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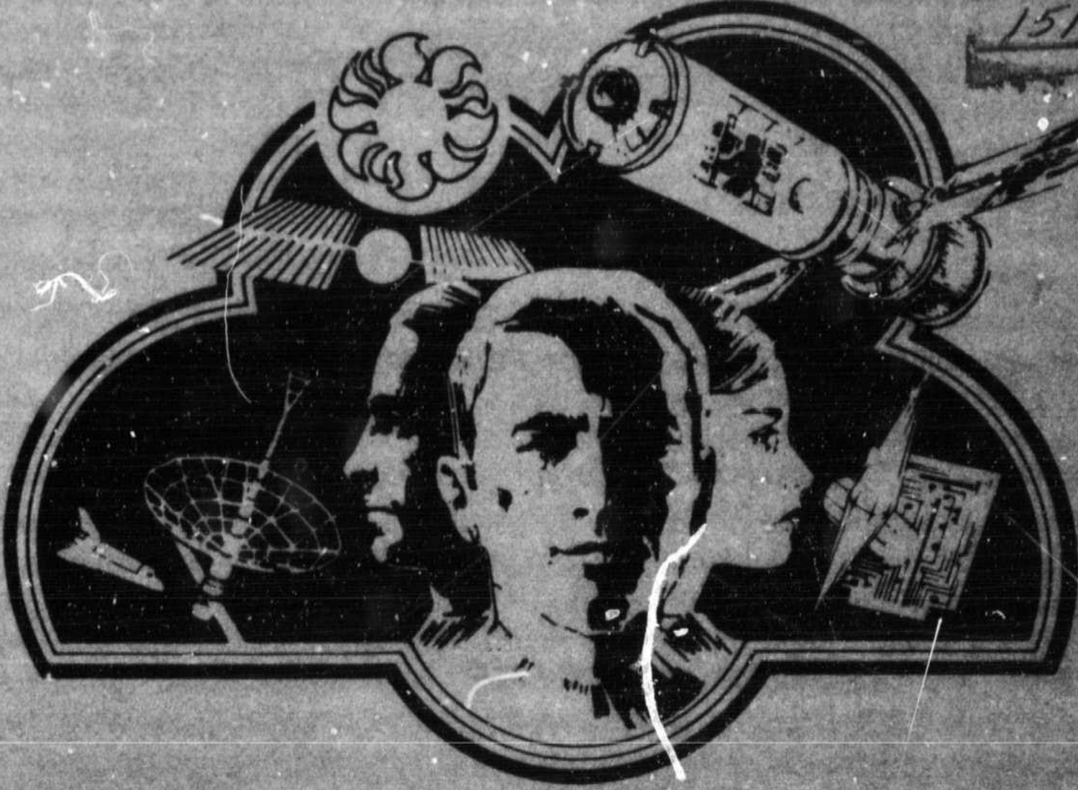

SPACE STATION SYSTEMS ANALYSIS STUDY

PART 2 FINAL REPORT

VOLUME 1
Executive Summary

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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

MCDONNELL DOUGLAS

CORPORATION

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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 manned space facility capable of orderly growth with regard to both function and orbit location. The study activity has been organized into three parts. Part 1 was a 5-month effort to review candidate objectives, define implementation requirements, and evaluate potential program options in low earth orbit and in geosynchronous orbit. It was completed on 31 August 1976 and was documented in three volumes (report MDC G6508 dated 1 September 1976).

Part 2 has defined and evaluated specific system options within the framework of the potential program options developed in Part 1. This volume is the first of three and summarizes the issues considered and the conclusions reached during this second part of the study. The companion volumes include the Technical Report (Volume 2) and the Appendixes (Volume 3).

The third and last portion of the study is a 5-month effort (February to June 1977) to define a series of Space Construction Base (SCB) concepts and to develop related figures of merit that will provide NASA planners with a basis for selection. Selected SCB concepts will be described in terms of preliminary program plans.

During Parts 1 and 2 of the study, subcontract support was provided McDonnell Douglas Astronautics Company (MDAC) by TRW Systems Group, Ford Aerospace and Communications Corporation, the Raytheon Company, and Hamilton Standard.

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INTRODUCTION

The progress of space technology has permitted space activities to expand from the early exploratory steps of the 1960's to the realization of the cost-effective applications of the 1970's. The economic benefits derived from communication satellites in providing global communication networks and from meteorological satellites in improving the accuracy and range of weather forecasts have been amply demonstrated.

The anticipated reduction in the cost and complexity of delivering payloads to space as provided by the Shuttle Transportation System, currently under development, can mark the beginning of a new era in the exploration and use of space. To fully exploit this potential in the 1980's and beyond, increasing use of manned facilities can be anticipated. The rich heritage of manned space experience, culminating in Skylab and Apollo-Soyuz, when combined with the flexibility of the Shuttle, can provide the mechanism for investigating, understanding, and solving many of the critical problems which we and the rest of the world will face in the next 50 years. The growth path will progress from the limited-duration Shuttle and Spacelab missions to permanently manned stations. Initially, these stations can be assembled from modular units delivered by the Orbiter and can grow in size and capability to provide construction bases for the large public service communication antennas, for new energy systems, and for the industrial applications of the future.

The fact that this capability can be developed does not establish the fact that it will be, nor does it determine when it should be developed. Priorities depend on changing political, economic, social, and technological factors.

The purpose of this study is to provide information to NASA program planners which can help solve the difficult problems of apportioning limited resources among an almost unlimited number of candidate projects – and in doing so, to provide a sound technological base capable of developing and preserving the options open to our nation in the decades to come. The course to be charted requires long-range planning to ensure that fiscal commitments will be met and that required systems and components will be available when needed. At the same time there must be flexibility for allowing modifications as constraints and objectives change.

The direction in which this nation's manned space program should proceed depends on the answers to the following questions:

1. **What key objectives should be pursued in the next 10 years?**
2. **Are there common support requirements for these objectives, and if so, what are they?**
3. **What is the potential role of the Shuttle? Spacelab? The Space Construction Base?**
4. **What program options represent potentially viable candidates?**
5. **What configuration concepts can support these program options?**
6. **Are orbital construction facilities practical?**
7. **Where should space construction projects be accomplished – at low earth orbit or geosynchronous orbit?**
8. **What are the transportation requirements for the potential program options?**
9. **What technological steps, developments, or breakthroughs are required?**
10. **What are the expected milestones and schedules?**
11. **What are the expected costs?**
12. **What have we learned so far?**
13. **What planning and analyses remain to be done?**
14. **At this time, does there appear to be sound justification for a national commitment to proceed with the development of a Space Station?**

The issues examined, and the answers to the above questions which have been developed in the study to date, are discussed on the following pages.

Question 1
WHAT KEY OBJECTIVES SHOULD BE PURSUED IN THE NEXT 10 YEARS?

At the outset of Part 1 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 as potential candidates for Space Station systems support.

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 the success of a mission and enhance the productivity of spaceflight activities with respect to modification and improvisation. Accordingly, in the initial study effort, emphasis was placed upon those potential areas where manned space programs might be expected to make a significant contribution. Forty-seven of the 61 objectives from SP-386 were identified as requiring the support of man in space, either in the Shuttle sortie mode or in extended-duration facilities.

In our analysis, the 47 SP-386 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 10 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 Laboratory
- Sensor Development
- Living and Working in Space

The objectives 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 frames for application of the individual objectives lay beyond the period of interest for Space Station program options (approximately through 1995), they were not included.* As a result of this effort, eight objectives were recommended for consideration in the development of program options during Part 2 of the study.

The objectives selected from Part 1 of the study to be the point of departure for Part 2 are summarized as follows:

- **Satellite Power System (SPS).** Provide a facility for the construction of test articles and permanent space test capability for evaluation of the technical and economic feasibility of SPS.
- **Earth Services.** Conduct research and development and construct large antennas and associated hardware required for:
  A. Domestic and international communications services
  B. Earth and atmospheric surveys
- **Space Cosmological Research and Development.** Perform R&D on space cosmology-related components and construct a large microwave telescope.
- **Space Processing.** Conduct R&D to determine the technical and economic feasibility of commercial inorganic processing and biological materials applications, and support, as appropriate, the initial commercial use of these processes.
- **Multidiscipline Science Laboratory.** Provide a multidiscipline laboratory to conduct space research in the basic and applied sciences.
- **Sensor Development Facility.** Provide a facility for the test and evaluation of optical sensors for earth sciences and cosmological phenomenon.
- **Living and Working in Space.** Demonstrate long-term living and working in space as related to other manned space objectives.
- **Orbital Depot.** Perform the necessary R&D and develop the orbital operations for an orbital transfer vehicle system.

Each of the objectives selected was studied in greater depth to define the steps that would be necessary to realize the stated objective. In each case, a set of functional requirements was derived which identified specific technology advancement needs, tests that must be conducted, and processes that must be developed.

*It was recommended that the development of space-based nuclear energy systems be deferred on this basis. The cluster support system concept was also deferred since it also did not show promise of sufficient application in the time period of interest.

Methods for satisfying the functional requirements were then derived, and those that required Space Station support were identified. For each of these, an objective element was defined – an objective element being the physical facility, equipment item, test apparatus, structural assembly, etc. needed to perform the required function. These objective elements and the requirements they impose form the basic set of information needed to define facility requirements and potential program options.

As an illustration of the factors considered in the analysis of requirements for future space facilities, three examples are presented: satellite power systems, space processing facilities, and earth services facilities.

Satellite Power System Objective

This objective was chosen because it preserves an option for developing an alternate power source that cannot be depleted, is not imported, and appears to be economically and environmentally acceptable. Power generation in space by SPS has significant potential by virtue of almost continuous sunlight (6 to 15 times terrestrial availability). SPS energy is easily exportable and offers balance-of-trade potential.

In order for a commitment to be made to SPS, demonstration of technical and economic feasibility is required. Then, if a commitment decision is made, a development program must be initiated.

Accordingly, a minimum system capable of resolving the most critical technology issues at the lowest possible cost was derived and was designated Test Article-1 (TA-1). This would be followed by a second test article (TA-2) which would provide cost data and information pertinent to the determination of how an SPS might be fabricated and assembled on orbit, as well as key end-to-end functional verification of such issues as two-dimensional phase control and the thermostructural effects. This effort would be planned to be completed in time to provide data and experience to support programmatic decisions with respect to SPS by 1987. Finally, assuming a commitment is made, a partial prototype test article (TA-3) of the full SPS would be fabricated.

A summary of the critical SPS test article functional requirements is listed in Figure 1, along with an indication of the capability of the various SPS

FUNCTIONAL REQUIREMENTS	TEST ARTICLES		
	LEO		GEO
	TA-1L	TA-2	TA-1G
EVALUATE SPACE FABRICATION OF LARGE STRUCTURES			
SOLAR COLLECTOR		X	
MICROWAVE ANTENNA	X	X	X
STRUCTURAL INTERFACES	P	X	P
EVALUATE LARGE-SCALE ENERGY COLLECTION AND DISTRIBUTION			
20K VOLTS	P	X	
SWITCHING		X	
EVALUATE LARGE-SCALE MICROWAVE TRANSMISSION AND CONTROL			
IONOSPHERIC DEGRADATION OF PHASE CONTROL SYSTEM			X
THERMOSTRUCTURAL EFFECTS ON PHASE CONTROL SYSTEM	X	X	X
EVALUATE RADIO-FREQUENCY INTERFERENCE EFFECTS			
DIRECT TRANSMISSION FROM AMPLITRONS	X	X	X
SWITCHING AND ROTARY JOINT SOURCES	X	X	P
VOLTAGE LEVEL REGULATION	P	X	P
IONOSPHERE INDUCED			X
SPACE PLASMA EFFECTS			
ARCING AND LEAKAGE	X	X	X
SPACECRAFT CHARGE PHENOMENA			X
END-TO-END FUNCTIONAL VERIFICATION			
THERMAL-STRUCTURAL INTERACTION	P	X	
PHASE CONTROL SYSTEM	X	X	
POWER TRANSFER AND ROTARY JOINT CURRENT DENSITY	P	X	
PROTOTYPE MANUFACTURING AND ASSEMBLY PROCESSES	P	X	

P=PARTIAL SATISFACTION

Figure 1. SPS Objective Element and Requirements Matrix

objective elements to resolve the issues. The functional requirements are SPS technology advancement issues. This list was derived jointly by Johnson Space Center, Lewis Research Center, MDAC, and Raytheon. TA-1 operates in both low earth orbit-LEO (TA-1L) and geosynchronous orbit-GEO (TA-1G), while TA-2 is used only in LEO. The TA-1L test activity consists mostly of checkout and performance calibration prior to its being sent to GEO. TA-1 would be used to resolve microwave issues, particularly for operation in the GEO environment and transmission through the ionosphere (heated up-beam HF). TA-2 would be involved primarily with investigating the solar collector issues and system end-to-end functional verification.

