs ranged from a low of \$6B to a high of \$25B.

3.1 SELECTION OF CANDIDATE OPTIONS

From the original spectrum of options, a limited number were selected for further analysis. The selection process included consideration of the following factors:

Achievement Level. How much does each option accomplish? An additional consideration within this category was early achievement, because early efforts in large structures, SPS, and space processing were considered to be especially significant.

Potential Revenue Return. To what extent does each option offer the potential to produce revenue?

Technical Risk. How much technical risk is inherent in each option?

Growth Potential (flexibility of approach). How easy would it be to redirect each option in the event a change in direction was necessary after the effort was started?

Transportation. What transportation implications are inherent within each option?

Unique Features. Are there unique features that make an option especially attractive?

Cost. What is the cost of each option, including annual funding level and cumulative or total program cost? An important additional consideration was the cost of the initial program. In a short-term sense, this is an important parameter.

Initially seven options were selected. They covered a broad range of cost and achievement, and each was judged the best option in its particular range. This process is shown schematically in Figure 10 by the seven bars.

Each of the options was then reviewed with NASA/JSC and subsequently modified to include some additional features, and two additional options also were defined (18 and 20). The circled numbers on Figure 10 indicate the final options, which, in all cases, were modifications of the

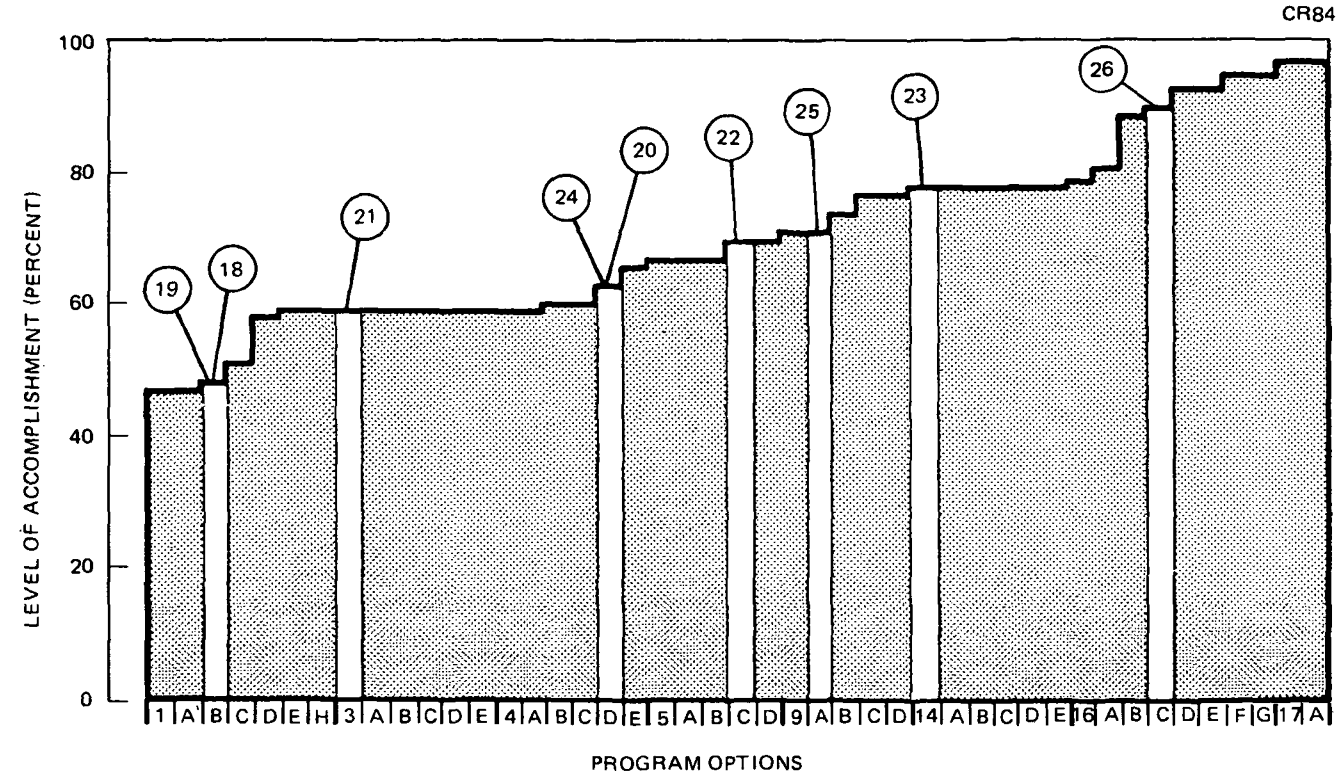


Figure 10. Selection of Candidate Options

original options. The nine options then were refined and became the set of candidate options recommended to NASA for consideration as candidates to be further analyzed.

3.2 CANDIDATE OPTION DESCRIPTIONS

3.2.1 **Option 18.** The main thrust of this option is early achievements in large space structures, SPS test and construction, and space processing. Later activities were limited to reduce the total program cost. The option features a low earth orbit (LEO) construction base; because all activities are limited to LEO, only Shuttle flights are required.

The initial space station is sized for a crew of 10 men, 5 being launched initially and 5 more about a year later to support increased activity for SPS Pilot Plant I. Since later activities do not require any additional crew increase, this station configuration was intentionally kept as simple as possible by combining functions within modules. Although this resulted in the smallest number of modules (8) of any of the option configurations, it would make later station growth more difficult.

The initial major program activities accomplished in this option are (1) SPS Component Development and Test in 1984, featuring the construction on-orbit of an 86m, linear, tapered array antenna to conduct tests for phase control, beam mapping, RFI effects, and microwave tube contamination, (2) construction on-orbit of SPS Pilot Plant I in 1985 for an integrated SPS system feasibility demonstration of fabrication, operation, and system performance to verify techniques that will be used later for an SPS prototype, (3) Space Processing Process Development and Test in 1984 to evaluate basic processes for biologicals, inorganics, and silicon ribbon to determine the processes that are suitable for volume production application, (4) Earth Services 30m radiometer construction on-orbit in 1985 to evaluate construction techniques and productivity, and conduct system performance tests and develop data processing techniques. The Multidiscipline Science Lab is activated in 1984 with a crew of two devoted to space-based research in the basic sciences. The remaining objectives are supported at a minimum level with the exception of Space Cosmology, which is not addressed in this option.

The growth period for Option 18 is limited to Space Processing Process Optimization in 1987. The activity includes dedicated modules for biologicals and inorganics to develop the respective processes for quantity production.

The option had the lowest costs of all the options, both for the initial program and total program. However, the achievement level is low, there are no potential revenue elements included, and growth period activity is very limited.

3.2.2 **Option 19.** The major thrust of this option is early achievements, as in Option 18, with some additions to the later activities to achieve a better balanced program. This option is limited to LEO and only requires Shuttle as a transportation element.

The initial station is sized for a crew of 10 men, with 6 being launched initially and the other 4 later to support SPS. For the growth period, a crew of 18 is required. The initial station configuration has 10 modules, the additions from Option 18 being required to facilitate the later growth to 14 modules. This station has good additional growth capability.

The initial program activities for this option are the same as in Option 18, except that Component Development for the Large Cluster Objective has been added in 1984 to start development of laser-power transfer techniques and components.

During the growth period, the Space Processing Commercial Pilot Plant has been added in 1990 to allow quantity production of products for sale on a commercial basis. Living and Working in Space activity has been increased to include a dedicated module for the Extensive Research level in 1986. The sensor objective has been augmented by adding a dedicated module for the Fabrication and Evaluation level in 1988 to develop and fabricate optical sensors in space.

Although the option still had a relatively low initial program cost, total program cost was increased modestly.

3.2.3 **Option 20.** This option adds activities into the growth program, especially the construction and test of large earth-services antenna, including the first deployment to GEO. This program requires an Unmanned Orbit-Transfer Vehicle (UM-OTV). An additional objective (Sensor Development) is eliminated. Thus, the option supports all but two of the total complement of objectives.

The initial program is virtually the same as for Option 19; therefore, the initial Space Station and crew complement are the same. The growth-period station has one less module (dedicated sensor module), but the crew size is about the same because of the additional growth activities.