A schematic description of the various SPS test articles that were considered is presented in Figure 2.

A sketch of the TA-1L/G antenna is presented in Figure 3, which also shows the length of the various waveguide sections and the installation of the antenna and its phase control electronics. The horizontal arm of the antenna has a 2.39-m waveguide in the center, and the vertical arm has two of these 2.39-m sections, one on either side of the center. The antenna is two waveguides wide (one operating and the other for redundancy). The 46 amplitrons allow 100% redundancy. The outboard waveguides (14.36 and 28.72 m) use corporate feed with the amplitron in the center of the waveguide; all other waveguides are fed at the end.

Even though the waveguide length being powered by a single amplitron varies from 2.39 to 28.72 m for amplitude tapering purposes, a separate phase shifter would be proposed to be employed every 2.39 m to properly facilitate phase steering.

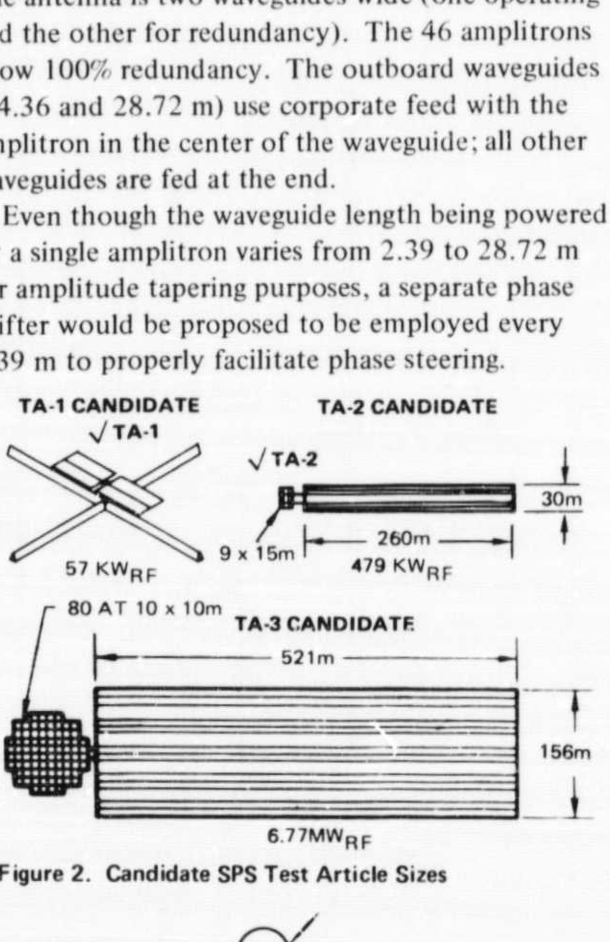


Figure 2. Candidate SPS Test Article Sizes

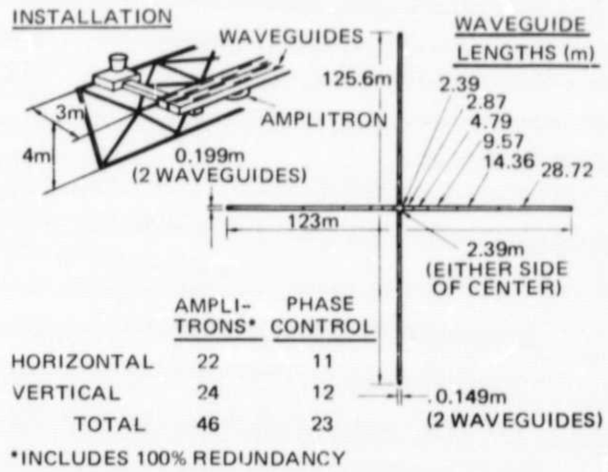


Figure 3. SPS Test Article 1 Antenna

Space Processing Objective

Preliminary studies and experimental results from the Apollo, Skylab, and ASTP missions indicate that space processing may be a potential commercial source of improved or unique products for use on earth. Market projections for new products such as silicon ribbon, ultrapure glasses, pharmaceuticals, and biological materials (e.g., the enzyme urokinase) show significant potential.

Space processing will ultimately be justified if it can become a commercial source for materials not obtainable at competitive costs on earth. In this context, this objective has a strictly commercial emphasis, i.e., made-in-space products having a unique utility in the economy. Therefore, the characteristics of the program to transition from R&D to full-scale commercial production in space must reflect the following:

- Continued applied R&D activities in basic chemistry and physics, materials sciences, pharmaceuticals, electronic materials applications, optical materials and components, and other man-made products that offer a commercially significant potential.
- Development of in-space processes and procedures that ensure control of material characteristics, uniformity, dimensional precision, and on-schedule production of quantities commensurate with industrial operations.
- Demonstration of production yields in sufficient quantities and quality to assure commercial interest and economy as opposed merely to demonstrating scientific or technical feasibility.
- Demonstration of man-machine interactive

designs that will take cost-effective advantage of automated, semiautomated, and manual operations, including all aspects of the production process (i.e., fabrication, assembly, test, quality control, packing, and transportation).

Three cases were selected as being representative of a broad class of future commercial space processing activities (see Figure 4). The first case was the production of the enzyme urokinase, which involved a process designed around a separation

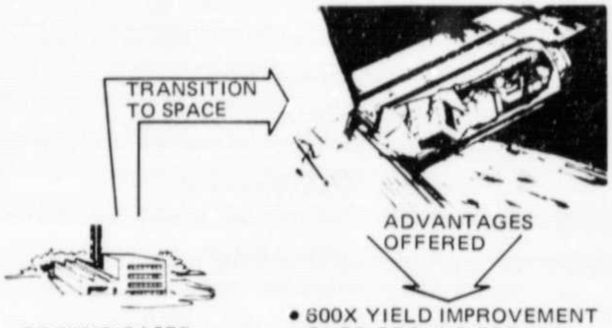


Figure 4. Space Processing Commercial Interests

procedure and two cell growth cycles. This process is typical of the production of a biomaterial in final form in space. According to researcher Dr. Grant Barlow of Abbott Laboratories, this type of process may offer great improvement in the product potency over that possible on earth. He bases this estimate in part on the successful electrophoresis technology experiment conducted on Apollo-Soyuz. The encouraging results of this experiment showed that one fraction of the cells separated produced six times more urokinase per cell than did ground-based control cultures. He predicts that additional improvements in all steps of the procedure (i.e., the separation process and the two growth steps) will yield an overall projected improvement of 600 times that which could be expected on earth. This potential improvement by space processing could prove to be the breakthrough necessary to make such life saving pharmaceuticals available to the public, thereby making possible their use in routine clinical practice rather than in experimental medicine only.

The second case selected described the production of an ultrapure glass in space representative of the high technology-unique materials useful in new and novel products of the future. At the suggestion of Owens-Illinois, the prototype product upon which this case was focused consisted of glasses formed in space which would possess superior characteristics insofar as optical properties and internal impurities are concerned. These improvements would be important in fiber optics applications. The TRW Systems group estimates the ultrapure material used in the manufacture of fiber optics communication cables could reduce the transmission losses to the point where a savings in other components of the communication system (i.e., repeaters) would equate to $59,000 for every kilogram of ultrapure glass used in the system. Projected annual savings, along with the specific savings, were estimated by TRW and Owens-Illinois to be $236 million at the time the original case selection was analyzed.

The third and last case selected was production of semiconductor-grade silicon in ribbon form. A survey of private industry provided a projection of the demand for integrated circuits, for which semiconductor silicon is the basic raw material, to reach 200,000 kg (478,000 lb) by the year 1990. At a finished cost of $100,000 per kilogram, this demand equates to a $20 billion annual market. A Feasibility Study of Commercial Space Manufacturing conducted by MDAC-E (Reference: Contract NAS-8-31353 with NASA MSFC) provides an estimated savings (increase in value added) of 22% of final demand by using silicon ribbon produced in space in place of conventional material. The economics of this case study pointed to a total potential increase in value added of $4.4 billion annually. Even if space-produced silicon ribbon captures a mere 10% of the total market for integrated circuits, this would represent a potential revenue of $440 million annually by the year 1990. This high economic leverage represents one of the more important features of this third case.

Earth Services Objective

To conduct passive microwave radiometry, the Outlook for Space called for long-wavelength microwave system development leading to operational systems for conducting marine resource evaluation, all-weather crop prediction, and regional water balance forecasting. Other studies, among them the Study of the Commonality of Space Vehicle Applications to Future National Needs, Aerospace NASW2727, have suggested the high value and use of small portable personal communication facilities, electronic mail, and other communication-oriented capabilities.

To accomplish these objectives, the designs, tools, methods, and materials required to construct, assemble, and test large antennas in space which will maintain their structural integrity and beam-pointing capability when subjected to thermal and other stresses must be developed. It is anticipated (reference Aerospace NASW2727) that three antenna types for radiometric and communications applications will require development, i.e., parabolic "dish," multibeam lens, and large-phased array antennas. As a precursor to the development of 100 to 300 m or larger antenna systems, it appeared desirable to introduce a smaller prototype into the antenna development program at an early stage. The intent is to reduce development risk and the cost of changes or modifications incurred in the learning process of on-orbit large-scale construction.

Accordingly, based upon the design requirements and trade studies, a design concept for a 30-m radiometry satellite was evolved. Its system and antenna characteristics appear in Figure 5. It is designed to cover all frequency bands of interest in earth observations while scanning perpendicular to the orbit track of the Space Station. Stabilization requirements were assumed at approximately 10% of the beamwidth. Since the satellite is passive in nature, power requirements should not exceed 2 kW.

Large space antennas will either be assembled in space or will be designed to be deployable. Antennas are placed in the assembly or erectable category if their shape is such as to make deployment difficult, i.e., if unfurling mechanisms and hinges become complex, and if damping must be employed to prevent excessive backlash. Another factor to be considered is the surface tolerance which can be achieved. Higher frequencies require tighter tolerances.

The 30-m scanning parabolic torus, which is proposed for earth observations and limb-sounding radiometry, falls in the space assembly category due to its odd shape and requirement for precise alignment (Figure 6). By way of comparison, the 9.1-m

SYSTEM	
FREQUENCY BANDS (GHZ)	0.6 – 118
RADIOMETER CHANNELS	28
BEAM STABILIZATION (DEG)	±0.0015
ALTITUDE (km)	340 – 800
INCLINATION (DEG)	54
POWER REQUIRED (kW)	2
ANTENNA	
DIAMETER (m)	30
BEAMWIDTHS (DEG)	2.3 – 0.012
POLARIZATION	HORIZONTAL AND VERTICAL
SCAN ANGLE (DEG)	100
SURFACE TOLERANCE (cm)	0.03

ANTENNA TYPES

PARABOLIC "DISH"

5 TO 20 DEG OFF AXIS. FUNCTION OF AMOUNT OF ACCEPTABLE ABERRATION (CHROMA)

LONG FOCAL LENGTH REDUCES PROBLEM BUT RESULTS IN UNWIELDY DESIGN

√PARABOLIC TORUS

±60 DEG PERPENDICULAR TO GROUND TRACK

Figure 5. Radiometry Satellite Design Requirements

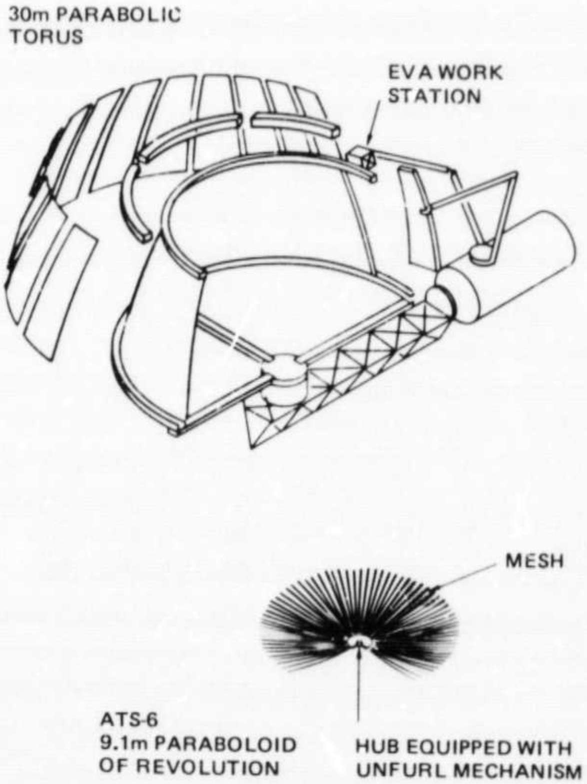


Figure 6. Types of Large Space Antennas

ATS-6 antenna is in the deployable category. The symmetrical shape of the ATS-6 provided by the paraboloid of revolution allows a simple unfurling mechanism to be employed. The ATS-6 type is usually used to produce spot beams in TV broadcasts, high-rate communications, and planetary radiometry applications. Today's technology would allow operation of this type of antenna to 10 GHz at 40-m diameters and 0.5 GHz at 180-m diameters.

Due to the complexity engendered in attempting to scale up the 30-m antenna to larger diameters while retaining the surface tolerance and scan rate requirements of the higher frequencies, it was decided to split spectral band assignments. As shown in Figure 7, divisions were made where the diameters required to provide 1-km resolution at 800-km altitude were exceeded. The result was to identify three frequencies of interest for the 100- to 300-m antennas, four frequencies of interest for the 30-m antennas, and three frequencies of interest for the 4-m antenna. For the purpose of defining space construction requirements, emphasis in the present study has been placed upon the larger antenna sizes (30 to 300 m) with surface tolerance root mean square requirements of 0.035 to 0.48 cm.

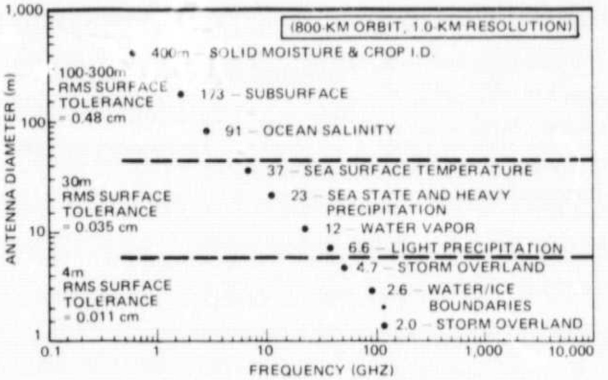


Figure 7. Allocation of Spectral Bands to Antennas

In summary, many objectives have been identified in previous studies which have the potential of satisfying a basic need or goal of mankind. Eight specific objectives have been identified in the present study which should be pursued in the near-term. Four of these objectives – satellite power systems, earth services (large antenna systems for communications and radiometry), space cosmological research and development, and space processing – represent major goal-directed program concepts. The remaining four – multidiscipline science laboratory, sensor development facility, living and working in space, and orbital depot facility – represent support functions that will be required as basic building blocks in the future expansion of all areas of space activity. These building blocks would not only support the four major program concepts but would provide the basic system elements capable of meeting additional requirements as they arise.

As an example of the way in which the basic facilities can be directed toward new goals as they are established, consider a planetary sample return mission. Although it would be possible to return the sample (from Mars, for example) directly to earth, orbital examination provides advantages in terms of prevention of possible contamination and should be given serious consideration in future planning of such a mission. This would suggest that a manned space platform can play a significant role in a planetary sample return mission.

A typical Mars sample return (MSR) mission profile is shown in Figure 8. The mission would depart from a Shuttle-compatible earth orbit and travel on a conjunction-class interplanetary trajectory. The conjunction class mission takes longer because of the year required in the same orbit as Mars, but has lower overall velocity requirements.

The direct Mars entry shown does not need a separate Mars Orbiter and requires less velocity than Mars orbit rendezvous. It also is simpler since it does not call for automated in-orbit rendezvous and sample transfer.

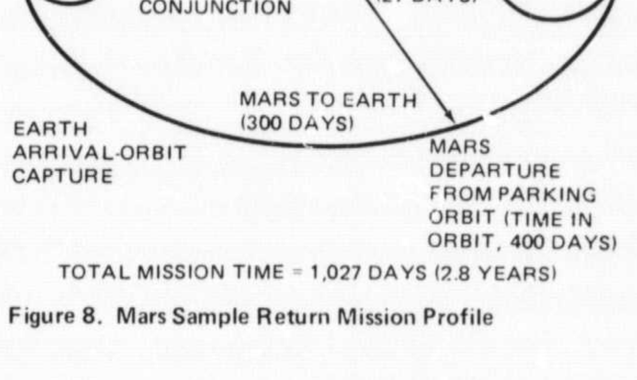


Figure 8. Mars Sample Return Mission Profile

Departure from Mars would be from parking orbit, and orbit insertion at earth arrival is preferred because it permits the taking of necessary steps for dealing with the hazards of back contamination.

As shown in Figure 8, the total mission time would be almost three years.

Upon return from Mars, an earth-orbiting capsule (EOC) and sample container will be placed in earth orbit. A Shuttle Orbiter will retrieve the capsule and proceed to rendezvous and dock at the manned space base. At that time, a crane will remove the EOC and container and place them at the Mars sample return laboratory airlock (Figure 9).

The sample container can then be removed from the EOC via remote manipulator and placed in the designated Mars sample isolation chamber part of the Multidiscipline Science Laboratory, from whence subsequent scientific examinations will take place. Decisions can then be made as to whether to leave the sample in the orbiting laboratory, destroy it, or bring it to earth.

A number of requirements for a planetary sample return facility have been identified during the study, and other requirements were provided by NASA/JSC. These include environmental conditions to be maintained; TV, communications, and scientific data systems needs; numbers and types of

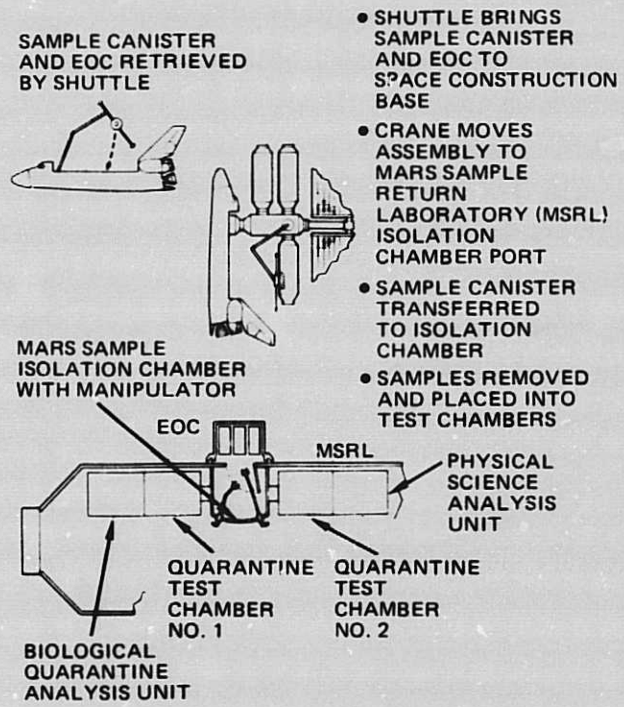


Figure 9. Retrieval of Mars Sample Canister

experiment systems, etc.

As can be seen, the basic Space Station and construction base facilities have the flexibility and growth potential to accommodate a broad range of new requirements as they emerge.

Question 2

ARE THERE COMMON SUPPORT REQUIREMENTS FOR THE THESE OBJECTIVES, AND IF SO, WHAT ARE THEY?

Considerable commonality was found among the support facilities required to accomplish the objectives examined in this study. The commonality of operational requirements can also result in a desirable synergism in cost savings which can be expected to extend at least over the next 10 years. The most common support requirements were found to be the need for crane operations, space fabrication facilities, space assembly capabilities, extravehicular activities, and general support for long-duration operations. In Figure 10, major requirements for a particular objective element are indicated by a large check mark, minor requirements by a small check mark.

OBJECTIVE ELEMENT	CRANE OPNS	SPACE FAB	SPACE ASSY	EVA REQMTS	LONG DUR
TEST ARTICLE 1 (TA-1)	✔	✔	✔	✔	✓
TEST ARTICLE 2 (TA-2)	✔	✔	✔	✔	✓
30 m RADIOMETER ANTENNAS	✔	✓	✔	✔	✓
SPACE PROCESSING	✓				✔
MULTIDISCIPLINE LABORATORY	✓			✓	✔
LIVING & WORKING IN SPACE	✓	✓	✓	✓	✔
SENSOR DEVEL & TEST	✓		✓	✓	

Figure 10. Objective Elements Have Common Requirements

As can be seen in the figure, all objective elements require crane operations to a major or minor extent. In particular, crane operations for SPS TA-1 and TA-2, and for the 30-m radiometer, are a major requirement in the fabrication and assembly of those elements. However, the laboratory-type elements basically require crane operations only initially to position the module or to supply necessary materials.

Requirements for space fabrication facilities were identified in developing the test articles for advanced solar power satellites as well as in constructing the final operational system. Similar technology and orbital facilities will be required in the construction of large antenna systems and, to a lesser extent, space fabrication will be required in the basic buildup of the Space Construction Base itself. Space fabrication of components, as opposed to transporting finished parts to orbit, can be justified if total construction costs are thereby reduced. In general, two conditions must be met to satisfy this requirement. First, density of the component in question must be so low that transportation costs may be significantly reduced by shipping only bulk materials to orbit. Secondly, the fabrication process "orbital overhead" costs must be less than the transportation cost saving. This second condition typically involves automation of the process to reduce required fabrication manhours. Hence, sufficient production to amortize the necessary investment in fabrication equipment is also a strong requirement.

Examples of fabrication processes that may be simply automated are pultrusion (plastics and composites) and roll forming (ductile metals). Such machines are currently highly developed and capable of producing a great variety of cross-sections (tubular, channels, Z-sections, etc.).

In space assembly the crane is of primary importance because it is used on all construction projects as well as in both the initial buildup of the base and continuing support of base housekeeping and logistics support. Furthermore, general-purpose maintenance provisions, including shop support for minor repairs, will be particularly important in all space operations, including assembly tasks, because of logistics transport costs. This implies not only a considerable spare parts inventory on orbit but a necessity for careful consideration of maintenance and fault location system requirements during the design phase.

It is interesting to note that analysis of the operations requiring space fabrication and/or assembly revealed that significant supporting EVA effort is required. Of particular interest was the evaluation of what an EVA crewman needs to do his job. At each EVA work station, a significant complement of tools, services, restraints, force/torque reaction capability, etc., was found to be necessary. It became clear that the required equipment is beyond that which can be conveniently carried by the EVA crewman. This led to the conclusion that separate, semicontained quarters at each EVA work station are needed.

Two EVA crewmen working together are needed not only to perform many of the tasks, but because of the desirability of having each act as the other's companion for safety.

In the area of long-duration crew support, basic habitability functions such as food and waste management systems, environmental control and life support systems, hygiene, etc., can be expected to be common to all of the objectives. In the same fashion, many resource functions such as electrical power systems, communications, data management command and control systems, stabilization, and guidance concepts will also have a great deal of commonality over the spectrum of potential objectives.

Question 3
WHAT IS THE POTENTIAL ROLE OF THE SHUTTLE? SPACELAB? THE SPACE CONSTRUCTION BASE?

Expendable launch vehicles will be phased out as the Shuttle becomes operational; as a result, the Shuttle Orbiter will be the logistics workhorse of space for many years to come. With regard to Spacelab, a review of currently proposed NASA mission models and other related mission-planning materials indicates that significant research and development work will be accomplished during STS-Spacelab missions programmed for the 1980 to 1983 time period in the areas of space processing, life sciences, physics and astronomy, earth sciences, and space technology. The experience and data from these earlier efforts will provide the point of departure for the missions to be defined for the time period beyond 1983.

Furthermore, it can be anticipated that the STS-Spacelab system will not only continue to be useful for special missions and support operations after 1983, but because the initial dollar investment in these facilities will have already been made, economic considerations alone would dictate the continued use of Shuttle-Spacelab whenever feasible. This system can be expected to continue to support manned operations of short duration (7 to 30 days) for many years.