The growth period additions for this option are the 100m radiometer (1988) and the multibeam lens communications antenna (1990) for the Earth Services objective. The former provides large structure construction productivity, earth observation performance verification, and signature data. The latter provides system performance verification for a large, multiple-access communications antenna, and demonstrates transportation of large elements to GEO. The Small OTV Depot is added in 1989. It provides the facilities to launch small, unmanned satellites to higher orbits and interplanetary spacecraft by using the space station as a staging base.

Initial program cost for Option 20 was the same as for Option 19; however, additional growth items further increased the total program cost and peak annual funding.

3.2.4 **Option 21.** This option places heavy emphasis on the growth period of SPS activities while maintaining a reasonable balance among the other objectives. All nine objectives are supported to some degree.

The initial station and crew size are identical to those for Option 19. The growth station has the same number of modules as in Option 19, but an additional crew member is required to support the additional objective (Space Cosmological R&D). The initial program activities for this option are the same as for Options 18 and 19.

The growth program adds the large SPS Pilot Plant II in 1991 to demonstrate large-scale construction productivity, verify prototype automated processes and tooling, and test large-scale integrated system performance. Supporting elements for SPS Pilot Plant II are the Silicon Ribbon and Solar Cell Blanket Pilot Plants (1990) to furnish solar cell blanket material, and Living and Working in Space Demonstration Techniques (1990) and Construction Supports (1991) to address the extensive man-machine interfaces and productivity issues involved. Space Cosmological R&D Component Development and Test is added in 1987 to conduct low-noise receiver and antenna feed system tests. The initial program cost for this option is the same as for Option 20; however, the addition of the SPS Pilot Plant II has raised both the total program cost and peak annual funding.

3.2.5 **Option 22**. This option is similar to Option 21, the differences being more content in the Earth Services antenna construction and less in Space Processing, and no Space Cosmology objective activities.

These activities require a LEO Space Station and construction base with some elements being delivered to GEO for testing. Thus the Shuttle and an UM-OTV are required for transportation.

The initial program, initial Space Station, and crew are identical to Option 21. The growth station configuration is the same as Option 21, but one additional crew member is required to support construction of the larger communications antenna.

For the growth program, the 100m radiometer (1988) and the multibeam lens communications antenna (1990) have been added, and the Space Processing Commercial Processing Pilot Plant and Space Cosmological R&D Component Development have been deleted.

The cost for Option 22 approximates Option 21, both for the total and initial programs.

3.2.6 **Option 23**. This option represents a considerable increase a both program content and program complexity. All objectives are added, a radiotelescope is constructed in the Space Cosmology area, MDSL activity is expanded, and the large SPS Pilot Plant is constructed and tested in geosynchronous orbit. This requires a Space Station and construction base at GEO and a manned OTV for support.

The initial program adds additional scope to the MDSL objective by expanding the size of the MDSL facility and adding additional crew for its support. The number of initial Space Station modules are increased to 13 and initial crew size to 12. Growth-period LEO activities require additional crew growth, and a small Space Station and construction base is deployed at geosynchronous altitude to construct the SPS Pilot Plant and support testing.

The growth period activities also include the construction and test at GEO of a radiotelescope for the Space Cosmological R&D objective in 1990. A depot facility for a large OTV is included because of the relatively large number of OTV flights required to support the Space Station at GEO and its construction and test activity.

The cost for Option 23 was substantially higher than any discussed so far because of the additional content and complexity.

It should be noted that there is no general agreement that the deployment to GEO of a large SPS Pilot Plant is a requirement for the SPS objective. However, there are substantial arguments in favor of testing large SPS devices of some sort at GEO and, in this option, we have demonstrated the programmatic effects of constructing large devices at GEO. In later options, we will examine other ways of accomplishing this objective.

3.2.7 **Option 24**. This option is similar to Option 23 in that a large element is deployed at GEO, in this case by transporting the Large-Cluster Pilot Plant from LEO to GEO in a self-propelled mode using solar electric propulsion. The activity is supported at GEO by a series of short-duration, manned, sortie flights from LEO with the crew living in the manned OTV while working at GEO.

The initial program is the same as Option 23, except that the multibeam lens communications antenna is added in 1986 so that it falls into the initial program period. The initial and growth station at LEO is the same as for Option 23, but the growth GEO station is not required.

The growth period activities include the Large-Cluster Pilot Plant in 1990 to demonstrate the generation of laser energy at GEO and transmit this to a laser-powered OTV for interorbit transport. The SPS Pilot Plant and supporting activities, and the radiotelescope, have been deleted to reduce cost.

The cost of the option approximates that of Option 23.

3.2.8 Option 25. This option features Space Stations in both LEO and Polar Earth Orbit (PEO) as a means of satisfying objectives which can benefit from the polar orbit location.

The total complement of activities was selected to cover all objectives except Space Cosmology, and, within objectives, most elements were addressed except the portion requiring deployment to LEO. This was done to restrict the total program cost.

The objective elements deployed in PEO are those with requirements that appear to benefit significantly from this orbit. In Space Processing, the use of a sun-synchronous orbit permits the use of continuous sunlight for solar furnace applications. In Earth Services and Sensor Development, the instruments could have high-latitude coverage and better viewing angles for ground observations. In Life Sciences, the polar environment offers a different radiation exposure for man-in-orbit, presenting both an opportunity to gather data and an additional risk.

3.2.9 Option 26. This option includes the maximum possible content in all objectives (except polar). It illustrates a maximum total program which can be accomplished in low-inclination orbit.

The SPS Pilot Plant II and the Large Cluster Pilot Plant are both deployed to GEO by using a self-propelled solar electric system. A small Space Station is established in GEO to house the crew that supports the testing of these items. A manned OTV transports the new to GEO and an unmanned OTV transports hardware and supplies. A Shuttle-derived HLLV appears to be cost-effective because of the high volume of logistics flights required.

The cost of this option was the highest and peak funding was also high. The initial program is somewhat lower than for Options 24 and 25 because both of these were special situations that do not apply to Option 26: Option 25 had two Space Stations in the initial program (LEO and PEO); Option 24 had the multibeam lens-communications antenna moved into the initial period.

3.2.10 Comparison of Candidate Options. Table 2 summarizes the major features of the candidate options and gives the date that the orbital development of a particular objective element is initiated. The date indicates which objective elements are included in each option and when each is to be done. As can be seen, the varying content of the options allows a wide spectrum of choice. Options 21, 23, and 26 address portions of all nine options with only Option 26 addressing all elements defined to date.

Table 3 summarizes the major characteristics of the basic Space Station and construction base, and the estimated initial facility cost for the program.

The number of modules varies from 5 to 7 for those options that have only a single station, to 13 to 14 required for those options that have two stations (either LEO and GEO, or low inclination and polar).

The crew size varies from 10 for Option 18 to 36 for Option 25 (24 in low inclination and 12 in polar). The cost of the basic Space Station is approximately the same for those options that

ORIGINAL PAGE IS
OF POOR QUALITY

Table 2. Comparison of Candidate Options (Objective Element Usage)

	Option Number									
	18	19	20	21	22	23	24	25 LEO	25 PEO	26
Satellite Power System										
Component Development and Test	1984	1984	1984	1984	1984	1984	1984	1984	–	1984
SPS Pilot Plant I	1985	1985	1985	1985	1985	1985	1985	–	–	1985
SPS Pilot Plant II (LEO)	–	–	–	1991	1991	–	–	1991	–	1991
SPS Pilot Plant II (GEO)	–	–	–	–	–	1991	–	–	–	1993
Space Processing										
Process Development and Test	1984	1984	1984	1984	1984	1984	1984	1984	1984	1984
Process Optimization	1987	1987	1987	1987	1987	1987	1987	1987	–	1987
Silicon Ribbon Pilot Plant	–	–	–	1990	1990	1990	–	1990	–	1990
Blanket Pilot Plant	–	–	–	1990	1990	1990	–	1990	–	1990
Commercial Processing Pilot Plant	–	1990	1990	1993	–	–	–	1993	–	1993
Earth Services										
30-Meter Radiometer	1985	1985	1985	1985	1985	1985	1985	–	1985	1985
100-Meter Radiometer	–	–	1988	1988	1988	1988	–	–	1988	1988
300-Meter Radiometer (LEO)	–	–	–	–	–	–	–	1989	–	1989
300-Meter Radiometer (GEO)	–	–	–	–	–	–	–	–	–	1989
Multibeam Lens (LEO)	–	–	1990	–	1990	–	1986	1990	–	1990
Multibeam Lens (GEO)	–	–	1990	–	1990	–	1986	–	–	1990
Cross-Phased Array (LEO)	–	–	–	–	–	–	–	1990	–	1991
Cross-Phased Array (GEO)	–	–	–	–	–	–	–	–	–	1991
Multidiscipline Science Laboratory										
Basic Research, Minimum	1984	1984	1984	1984	1984	–	–	–	–	1984
Basic Research, Maximum	–	–	–	–	–	1984	1984	1984	–	1984
Living and Working in Space										
Limited Research	1984	1984	1984	1984	1984	1984	1984	1984	1984	1984
Extensive Research	–	1986	1986	1986	1986	1986	1986	1986	–	1986
Demonstrate Techniques	–	–	–	1990	1990	1990	–	1990	–	1990
Construction Support	–	–	–	1991	1991	1991	–	1991	–	1991
Space Cosmological Research and Development										
Component Development and Test	–	–	–	1987	–	1987	–	–	–	1987
Mark II Radiotelescope	–	–	–	–	–	1990	–	–	–	1990
Test Operations (GEO)	–	–	–	–	–	1990	–	–	–	1990
Depot										
Component Development and Test	1984	1984	1984	1984	1984	1984	1984	1984	–	1984
Large OTV Depot	–	–	–	–	–	1990	1990	–	–	1991
Small OTV Depot	–	–	1989	–	–	–	–	1991	–	1991
Cluster										
Multiple-Purpose Space Power Platform	1984	1984	1984	1984	1984	1984	1984	1984	–	1984
Large Cluster Component Development	–	1984	1984	1984	1984	1984	1984	1984	–	1984
Large Cluster Pilot Plant	–	–	–	–	–	–	1990	–	–	1991
Sensor Development										
Development and Test	1984	1984	–	1984	1984	1984	1984	1984	1984	1984
Fabrication and Evaluation	–	1988	–	1988	1988	1988	1988	1988	1988	1988

have only a single station, the slight variation being due to the cost of the additional crew module required for the growth period in all options except 18. For those options that require two stations the cost is increased by about $900M.

As noted in Table 3, when considering only the Space Station Construction Base, Option 18 has the lowest total program cost ($2.56B) and Option 25 has the highest ($3.66B). In every case, the peak annual funding for the Space Station Construction Base can be kept to between $0.6B to

Table 3. Comparison of Candidate Options (Initial Construction Base Costs)

	Option Number								
	18	19	20	21	22	23	24	25	26
Number of Modules									
Initial Program	5	7	7	7	7	7/0	7	7/6	7/0
Growth Program	5	8	8	8	8	8/5	8	8/6	8/5
Crew Capability(1)									
Initial Program	10	10	10	10	10	12	12	24	12
Growth Program	10	20	20	20	20	34	24	36	31
Orbit Regime/Location	LEO Only	LEO Only	LEO UM-GEO	LEO Only	LEO UM-GEO	LEO GEO	LEO GEO Sortie	LEO PEO	LEO GEO
Transportation Elements	Shuttle	Shuttle	Shuttle UM-OTV	Shuttle	Shuttle UM-OTV	Shuttle UM-OTV M-OTV HLLV	Shuttle M-OTV SEPS	Shuttle (2)	Shuttle UM-OTV M-OTV HLLV SEPS
Initial Program Cum Cost ($B)	2.56	2.62	2.62	2.62	2.62	2.62	2.62	3.54	2.62
Initial Program Peak Funding ($B) (Year)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.8 (82)	0.6 (81)
Total Program Cum Cost ($B)	2.56	2.74	2.74	2.74	2.74	3.52	2.74	3.66	3.52
Total Program Peak Funding ($B) (Year)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.6 (81)	0.8 (82)	0.6 (81)

(1) Crew capability is what station is capable of accommodating; it is sometimes more than the actual crew used.
(2) Shuttle polar capability required.

$0.8B. This peak would be expected to occur during the 1981-82 period.

Table 4 compares the total program characteristics for each of the candidate options (basic station, mission hardware, and transportation). Again it can be seen that, with the exception of the austere Option 18, the number of modules stays about the same – 10 for the initial program and 14 for the growth program for all the options that have a single Space Station. The options that require two stations require from 19 to 24 modules and can accommodate from 31 to 36 crewmen, compared with 20 crewmen for the others. Although there is some variation in achievement, those options that require two space stations or that require manned GEO operations tend to be the highest priced, reflecting the increased cost of the hardware and logistics support necessary in those cases. As noted in Table 4, total program for the various options ranges from $5.9B to $25.1B, and the peak annual funding for the total program ranges from $0.95B to $3.5B.

Table 4. Comparison of Candidate Options (Total Program Costs)

	Option Number								
	18	18	20	21	22	23	24	25	26
Number of Modules									
Initial Program	8	10	10	10	10	13	13	23	13
Growth Program	8	14	13	14	14	19	14	24	19
Crew Capability(1)									
Initial Program	10	10	10	10	10	12	12	24	24
Growth Program	10	20	20	20	20	34	24	36	31
Orbit Regime/Location	LEO Only	LEO Only	LEO UM-GEO	LEO Only	LEO UM-GEO	LEO GEO	LEO GEO Sortie	LEO PEO	LEO GEO
Transportation Elements	Shuttle	Shuttle	Shuttle UM-OTV	Shuttle	Shuttle UM-OTV	Shuttle UM-OTV M-OTV HLLV	Shuttle M-OTV SEPS	Shuttle (2)	Shuttle UM-OTV M-OTV HLLV SEPS
Initial Program Cum Cost ($B)	5.0	5.1	5.1	5.1	5.1	6.4	7.1	7.0	6.4
Initial Program Peak Funding ($B)	0.9	0.9	0.9	0.9	0.9	1.2	1.4	1.5	1.2
(Year)	(81)	(82)	(82)	(82)	(82)	(83)	(83)	(81)	(83)
Total Program Cum Cost ($B)	5.8	7.2	8.8	11.3	11.5	15.8	16.4	16.7	25.1
Total Program Peak Funding ($B)	0.95	1.1	1.3	1.4	1.6	2.1	2.6	2.0	3.5
(Year)	(84)	(84)	(85)	(85)	(85)	(86)	(90)	(86)	(91)

(1) Station capability; crew used in a given phase may be smaller.
(2) Shuttle polar capability required.

4. CONFIGURATION DEVELOPMENT AND TRANSPORTATION REQUIREMENTS

During Part 1 of the study, the primary Space Station concept definition activity was oriented toward critical WBS Level 4 requirements in order to support programmatic activities in program option planning and related ROM costing. An initial set of assumptions was developed from previous Space Station studies and NASA technical reports. Using these assumptions, Space Station configuration outline descriptions were devised for each option as the basis for comparative ROM cost development.

The wide spread in crew size (5 to 36 men) and in power level (to 15 kW) suggested the desirability of modular flexibility, coupled with high efficiency per modular unit, to minimize the total number of modules in the Space Station systems growth configurations. Although the functional requirements of the objectives represent a wide spectrum of activities and products, many of them can be accommodated in conventional modules, and therefore do not place special demands on the configuration. Predominant design drivers were found to be the large space construction base and orbital depot, which will require new and unique configurations.

Preparation of Space Station configuration sketches emphasized several basic conceptual approaches to the initial four-to-six man station. In each case, the approach to achieving both evolutionary growth and option functional support flexibility was developed. These approaches were then applied to the definition of a candidate configuration for each of the options.

In preparation for detailed subsystem and configuration trade studies of Part 2, the Shuttle performance, orbital operations, and previous study assumptions were reviewed to assure that the design criteria and study assumptions are current and appropriate within current study requirements and environment.

The assumptions derived from previous study results were modified where appropriate to be consistent with increased demands of the current program options, e.g., larger crews, up to 36 in growth stations, and a large space structure construction base. All modules and operations were assumed to be Shuttle-compatible, including the large-volume structure required for the OTV maintenance hangar of the orbital depot. A wet configuration of the Shuttle external tank was used as the standard for costing.

The basic module length of 15m is consistent with installation in the Orbiter cargo bay, which has an Orbiter docking module installed.

The relatively high number of crewmen per crew module (10 ± 2) was selected to minimize the number of modules required for the larger stations while still providing comfortable crew quarters.