Figure 11 summarizes the mission durations, payload weight, crew sizes, power, orbital regimes, and manhours per year, which can be anticipated for the basic Shuttle-Spacelab system, and for the Space Construction Base (SCB). Areas of capability overlap are also indicated. The final program plan developed for the 1980's must achieve an optimal balance of the potential capabilities which will be available.

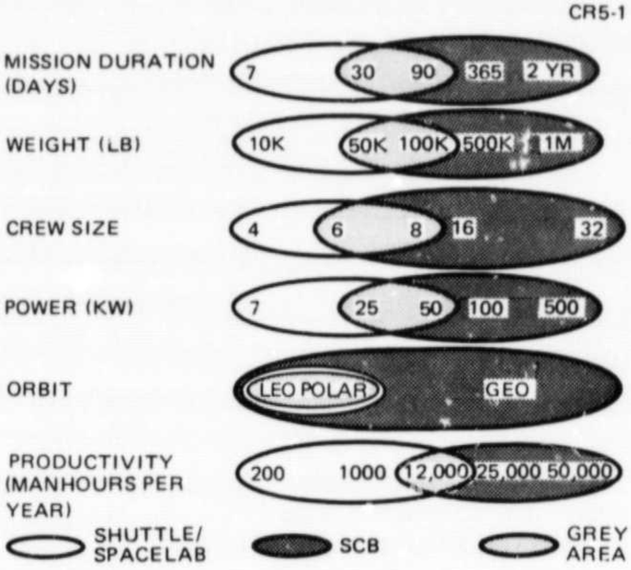


Figure 11. Operating Regimes for Space Construction Base and Shuttle/Spacelab

To illustrate the companion roles for the Spacelab and the SCB, consider the area of space processing. Production process development and optimization activities will require a significant on-orbit capability. However, as can be seen from Figure 12, the requirements described for the mission duration and average power in three types of processing generally exceed Spacelab capabilities. Therefore, it would not be feasible to mechanize the entire complement of mission hardware necessary to pursue product-oriented process development and optimization activities within the confines of Spacelab, although certain individual steps could be investigated during Spacelab missions. For example, the continuous electrophoresis separation process, which is a crucial part of the production process flow, could be evaluated in part by means of Spacelab missions. Once this system element is brought to the operational state, it could then be incorporated into the total processing system developed for the larger Space Station. In this same fashion, it is visualized that the Shuttle-Spacelab will continue to provide complementary support in all applications areas to the initial SCB and to larger space programs into the foreseeable future.

The boundaries of the transition zone between extended-duration Shuttle capabilities and those which are better provided by a permanent, con-

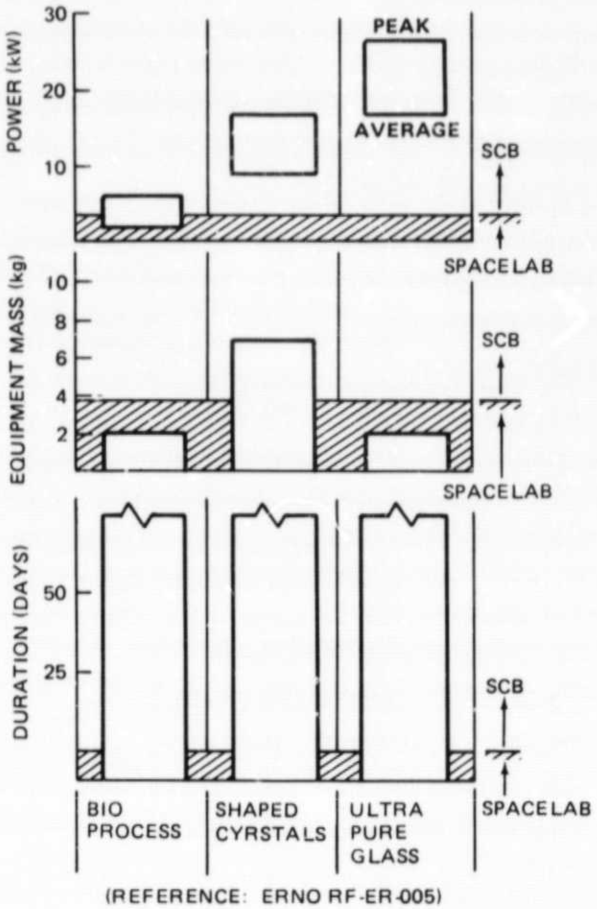


Figure 12. Comparison of SCB and Spacelab for Space Processing

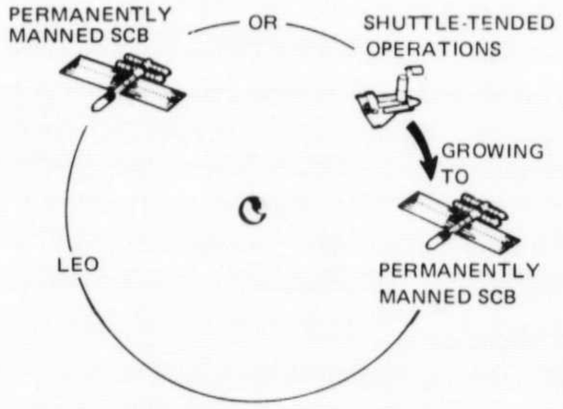
tinuously manned space platform, will be largely dependent upon the specific missions to be accomplished and the allowable rate of expenditure. In space construction activities, for example, the present study has examined "Shuttle-tended" approaches as well as the "continuously manned permanent platform" approach. In the "Shuttle-tended" case, support for the crew and basic operations is provided directly by the Shuttle Orbiter. The Orbiter is docked at the construction site and provides support for 30 days. At the end of this period, the construction crew and the Orbiter leave and are replaced by another Orbiter and a new crew at a later time. Under these conditions, the space construction base will have 120 days of unmanned free flight capability for maintaining orbital location. The alternative is to proceed directly to a permanent construction facility which is continuously manned. The findings to date suggest that for single objective, nonrecurring, construction tasks, the Shuttle-tended mode of operation can offer considerable savings in total program costs. Once a commitment is made, however, to provide a continuously manned facility, whether to support multiple construction tasks or for other research and application purposes, the Shuttle-tended or extended-duration Orbiter mode of continuous manning becomes more costly and therefore less desirable than proceeding directly to the development of a permanently manned space base.

Question 4
WHAT PROGRAM OPTIONS REPRESENT POTENTIALLY VIABLE CANDIDATES?

As potential program options were being examined, the objective elements (which are items of mission hardware) were categorized according to their operational requirements into low earth orbit (LEO, approximately 200 nm), geosynchronous orbit (GEO), and combinations thereof. The general definitions of the program options were:

Program Option	Prime Characteristics
LEO (L)	Operations limited to LEO
LEO/GEO1 (LG1)	Operations in LEO with some test operations in GEO
LEO/GEO2 (LG2)	Operations in LEO with some construction and test operations in GEO
GEO (G)	All operations in GEO

For LEO, two operational modes (Figure 13) were investigated:

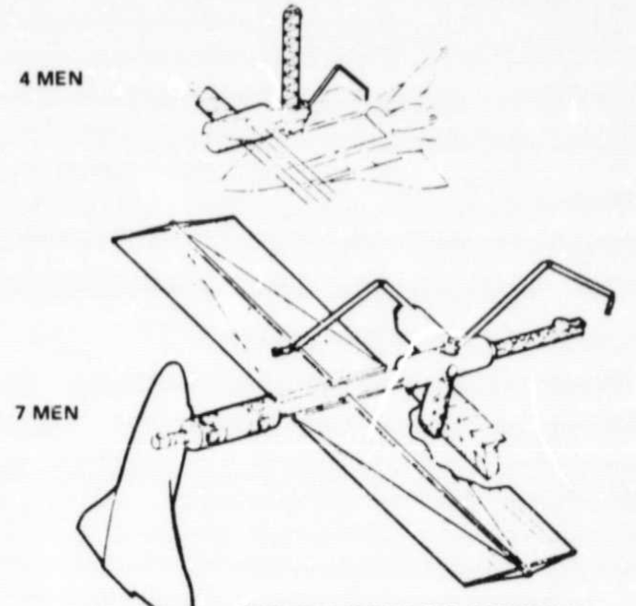


OBJECTIVE ELEMENTS
- SPS TA-1
- SPACE PROCESSING
- EARTH SERVICES 30M RADIOMETER
- SPS TA-2
- MULTIDISCIPLINE LAB
- LIVING AND WORKING IN SPACE
- SENSOR DEVELOPMENT

Figure 13. Program Option L, Low Earth Orbit Operations

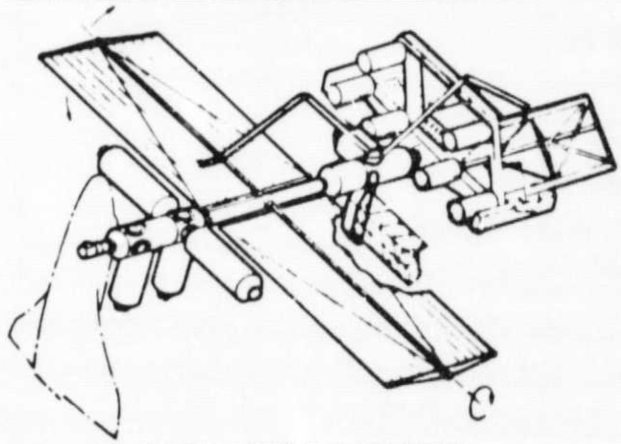
1. Early Shuttle-tended operations, during which elements of a permanently manned Space Station or space construction base (SCB) are used only while the Shuttle is present. Subsequently, when a full SCB is assembled and activated, the Shuttle continues to supply logistic support.
2. Construction and activation of a full SCB prior to operations.

As shown in Figure 14, the Shuttle-tended concept can provide a space construction fabrication



- FABRICATION AND ASSEMBLY

1984-1986
SHUTTLE-TENDED (4 TO 7 MEN)



- FABRICATION AND ASSEMBLY
- SPACE PROCESSING
- MULTIDISCIPLINE LABORATORY
- SENSOR DEVELOPMENT AND TEST
- LIVING AND WORKING IN SPACE

1986-1988
PERMANENTLY MANNED (7 MEN)

Figure 14. Evolution of Option L SCB Configuration

and assembly capability only, or it can be expanded to include space processing development activities. Crew requirements are compatible with the Shuttle support capability of up to seven SCB crewmen. Fabrication and assembly operations require three crewmen for nominal tasks (plus the Orbiter pilot, who must remain in the Orbiter for monitoring and system safety), and three crewmen to work the "second shift" in construction and to conduct space processing development tests. Thus, the number of crewmen in the Shuttle-tended mode may vary from four to seven.

For similar reasons, the initial growth step in the permanently manned class was established at a 7-man crew size. This permanently manned SCB configuration is shown in the 1986-to-1988 time frame. An alternative to this evolutionary sequence would be the direct path to the permanently manned SCB, which would advance in time the number of objectives accomplished.

Program Option LG1 expands the LEO activities to include construction of large structures in LEO, which are then transported to GEO for test and operations. These activities use an all-up SCB in LEO and an orbital transport vehicle (OTV) for transport to GEO; manned test and operations in GEO are accomplished by GEO sortie missions or by use of a small Space Station at GEO. As indicated in Figure 15, in this Program Option, all objective element activities are undertaken wholly or in part at LEO, and only those gaining significant advantage from GEO are transferred.

Program Option LG2 expands on LG1 by providing for the construction at GEO of the objective elements to be used there. This is accomplished by providing a permanently manned SCB at GEO, in addition to the one at LEO. Logistics is supported by Shuttle and an OTV. Figure 16 indicates the division of activities between LEO and GEO for LG2.