As a result of the increased number of crewmen and total modules in the growth version of a Space Station, a preliminary decision was made to place the ECLSS and waste management in the crew module. This would make crew modules initially autonomous in regard to additions to a growth Space Station, plus simplifying the increase in ECLSS capability. Proper installation and isolation, including acoustical treatment, would be employed to prevent disturbances being transmitted to the crew quarters area.

In previous studies, the buildup of a Space Station had been proposed to be done by erecting a module on the Orbiter docking adapter and driving the module into the Space Station docking port. Simulation of Orbiter operations, including the manipulator operations, indicates that the procedure and maneuver may not be possible. With a module 15m long, weighing approximately 15,000 kg, docked to the Orbiter docking module, the Orbiter control authority envelope is exceeded. This may be remedied by control computer modifications. An additional consideration is the effect on the Space Station stability and control subsystem complexity of docking the Orbiter at a radial docking port with its attendant significant effect on the moment of inertia. Therefore, an alternate approach was included which considers the use of an onboard mobile crane with the capability of traveling the length of the station. Variations in the crane concept include single-arm fixed location, single-arm mobile, and two-arm mobile. These include mobility concepts such as monorail and a self-propelling (i.e., walking) crane. It appears that a two-arm traveling crane configuration has several unique operational characteristics:

- It has the mobility to move to all extremities of the Space Station through the use of attach points externally located on the Space Station module's external surface.
- It can handle the exchange of cargo modules virtually without assistance.
- It can provide an airlock for EVA or crew transfer to the Orbiter at all Space Station berthing and docking ports. This has the important advantage of supporting crew rescue from a module by berthing the crane airlock to the module berthing port and removing the crew from an isolated module.
- Assuming the use of a new or considerably modified docking mechanism on the Space Station, the interface to the Orbiter can be supplied by this crane module.

4.1 CONFIGURATION DEVELOPMENT

The first step in describing the Space Station configuration was a preliminary review of all program options to identify a full range of candidate modules and elements. These were divided into the primary functional areas representative of the individual objectives selected to make up program options. Typical physical and operational characteristics were defined for each module and element and preliminary descriptions were compared to the option support requirements in order to make final selections.

The modules and configuration elements considered included the following:

Basic Station and Construction Base

Power Module
Crew Module
Control Center (Men)
Core Module
Fabrication and Assembly Module
Cargo Module
Crane

Mission Hardware

Laboratory Module
Laboratory Support Module
Other Equipment as Required

As an adjunct to the initial configuration description, a Space Station Construction Base buildup sequence was prepared to verify the needs and relationships of functional support requirements and assigned modules. This task also supported the transportation requirements analysis. Conceptual sketches of the external configuration were made for selected options to assure the feasibility of the buildup sequence and the module selection.

The buildup sequence is shown graphically in Figure 11. In a normal buildup sequence, the power module is launched first and placed in orbit in an unmanned mode. The solar arrays are deployed for initial power and the support subsystems activated. In Part 2 of the study it will be determined if the mobile crane can be launched with the power module. The second module launched would be the control center, which provides safety functions, caution and warning, communications, data management, and Space Station command post, thus readying the station for manned operations. Then, with the launching of the core (berthing) module, crew module, cargo module, and fabrication and assembly module, the initial construction base is complete. Initiation of crew transfer could occur at any point after the conjunction with the crew module when all crew support subsystems and accommodations are available. These buildup sequence will also be analyzed relative to crew operations and safety procedures.

The primary functional support requirement to be provided by the Space Station is a versatile general construction base capable of addressing various structural configurations and different degrees of complexity. A preliminary analysis of the candidate configuration has determined that it has potential in both characteristics and compatibility with the Shuttle as the launch system.

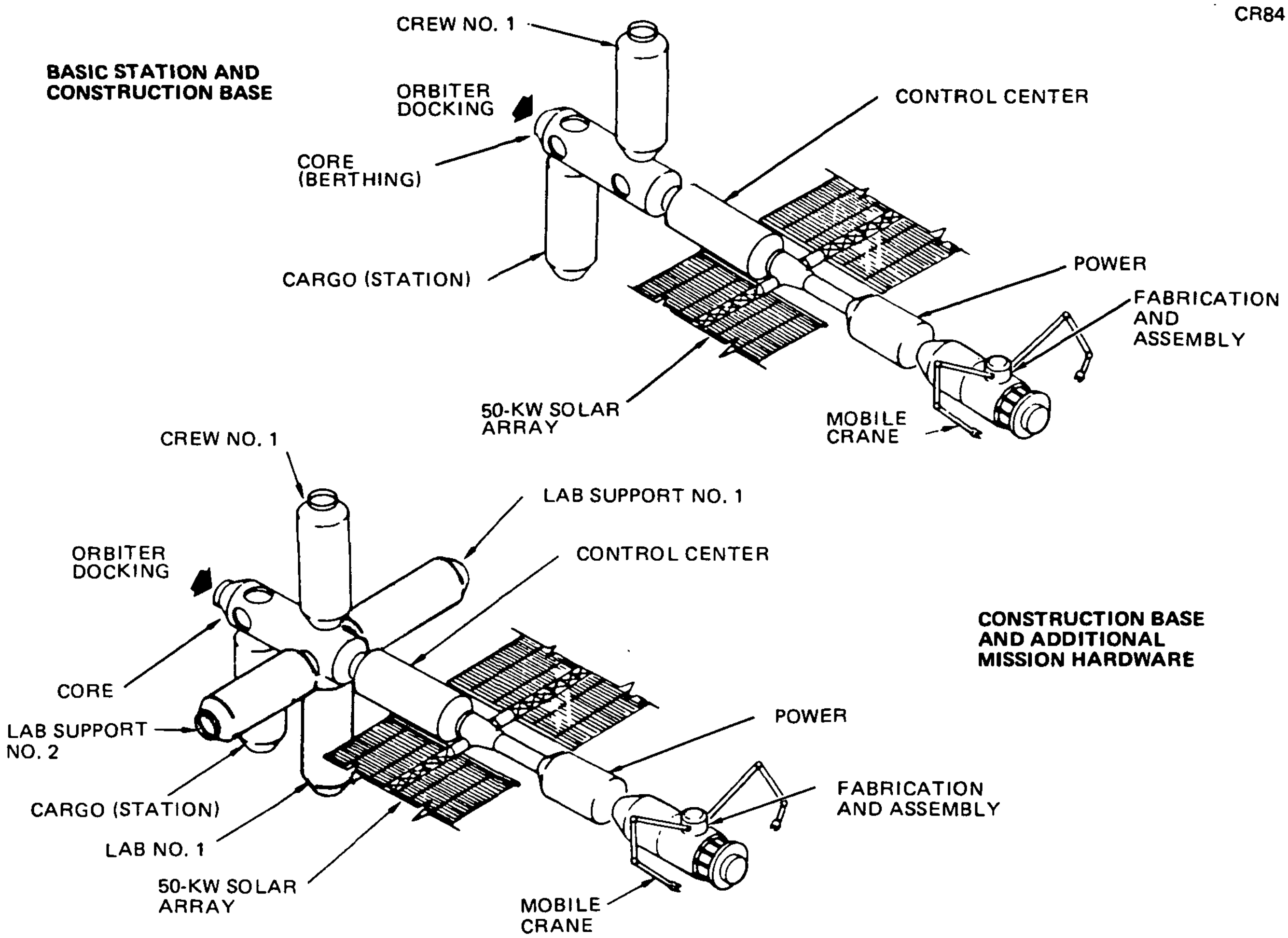


Figure 11. Initial Construction Base

By using the removable work station concept (Figure 12), the flexibility to advance in complexity and/or in degree of automation is assured without major changes or adjustments to the basic Space Station. The close proximity of the structural elements cargo pallet to the work station provides a convenient and efficient materials-handling method. The identification and definition of accessories and support equipment (e.g., deployment of solar blankets) will be undertaken in Part 2.

The preliminary conceptual analysis indicates that a variety of structural configurations can be assembled by this basic fabrication and assembly module (see Figure 13). In changing the EVA work station from support of one structure to another, the basic pressurized module would remain berthed to the Space Station and the work station would be exchanged or modified.