Program Option G consists of an all-geosynchronous option that accomplishes the five objectives shown in Figure 17. Two modes of this option were analyzed. The first mode was based upon the early establishment of a permanent SCB at GEO. The second mode also established a permanently manned SCB, but at a later time – it

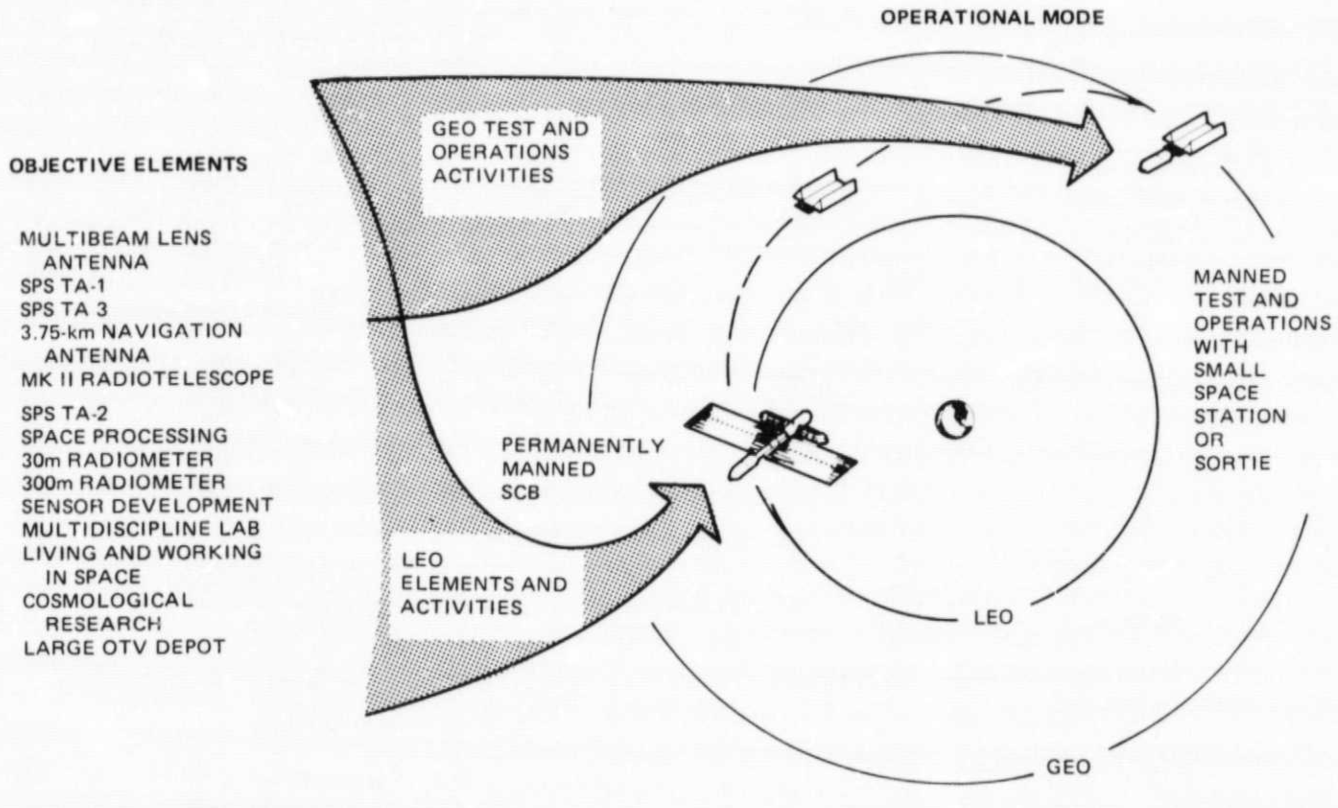


Figure 15. Program Option LG1

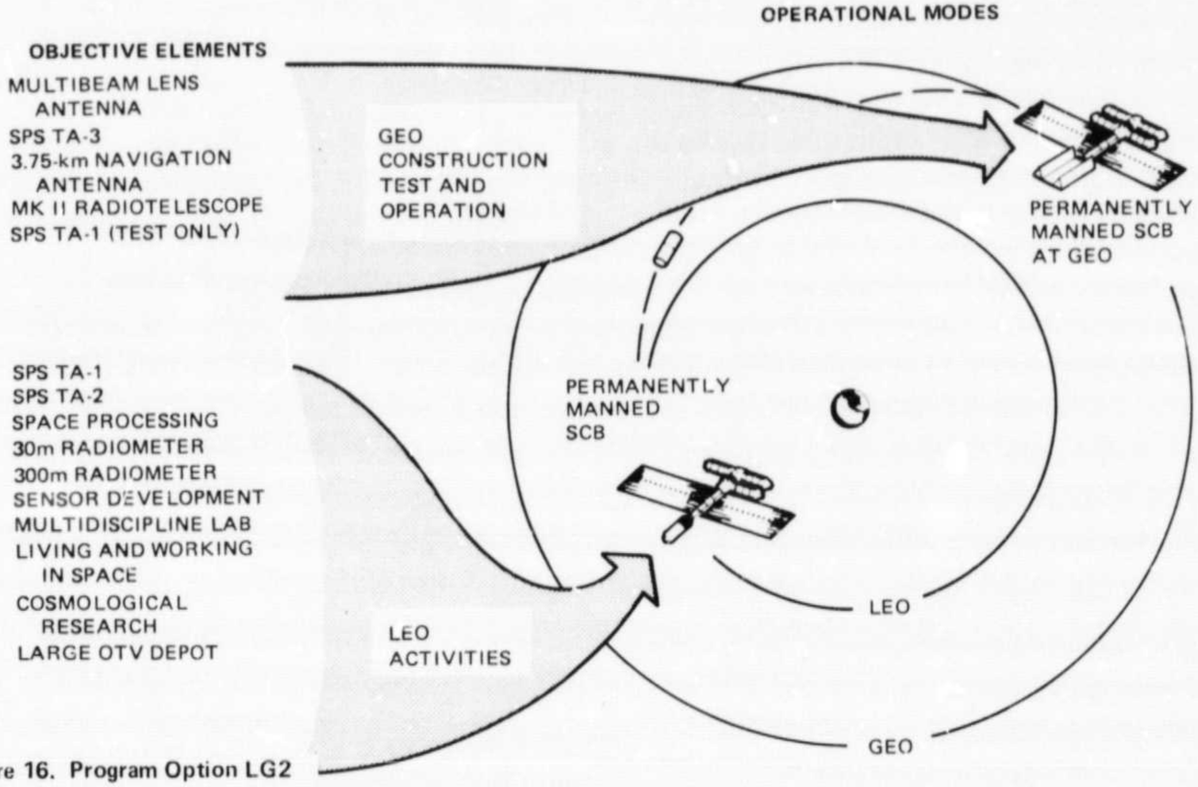


Figure 16. Program Option LG2

would be preceded by OTV-supported sortie missions. In Program Option G, the TA-1 objective is not begun until the permanent SCB has been established, while work on the other four objectives is initiated at the outset.

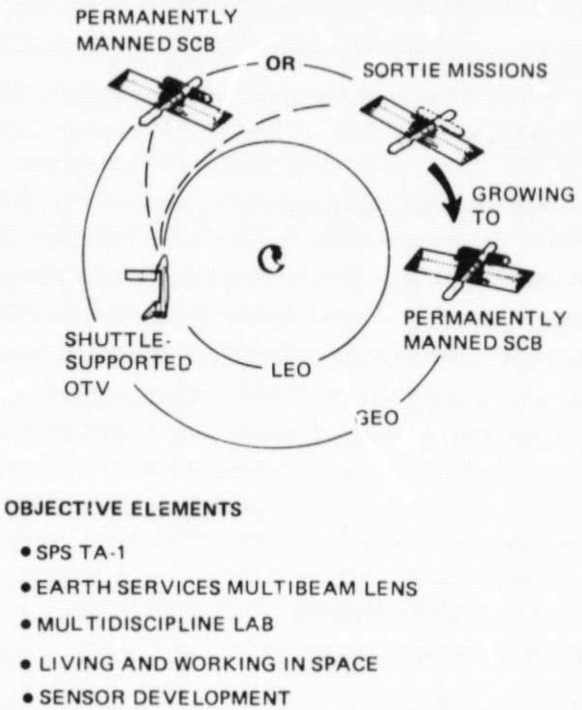


Figure 17. Program Option G

In the present study, the analyses conducted to date have concentrated on the requirements and programmatic considerations for the LEO program option.

Question 5
WHAT CONFIGURATION CONCEPTS CAN SUPPORT THESE PROGRAM OPTIONS?

As described in the response to Question 4, two basic philosophical approaches were taken to the development of the configurations to support the various program options: a "Shuttle-tended" approach and a "Permanently Manned" approach. Although both approaches lead to a permanent facility in orbit, the difference lies primarily in when the facility is established; i.e., the "Permanently Manned" approach leads to an early permanent capability as the initial step, whereas the "Shuttle-tended" approach provides a more gradual buildup of increasing capability as a function of time (see Figure 18).

Shuttle-Tended

In the Shuttle-tended cases, orbital activities occur only while the Shuttle is on station. The ground rules associated with the Shuttle-tended configurations include the restriction that the maximum duration of the Orbiter on station will be 30 days. There will be an allowance of 120 days of free-flight consumables provided to the portion of the facilities left unmanned on orbit, when the Shuttle returns to earth. As summarized in Figure 18, three basic implementation concepts were developed for the Shuttle-tended case: "strongback," "single Shuttle launch," and "direct growth." The Shuttle-tended configurations can accommodate crews of from four to seven individuals, with each implementation concept assuming single-shift work activities for a four-man crew living and working from the Orbiter, and two-shift operations with a seven-man crew.

One approach to the Shuttle-tended facility might consist of a "strongback" structure and an attached control module (Figure 19). When implemented, this facility would represent about 15,600 kg of mass and about 100 cu.m. of pressurized volume. In this case, a growth facility could be

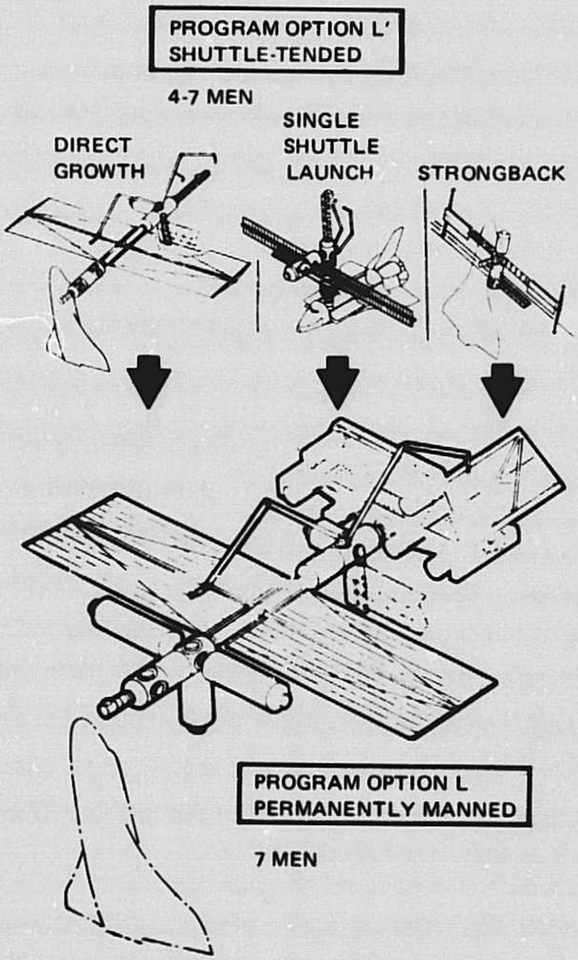


Figure 18. Configuration Development

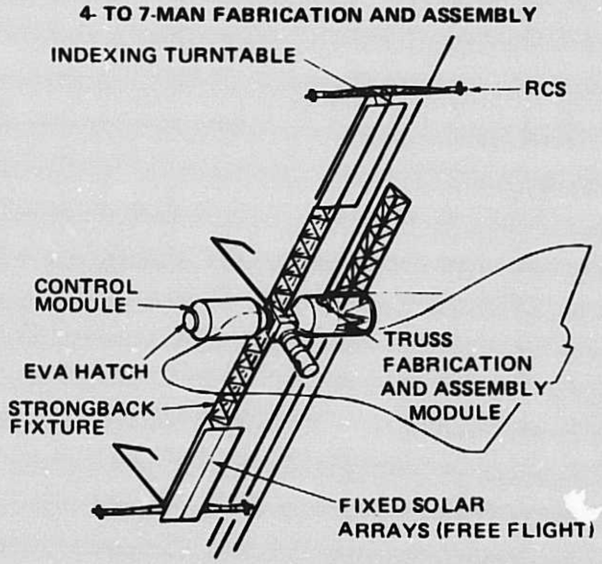


Figure 19. Shuttle-Tended Strongback Configuration

developed by the addition of modules along the original Orbiter docking axis. An electrical power system module could be added, for example, with a solar array sized to totally support a range of orbital facility construction and test operations. This might be followed by the addition of a core module to which the habitation, space processing, and logistics modules could be berthed.