Should a large construction work platform be required, it could be assembled as shown in Figure 13. The 10 x 10m dimension is typical and does not represent an upper limit. Assembly of platforms of several hundred meters in size should be possible. If antenna tolerance requirements exceed those obtainable by the basic EVA assembly method, a fixture can be assembled which has an adjustable template surface for obtaining the necessary tolerance.

The range of structures that are illustrated would represent a construction program lasting over several phases of Space Station growth.

4.2 TRANSPORTATION REQUIREMENTS ANALYSIS

Identification of the necessary transportation requirements was carried out following the pro-

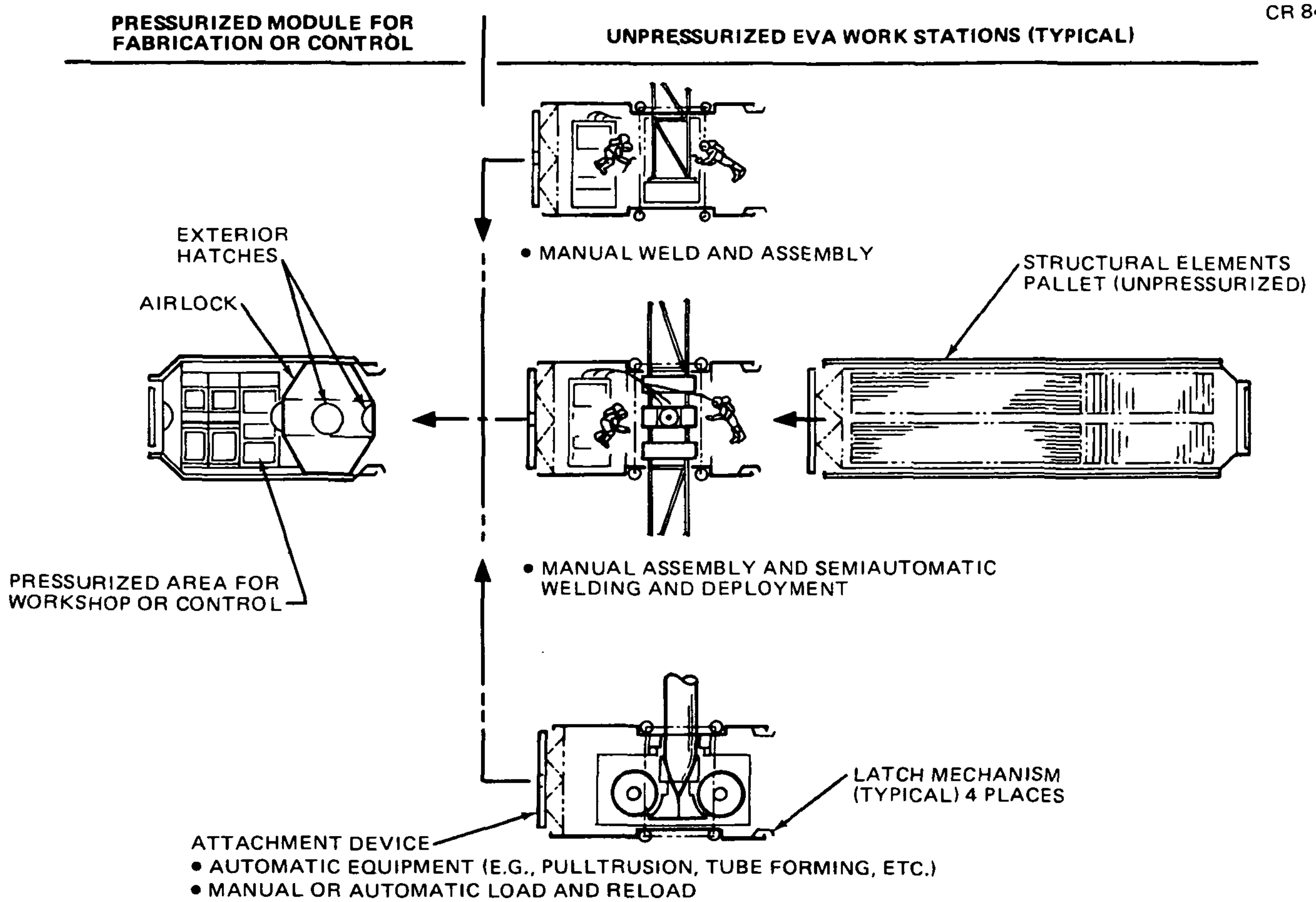


Figure 12. Candidate Fabrication and Assembly Module

gram option definitions and in coordination with the Space Station configuration definitions. This task also addressed the LEO-to-GEO transfer of both pilot plant and operational SPS facilities using self-produced electric power with and without auxiliary chemical propulsion subsystems. The auxiliary subsystem provides a higher thrust-to-weight ratio for rapid transit through the Van Allen belts.

The HLLV was investigated relative to its potential benefits to the high-traffic module program options. An evolutionary concept of the HLLV derived from Space Shuttle was defined.

In consideration of GEO operations with the attendant premium on high λ' as a cost-reduction measure, emphasis was placed on a lightweight OTV, manned and unmanned.

The transportation mission requirements include earth to LEO, PEO, and transfer to GEO.

The basic LEO and PEO requirements include all the orbital elements needed in orbit from payloads to propellant. The Shuttle and HLLV are the carriers for this phase.

The GEO transfer requirements include satelittes, objective elements, and modules needed at the geosynchronous orbit. Launch systems considered have included large and small OTV's, manned tugs, electro/chemical systems, and expendable stages.

The transportation system elements used are summarized in Table 5.

Table 5. Transportation System Elements

Shuttle	07700 Vol 14 (Rev D Change 15)
HLLV	Shuttle-Derived 60,000 to 112,000 kg payload
OTV-Cargo	29,500 kg GEO payload delivery
OTV-Manned	5,500 kg GEO round trip
SPS/Cluster Transfer	Electric – 1200 4.5N thrusters (10^{-3}g) Chemical – RL-10 equivalent (10^{-2}g)

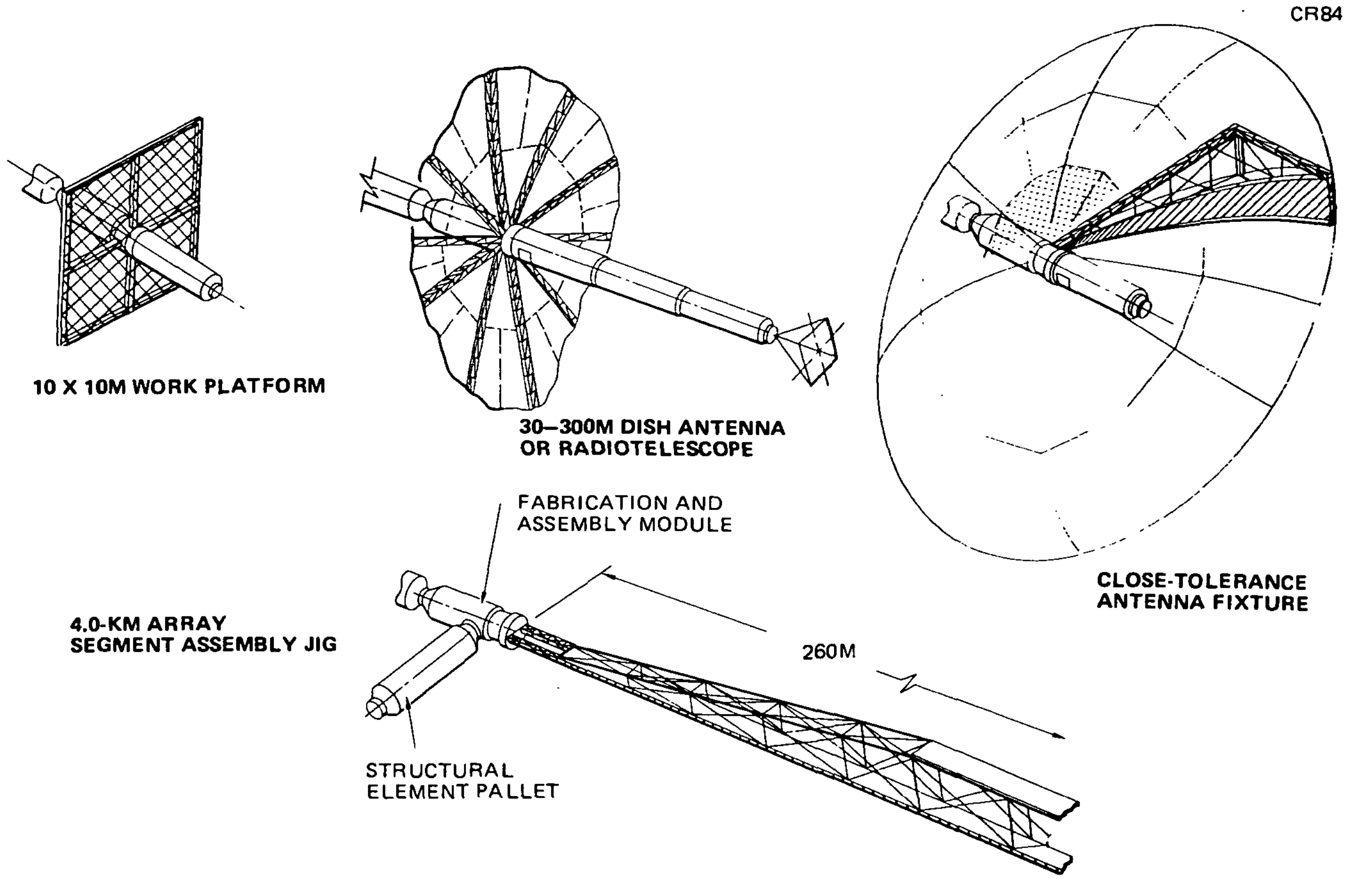


Figure 13. Typical Candidate Structures

The Shuttle consists of the latest definition per the reference. The initial HLLV used was a Shuttle-derived concept defined by JSC. It had a basic payload capability of 127,000 kg. The launch cost was given at $16M each, including the $2M expendable canister. Subsequent review of other HLLV concepts indicates that a payload capability range of 60,000 to 112,000 kg should be selected for future analyses.

The OTV was defined as a 29,500-kg payload to GEO capability. Subsequent parametric analyses will allow the adjusting of this size. The manned OTV was sized to transfer crew between LEO and GEO. Size and characteristics will be determined in Part 2 of the study.

Orbit transfer concepts for large payloads such as SPS have included electric, chemical, and combination systems. The system chosen for this early analysis was the latter. An electric propulsion system would be used to provide the low-g transfer. The power, supplied by the host solar array (SPS or cluster), is used to accelerate the system by expelling propellant (typically mercury or argon) at high velocity. Typically, 1200 4.5N thrusters would provide a 10^{-3}g acceleration. A chemical system would also be used to transfer the system quickly through the Van Allen belts to reduce radiation damage to the host solar cells. An RL-10 engine module or equivalent could be used.

The HLLV concept is in the formative stages and includes concepts for modest Shuttle upgrading to large ballistic launch vehicles in the 270,000-kg payload delivery class; this is a factor of 10 range. Shuttle-derived HLLV concepts were considered for this study, and the capabilities are in the 60,000-kg to 112,000-kg range to LEO (Figure 14). The Shuttle-derived concepts use the Shuttle external tank (ET), the SRM's, and the Orbiter main engines and orbit maneuvering system (OMS). The Orbiter is replaced with a payload canister that is expended in orbit. The payload canister size range of 8m or 9.2m and 9.6m

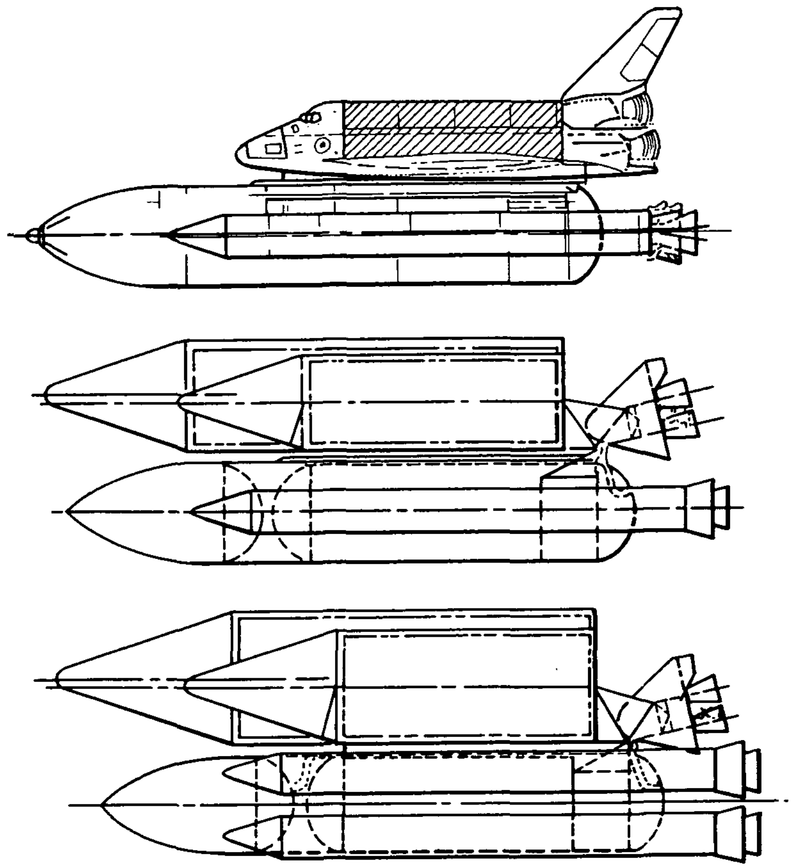


Figure 14. Heavy-Lift Logistics Vehicle

or 11.2m diameter for each concept shown causes the corresponding payload capability range. The main engines and OMS are retrieved for reuse by enclosing them in a return capsule designed for ground landing. The first upgraded concepts shown uses a pair of Shuttle SRM's while the second uses four SRM's with the ET modified to accommodate them.

Time-phased transportation requirements were calculated for each program option. A typical analysis (see Table 6) shows a total of 251 launches. The numbers across the top of Table 6 show crew size required as the mission progresses.

In the early years of the program, placement of the Space Station modules and crew rotation and logistics flights use the Shuttle flights needed. The delivered modules and logistics allow the early portion (primarily R&D) of the program to be accomplished. The flight requirements increase as objective elements are delivered. Specifically, the construction base and SPS pilot plant require several launches. The implementation of the geosynchronous Space Station again requires Shuttle flights for the delivery and filling of OTV's – manned and cargo. The yearly maximum varied from 10 to 236 for all options. Clearly, the program schedules for the high launch rate options must be reconsidered in both time and content to accommodate launch rate capabilities. These data were then used to determine overall transportation requirements and as an element of the system cost.

The total shuttle and HLLV flights needed for each program option are shown in Figure 15. The minimum required was 64 shuttle flights and the maximum was 686. The flight spread and the effect on the cost of each program option at $17.3M per flight is quite high ($1.1 to 11.9B).

The required OTV manned and cargo flights were calculated for each program option. The OTV-cargo flight requirements are in two ranges. Most of the program options, 34 of 45, required

Table 6. Typical Program Option Shuttle Flights

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	
Option		Crew Size			12	12	24	24	24	24	30	30	12/7	12/7	12/7	
Space Station (LEO)					7	7	3				4					
Crew Rotation (LEO)					4	4	8	8	8	8	10	10	4	4	4	
Space Station (GEO)												4				
Crew Rotation (GEO)												16	16	16	16	
OTV-Manned												1				
Construction Base										8						
SPS Pilot Plant											12	10				
Transfer System												14	14			
Silicon Ribbon											2	3				
Radiotelescope								1			2					
30m Commercial Antenna								1			1					
Depot												8				
OTV													1			
OTV Propellant													11			
Hangar										1						
					11	11	11	10	8	17	31	66	46	20	20	251 Total