Structure may be added to the original strongback truss beams, providing the basis for a construction platform to permit those objective elements which may require such a capability to be achieved. After the strongback evolves into an appropriate framework, longeron fabricating modules, rolls of array surface materials, automated robots, and other equipment complete the fixture as may be required.

Another Shuttle-tended concept, termed the "single Shuttle Launch," is predicated upon having a self-sufficient fabrication and assembly facility delivered to orbit as a unit. This second Shuttle-tended concept was so called because the basic fabrication and assembly capability is established on the initial launch. This concept provides a more advanced long-reach crane over that proposed in the "strongback" approach, a four-man airlock, a larger electrical power system, expanded permanent crew habitation, and additional berthing capability (see Figure 20). During its initial operational phase, this facility would be about 24,300 kg and have about 400 cu.m. of pressurized volume. The

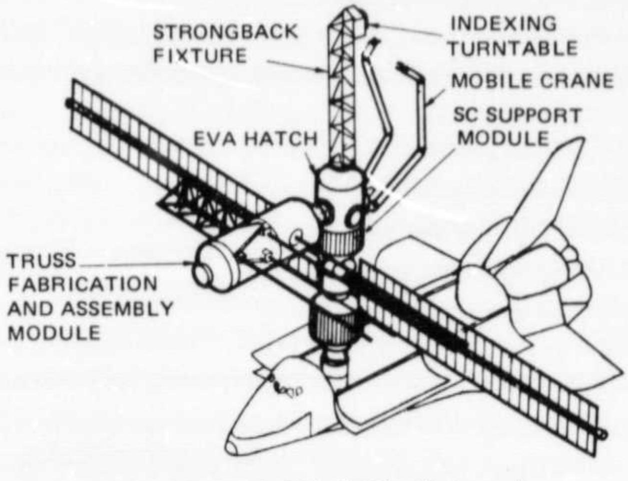


Figure 20. Shuttle-Tended Single Shuttle Launch Concept

evolution of this single-launch facility into a permanently manned facility would be accomplished by the addition of modules to increase the functional capacities and to add the capabilities for unattended orbital operations. The add-on electrical power system module, for example, is visualized as a large-area array capable of supporting all the facility housekeeping, construction operations, and objective element testing, including space processing operations (see Figure 21). A core module would be added to which habitation, space processing, and logistics modules, and Orbiter docking would be provided.

To support the construction of larger objective elements such as test articles for the development of advanced solar power satellites, a large solar

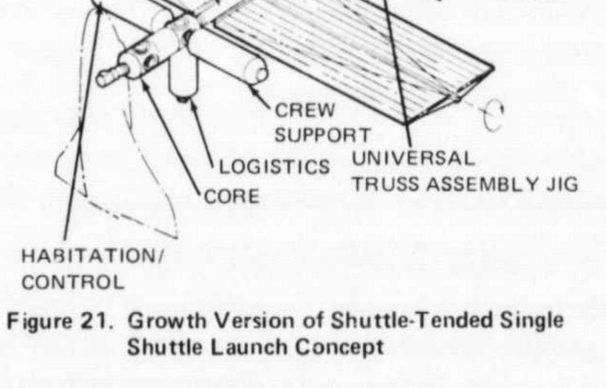


Figure 21. Growth Version of Shuttle-Tended Single Shuttle Launch Concept

collector fabrication and assembly jig could be added to the longitudinal axis of the fabrication and assembly support module, while a composite tube fabrication unit and a universal truss assembly jig could be added to the lateral/berthing ports. These facilities could accommodate the construction of linear array structures along the longitudinal axis of the configuration, as well as material supply logistics modules.

The third Shuttle-tended concept was termed the "direct growth" concept (Figure 22). It is characterized by the use of generally more sophis-

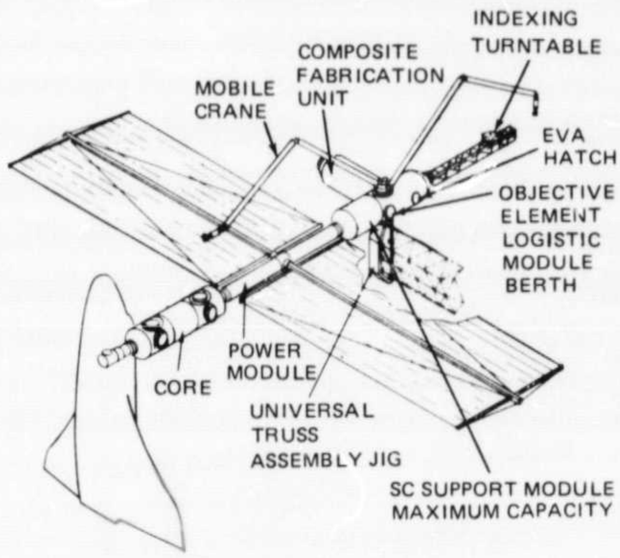


Figure 22. Shuttle-Tended Direct-Growth Concept

ticated systems and multiple modules, including a core module, a power module, a space construction module, and fabrication and processing modules, as required. Its total mass in orbit would be about 123,000 kg with 700 cu.m. of pressurized volume provided for crew operations, and it would provide systems more directly applicable to the needs of the final permanent manned space station.

The three basic "Shuttle-tended" concepts described above represent different levels of capability as their initial starting points. In each case, however, the concepts would grow in time into the permanently manned concept.

Permanently Manned

The permanently manned configuration (see Figure 23), with logistics and crew rotation performed by the Shuttle, provides docking and berthing ports, pressurized habitation and control facilities,

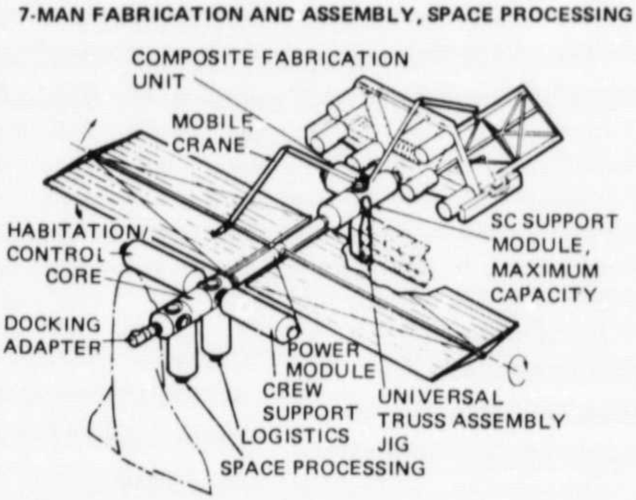


Figure 23. Permanently Manned Concept

power, and heat rejection capabilities to support all program options. The initial space construction activity undertaken by the permanently manned configuration may range from EVA-manual assembly to automated fabrication and assembly. Fabrication will most likely be only partially automated at the outset. As operations mature and construction project sizes and schedule durations dictate, more fully automated assembly support equipment may be phased into the program.

The basic seven-man permanently manned configuration (Figure 24) has the capability of supporting both fabrication and assembly of objective element mission hardware plus commercial space processing activities. The single power module would supply power up to 34 kW. The basic elements, in addition to the habitation elements, include the fabrication and assembly facility. This latter facility consists of the space construction support module, crane, composite tube fabrication module, universal truss assembly jig, and solar collector fabrication and assembly jig. Following deployment of the fabrication and assembly facility tooling, specific objective elements can be installed.

The 14-man configuration shown in Figure 24 is a further growth step from the 7-man station. In the 14-man growth version, multiple objectives can be simultaneously conducted, but with an increase in power requirements. As the power level reaches 60 to 70 kW, a second power module will have to be added. In addition to the aforementioned fabrication and assembly capabilities and space processing, the 14-man configuration can add a general-purpose facility for multidisciplinary science, sensor development, and to support continuing experiments related to living and working in space.

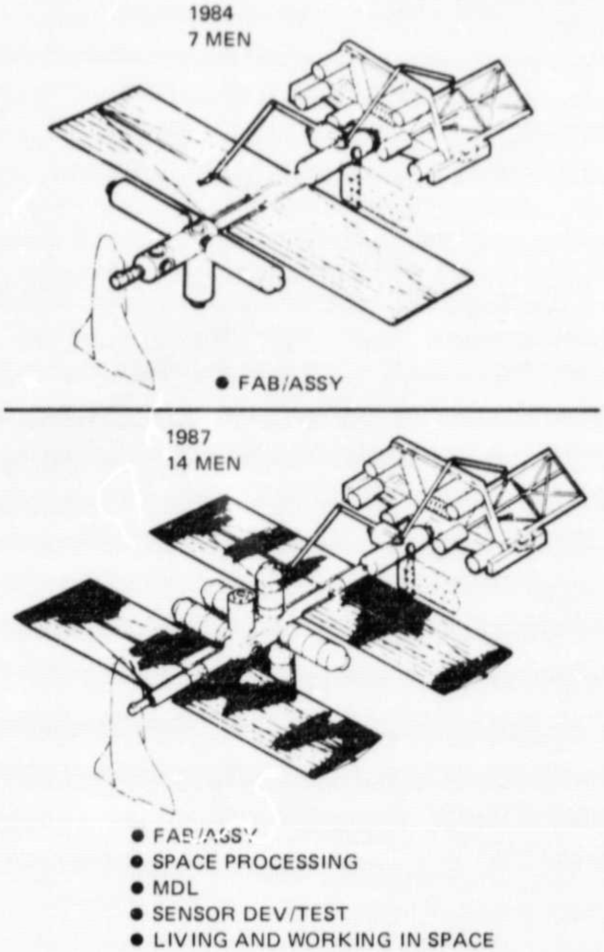


Figure 24. Program Option L SCB Configuration Evolution Permanently Manned

Question 6

ARE ORBITAL CONSTRUCTION FACILITIES PRACTICAL?

Several important objectives in the area of energy systems and earth services require the presence of very large structures in space (e.g., solar power satellites, earth-oriented radiometers, and advanced communications satellites). As the design of each objective element progressed in the present study, parallel operations analyses were performed to assure the producibility of the article in question and to address the issue of whether or not orbital construction facilities are feasible. Also, parallel trade studies of ground versus on-orbit fabrication were performed, as was determination of preferred fabrication and assembly techniques and equipment.

Space fabrication of components, as opposed to transporting finished parts to orbit, can be justified if the transportation costs are significantly reduced by shipping only bulk materials to orbit and if the fabrication process "orbital overhead" costs are less than the saving in transportation cost.

The large radiometer (Figure 25) and multibeam lens antennas (MBL) are examples of space hardware that are believed best suited to the "ground fabricated, space assembled" approach. While eventual production numbers of the MBL antennas may be large, the current state of technology for the fabrication of the composite antenna faces requires a great deal of manual labor, and would be difficult to automate.

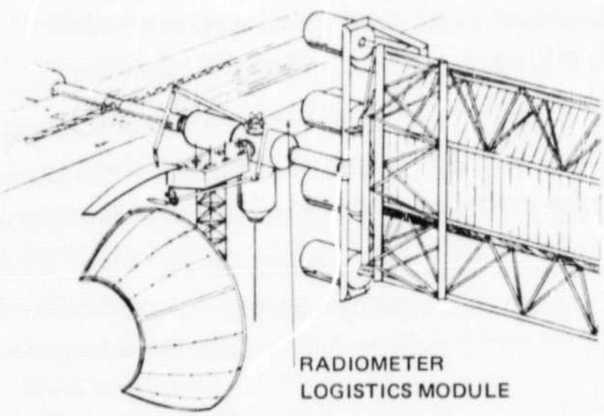


Figure 25. Construction of 30m Toroid Radiometer

Smaller assemblies such as the ground-fabricated 30-m (15,400-kg) radiometer antenna can be designed to be packaged (disassembled) as a single Orbiter payload (Figure 26). Since this requires the full length of the Orbiter's cargo bay, transfer of the payload package to the SCB would be accomplished without Orbiter docking by use of a crane-restrained mode in which one arm of the crane holds the Shuttle Orbiter while the other extracts the module.

While the 27-m (29,000-kg) MBL antenna size is similar to that of the radiometer, it would require three Orbiter flights for transport. The reason is primarily the panel thickness required by phase-delay components.