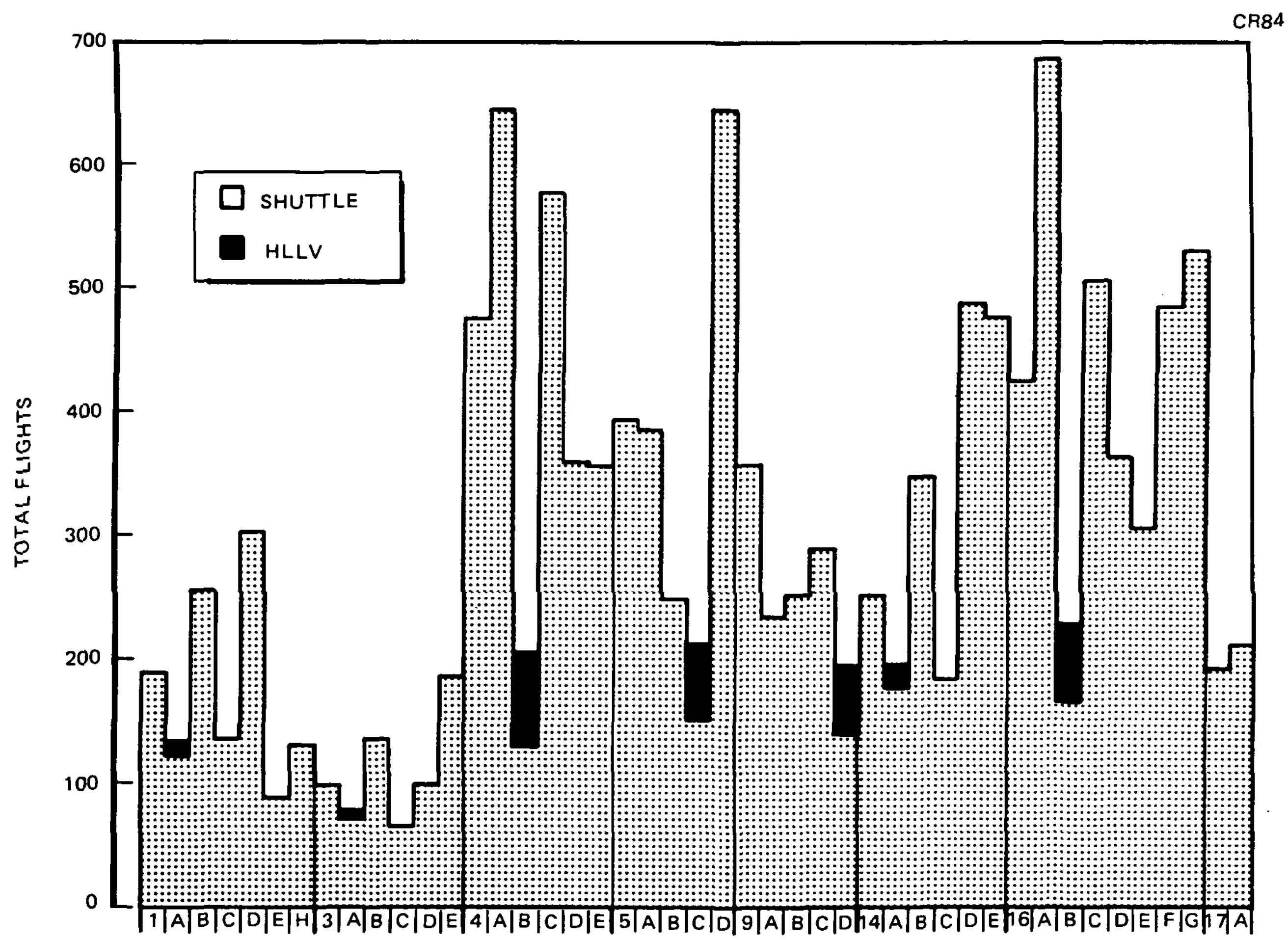


Figure 15. Transportation Requirements (1983–1995)

less than 10 OTV flights for unmanned deliveries. The remaining 11 required between 29 to 50 flights.

OTV-manned requirements are to accomplish GEO crew rotation and number in the range of 15 to 38 for those 28 options that need it.

The OTV-manned/cargo should be considered as a potential common vehicle because of the nearness of the performance requirements (mentioned earlier), compatible flight schedules, and the large number of options with a low number of OTV-cargo only flights needed.

The launch rate requirements for each option were calculated for the schedules given. The effect of launch rate capabilities on the program schedule of a typical program option is shown in Figure 16. A launch rate limit of 20 would require an inordinately long extension (up to 8 years) for some options. A 40-per-year launch rate capability would reduce the required extension to about 2 years. For this analysis the program was lengthened as needed to stay within the allowable launch rates.

The effect of launch rate capabilities of 20, 40, 60, and 80 per year on the implementation schedule of all 45 program options is shown in Figure 17.

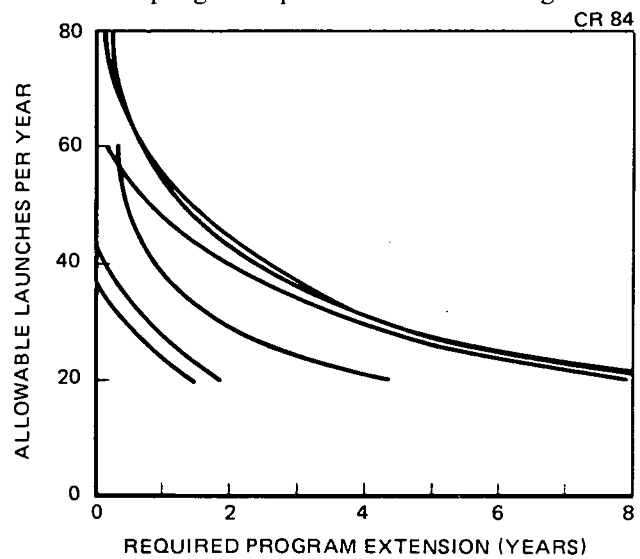


Figure 16. Launch Rate Effects

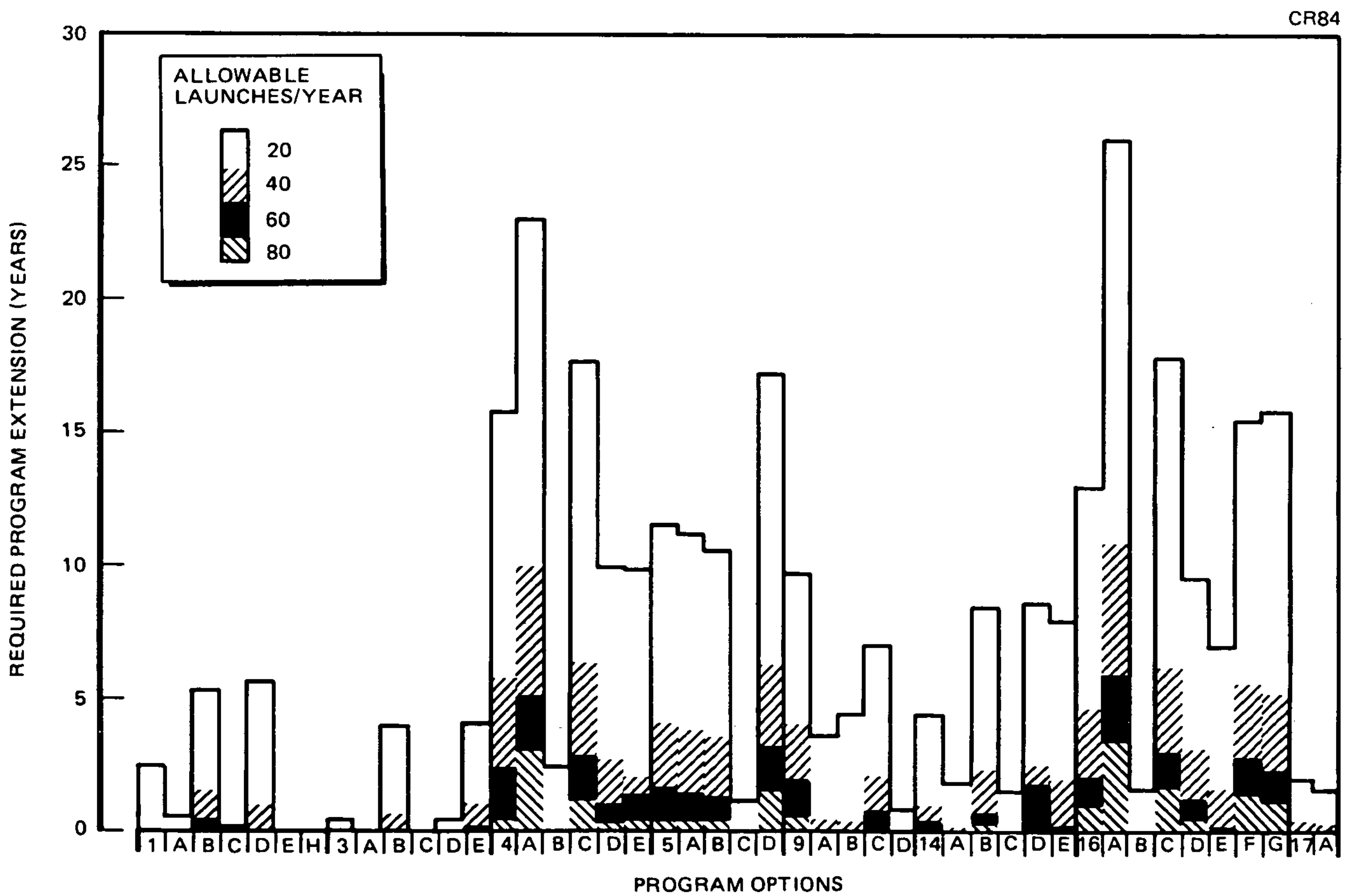


Figure 17. Effect of Launch Rate on Program Duration

A 20-per-year capability would require schedule extensions of 5 years or more on about half (23 of 47) of the program options. A launch rate capability of about 60 per year is needed to keep the schedule extension to less than 5 years for all options.

The program options must therefore be selected and defined with care to ensure launch rate compatibility. The need for HLLV is evident to reduce the rates for the high transport requirement options.

From the analysis of the transportation requirements the following conclusions were drawn:

- The large variation in required launches indicates the need for HLLV on some options and that some options should be scaled down.
- The relatively small number of OTV cargo flights suggests that the depot definition be reconsidered.
- The Shuttle-derived HLLV to be used for future option analysis should be in the 60,000-kg to 112,000-kg payload range.
- The similar OTV-manned/cargo performance requirements and compatible missions and schedules suggests that they be the same basic vehicle to make best use of development expenditures.
- As a goal payload or transportation system, interfaces will be kept to the minimum. Analysis to date indicates that Shuttle payload CG envelope restrictions will limit the full use of the Shuttle capability.

Page
Intentionally
Left Blank

5. SUMMARY AND CONCLUSIONS

Using the 61 future space objectives in the *Outlook for Space*, NASA SP-386, as the point of departure, together with supplemental references provided by NASA/JSC, analyses were conducted to derive requirements for future Space Station System elements. From this data base, JSC and MDAC personnel selected 10 areas (referred to as Space Station System Objectives) which appeared to be key determinants in identifying future Space Station system requirements. Substudies were performed in each of these 10 areas to identify Space Station functional requirements, and "data packages" were prepared to document this work. Predicated upon the substudy analyses, one objective – Nuclear Energy – was dropped from further consideration because of technological and scheduling uncertainties in its potential accomplishment. The nine remaining objectives provided the basic data for developing program options.

Each of the nine basic Space Station system objectives selected for further consideration in the study were further analyzed to identify Space Station and mission hardware requirements. This data was then used to construct 45 potential program options.

The creation of the potential program options, their evaluation, and the final grouping were established from a data base which included hardware requirements, Space Station system functional requirements, orbital regimes, schedules, and costs for various levels of objective achievement. This data base makes it possible to quickly modify or establish new options, should it be desired, and to develop comparative cost data for the various levels of objective achievement.

The accomplishment of each program option was determined by summing the number of objective requirements that it satisfied. The fraction satisfied (compared to a total of 74 requirements identified) was determined for all 45 program options. The lower content options satisfied as few as 45% of the requirements and the full content options 100%.

Seven program options were selected initially and were then analyzed further and modified to enhance their individual qualities in terms of total cost, early cost, early accomplishment, emphasis, etc. These redefined options resulted in the nine program options recommended to NASA for consideration in the next phase of the study.

The individual program option accomplishment levels and the respective program costs are plotted in Figure 18 for each program option. In general, increased expenditure results in increased accomplishment, but there are wide ranges in the slope of the relationship. The options in the lower right portion of the scatter diagram cost more for the same level of accomplishment than other lower-cost options and are, therefore, less desirable from a cost-effectiveness standpoint.

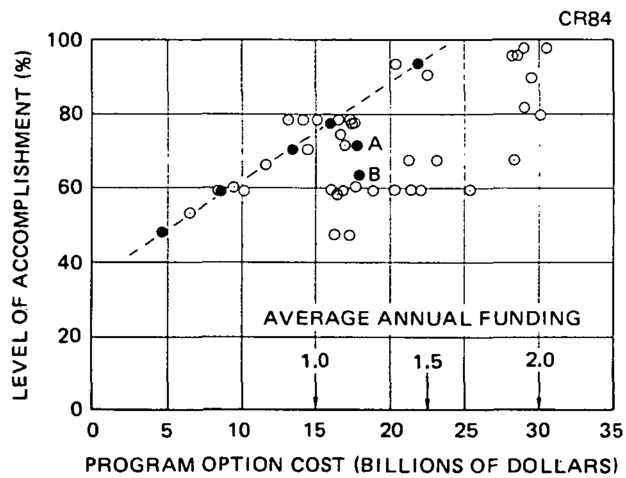


Figure 18. Option Cost Effectiveness

The seven initial program options selected are indicated by the solid circles and in general lie along an upper line representing the more cost-effective portion of the diagram. The two options, A and B, although below the maximum cost-effectiveness line, were selected because A provides a polar orbit option and B provides a cost-effective geosynchronous orbit option supported by manned sortie flights. As can be seen in Figure 18, the options are evenly distributed across the range of accomplishment levels and the range

PRECEDING PAGE BLANK NOT FILMED

of costs, thereby allowing a good range of program data for comparative purposes.

In planning future programs, it can be anticipated that the STS/Spacelab system will continue to be operational after 1983. Since the initial dollar investment in these facilities will have already been made, economic considerations alone would dictate the continued use of the Shuttle/Spacelab whenever feasible. This system can be expected to continue to support short-duration (7 to 30 days) manned operations for many years.

However, if future traffic models include operations requiring 30 days or longer for completion, or require the construction of large space structures, or have large power demands, a Space Station system supported by the Shuttle/Spacelab program would provide lower total program costs through the greater operational efficiency inherent in extended-duration operations.

Based upon these criteria, it is our recommendation that research-oriented and applications-oriented objectives which require the construction of large structures, require more than 30 days, or require more than 20 kW of power be considered as the principal activities requiring a Space Station.

Interest areas examined to date which appear to meet these criteria fall into the areas of space manufacturing and space construction. In addition, other support operations can be identified which would profit by the availability of a continuously operating manned facility in space.

During Part 1 of this study, it was found that many objectives required large space structures for their implementation and development. As a result, a concept of a basic Space Station Construction Base evolved during the study. This concept is believed to represent the significant first step to be taken in the development of the next generation of space operations beyond the early STS/Spacelab missions. The implementation of this construction base concept would also provide a basic Space Station system facility to which new modules and/or capabilities could be added in building-block fashion as demand warranted. Accordingly, it is recommended that during Part 2 this concept be pursued and a special emphasis task be initiated to define the requirements for fabrication and assembly module(s) that can evolve from small orbital operations to a full construction base capable of building the largest antenna system identified in Part 1. Questions of orbital construction versus earth-based construction should be addressed by examining specific point designs. It is suggested that an antenna and solar array for a satellite power system, a 30m radiometer, and a multibeam lens antenna system be considered as candidates for point design analysis.

A second area which would appear to warrant special emphasis during Part 2 is the area of space processing. Process steps for two or three selected production cases with attractive commercial promise need to be defined. This would require the definition of such factors as control parameters, elapsed times, equipment, and resources required in order to identify the system requirements for Space Station elements, mission hardware, and transportation systems.

As a third point of emphasis, effort must also continue to be placed on the control of costs during design. In particular, an examination of low-cost structure and its application to module design is recommended as an area of continuing emphasis throughout Part 2.

Finally, inasmuch as transportation costs are a significant factor in total program costing, it is recommended that attention also be directed in Part 2 at analyses leading toward developing the most cost-effective use of potential transportation vehicles.

In summary, the work of the past five months has resulted in the generation of objective and program option data in a form which will allow selection of the most desirable options for continuation into Part 2. In addition, the data base developed during this effort is available and documented in a format that will permit rapid derivation of additional program options if deemed necessary by the NASA.