In the case of solar power satellites (SPS), it is believed that by the time construction base activities in support of the SPS program are undertaken (circa 1984), the prototype SPS concept will have been defined. Thus, activities supported by the

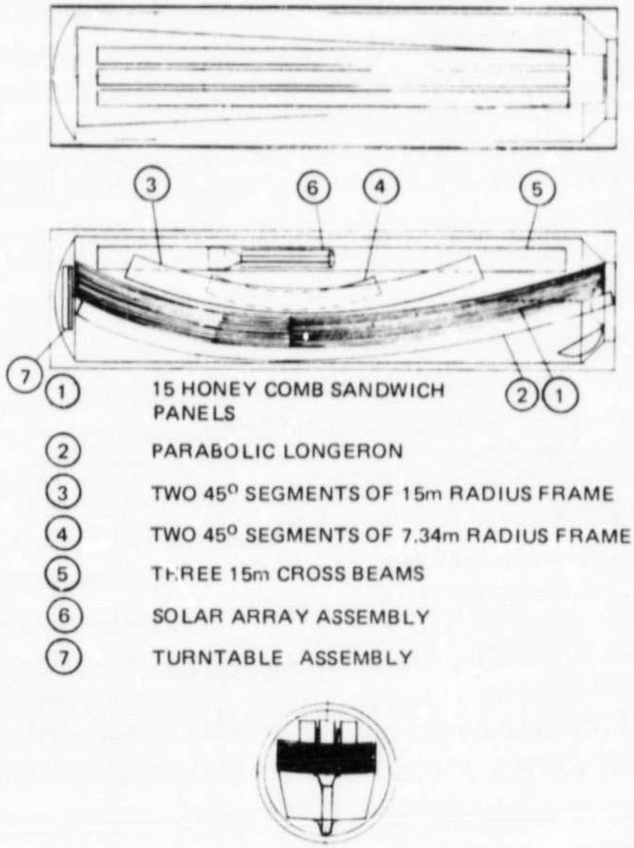


Figure 26. Radiometer Packaging Inside Fabrication and Assembly Module

base will, in all likelihood, be aimed at the development of a selected concept. This view is also supported by an opinion that test activities necessary for concept selection can be undertaken on the ground.

For study purposes, the Space Station System Analysis Study used a prototype SPS model predicated upon the findings of a JSC in-house study which included all anticipated construction requirements for future systems. While the selected model may not be the final concept, it is reasoned that the general manner in which the construction base supports SPS development will not vary greatly from this model. If SCB facilities are defined as general-purpose equipment capable of supporting a number of construction projects, they should be capable of supporting development of any SPS concept. Figure 27 illustrates the selected SPS concept used as the baseline model and Figure 28 illustrates one segment of the total array.

Our analysis suggests that the JSC prototype design model can be totally constructed using only one generic structural element – a 10-m triangular cross-section truss beam. Thus, development of a single automated fabrication and assembly fixture can satisfy production requirements for all major SPS structural components.

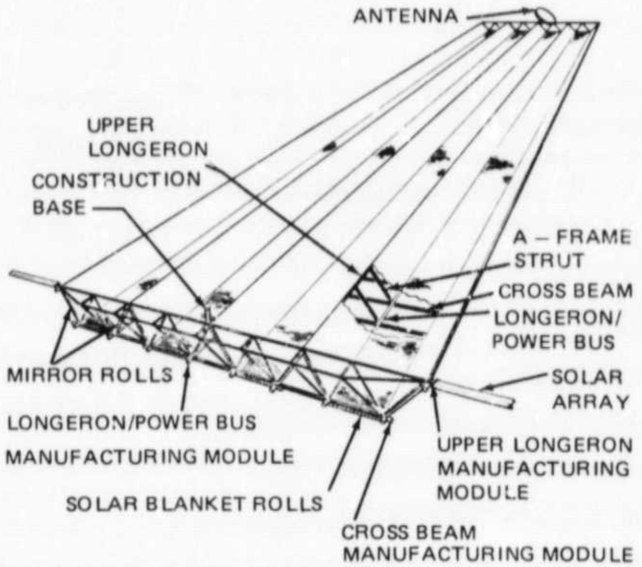


Figure 27. Prototype Model Solar Collector

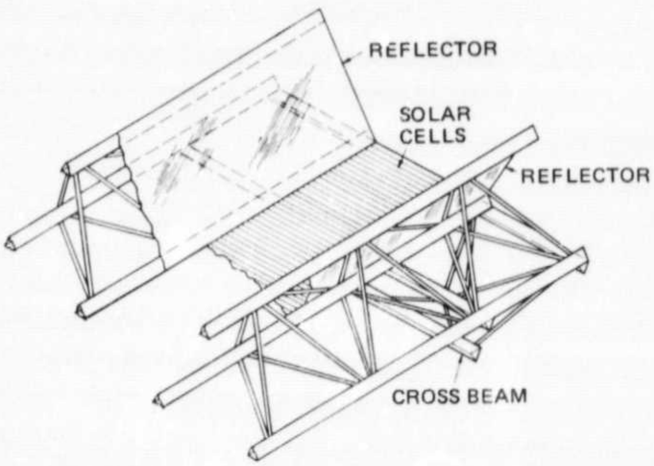


Figure 28. Solar Array Segment for TA-2

An MDAC concept for production of the full-scale SPS prototype 10-m beam cap is illustrated in Figure 29. Roll-forming machines are used to continuously produce the three triangular beam caps from rolls of aluminum sheet strips. Each cap is formed from two strips fastened together by projection welding. A centrally located roll-forming machine continuously produces discrete lengths of tubular truss members. Since these cannot use dynamic vacuum seals (as the beam cap components), the finished truss members pass into a revolving "gatling gun" airlock. Upon ejection from this airlock, the truss members are picked up by programmed robot arms and attached to the triangular cap flanges by the fastener tools. Beam alignment is maintained by controlling the individual roll-forming machines.

Automated SPS construction is founded on two well-developed technologies – continuous roll-forming of linear structural members from bulk sheet metal and automated assembly using programmable robots.

Figure 30 illustrates the Yoder roll-forming machine commonly used in aerospace applications. As adapted to the fabrication of 10-m triangular beam caps, fewer (though considerably longer) rolls would be required for the relatively simple forming task.

As visualized, the fabrication and assembly fixture design concept (see Figure 31) would continuously produce a finished solar collector in a fully automated assembly line. Roll-forming machines and associated projection welders for the 10-m beam caps would be located in unpressurized thermal control shrouds. Six of these would be mounted on a jig frame to simultaneously produce the required longeron caps. Two robots, mounted on the jig's main beam, would pick up prefabricated truss tubes from a spring-fed magazine and clip them to the emerging beam caps. As the truss cap junction passes through a truss attach head, a structural bond is formed (projection weld, large-diameter hollow rivet, or one of several other viable options).

Pretensioned reflector and solar cell blanket materials would be continuously deployed from rolls mounted between the jig frame arch and main beam, and on the main beam, respectively. Reinforced edges of reflector sheets could be attached to the beam cap flanges by staples or blind rivets. However, the heavier solar cell blanket material would induce extreme stresses into the beam caps during light and dark thermal cycling if it were rigidly attached. Blanket edges would therefore be suspended from the beam caps by constant-force springs. While several options exist, it appears that blanket-to-electrical power bus connections are required only at extreme ends of the collector.

Prior to beginning fabrication of the longerons, the fabrication and assembly fixture is used to

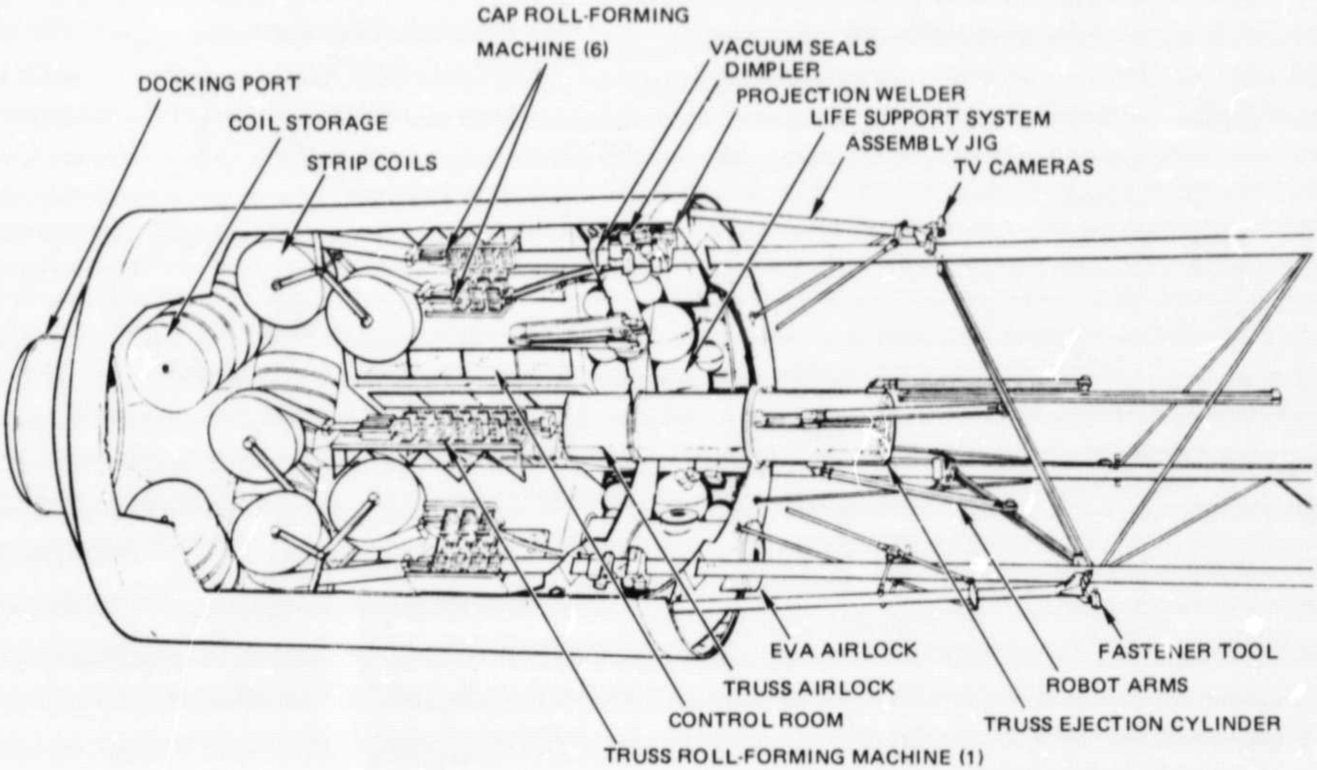


Figure 29. Production Prototype Truss Module

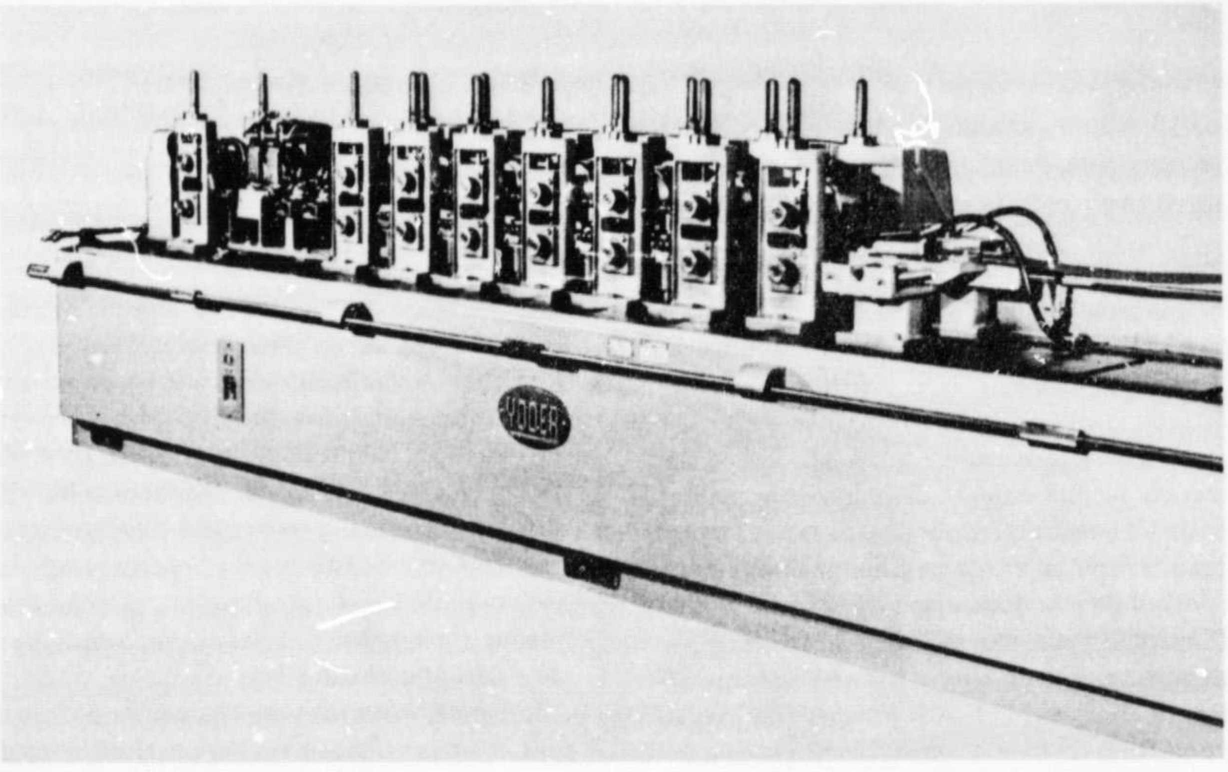


Figure 30. Industrial Roll-Forming Machine

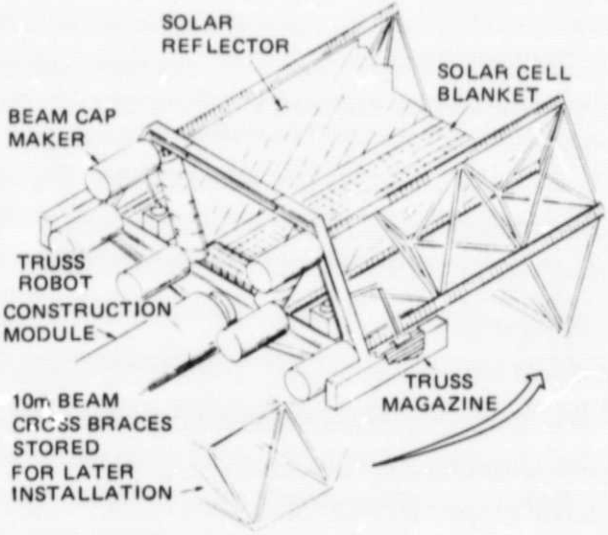


Figure 31. Fabrication and Assembly Fixture

produce three 30-m lengths of 10-m beam. These are stored on the construction module and used as needed for structural cross members in the collector. Attachment of these large members to the emerging longerons would be done using the mobile crane, and by EVA.

Electrical power required by the fixture is a linear function of cap development rate and is estimated to be approximately 1 kW/m/min (exclusive of lighting requirements).

The solar collector fabrication and assembly jig would probably be totally ground-fabricated, and its design would allow assembly and checkout prior to launch. Components could then be shipped to orbit on two pallets, which would be berthed to the construction support module while the jig is assembled. Actual assembly of the fabrication and assembly jig would be by EVA-assisted crane, as shown in Figure 32.

The steps visualized in the construction of the solar array itself are illustrated in Figure 33.

In reviewing SCB requirements, the importance of a crane facility must be emphasized because it is used on all construction projects as well as in both the initial buildup of the base and in continuing support of base housekeeping and logistics support.

Control and maintenance support of all construction equipment – together with support of the work crews – will be the primary function of the construction base. Control functions include not only the crane and the various automated construction equipment, but also control of EVA operations. Since construction activities will necessarily be remote from the control center, a considerable video capability to monitor all active EVA work stations will be needed.

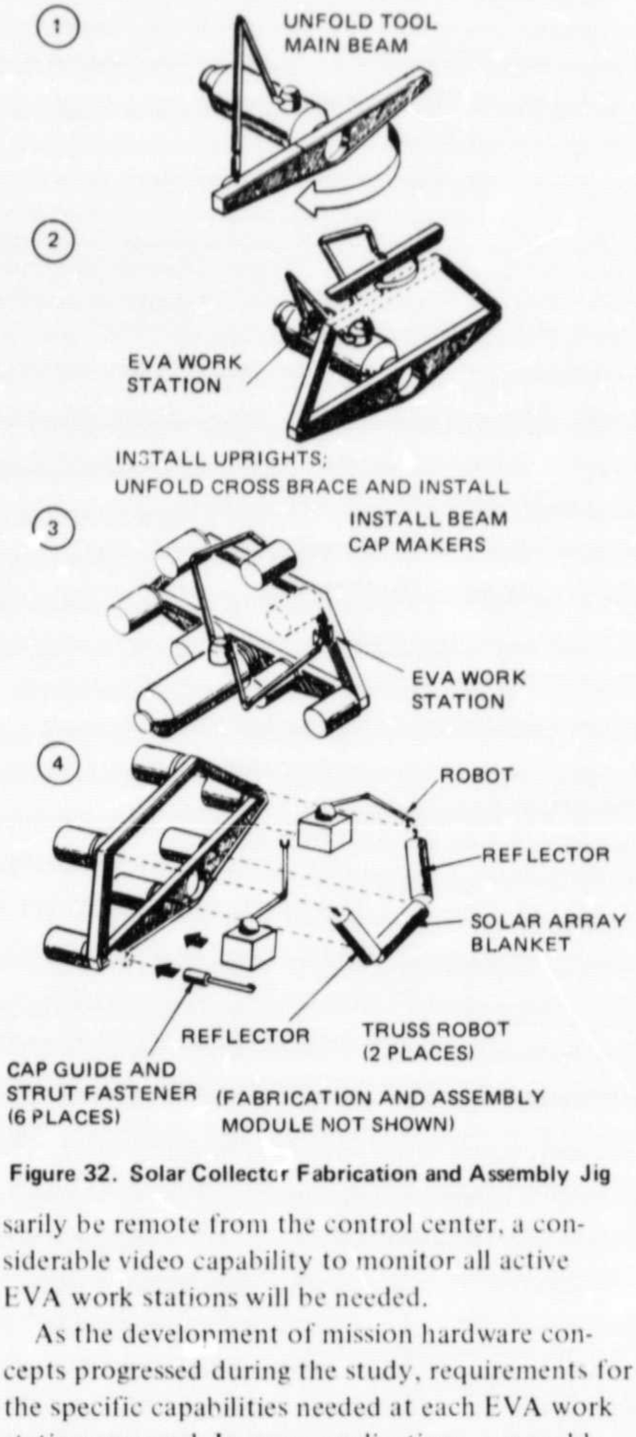


Figure 32. Solar Collector Fabrication and Assembly Jig

As the development of mission hardware concepts progressed during the study, requirements for the specific capabilities needed at each EVA work station emerged. In some applications, a movable scaffold arrangement to support EVA construction may be desirable. However, a "cherry picker" platform mounted at the working end of a crane would provide greater flexibility and, thus, would be even more desirable (Figure 34).

In parallel with the development of EVA work station concepts, analyses were performed to determine total EVA time for any given crewman on a construction job and the resultant exposure to radiation. As an example, in the permanently

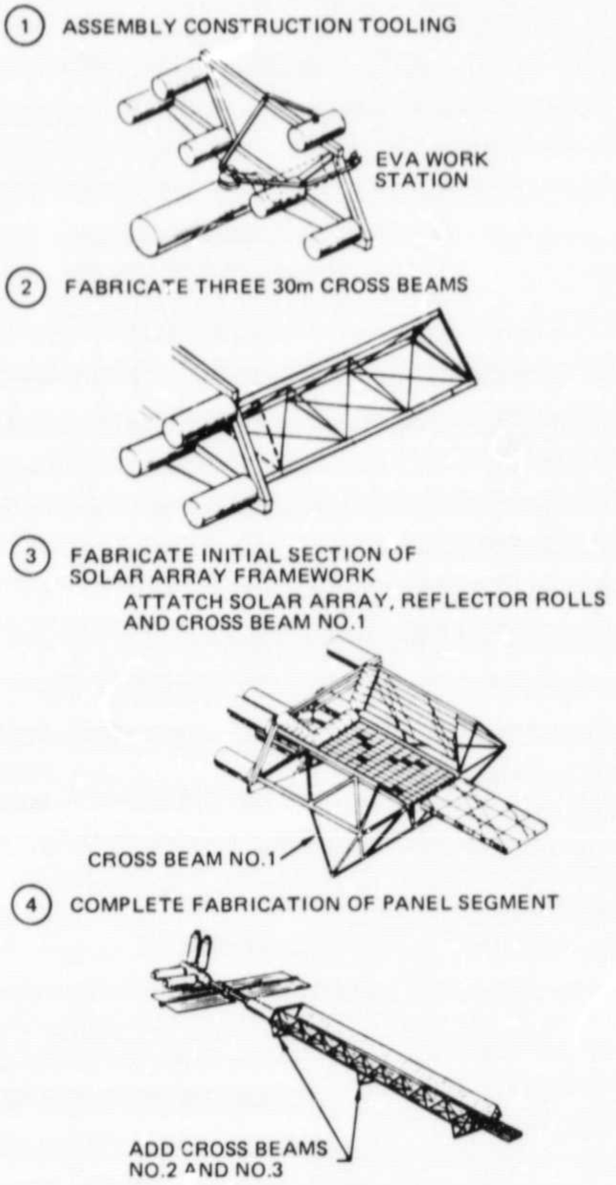


Figure 33. Solar Array Construction

manned mode during initial construction, a crewman might spend as much as 144 hours in EVA in a 90-day period, requiring approximately 0.4 gm/cm^2 of shielding (see Question 7). As construction jobs become more extensive, the radiation problem becomes more acute.

In view of the foregoing, the protection provided by the current Shuttle EVA suit must be increased by the 1984-1985 time frame. Our subcontractor, Hamilton Standard, has indicated that concepts for such a protective suit are available and apparently present no insurmountable difficulties. As EVA types of jobs become more extensive, the amount of shielding required becomes impractical for suits, and either shorter careers are indicated for crewmen or enclosed work stations are needed. Two concepts are (1) a hard-suit cherry picker in which crewmen work from a pressurized cabin through a glove box and (2) a pressurized cabin with remote manipulator arms.

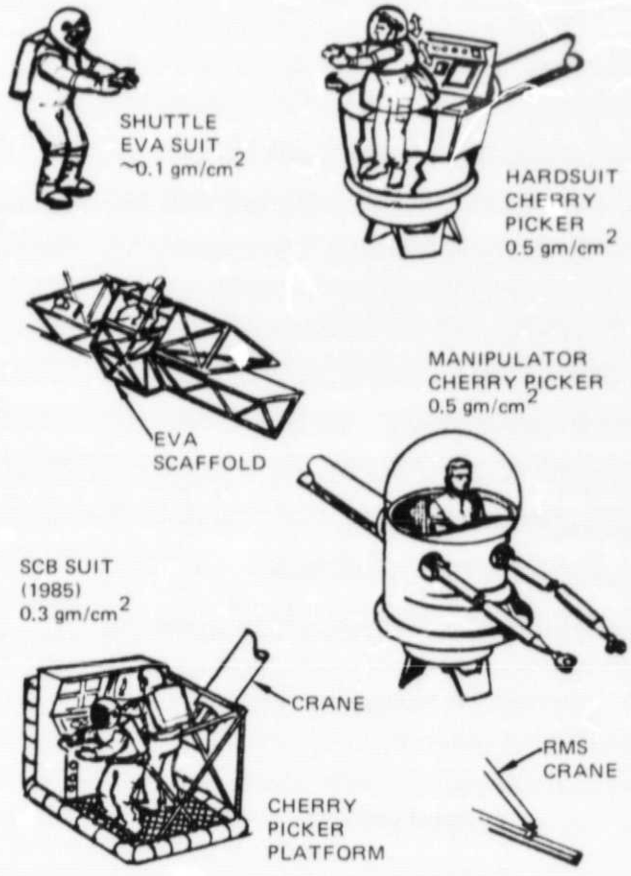


Figure 34. EVA Work Station Concepts

In brief, however, orbital construction appears to be practical and, as has been illustrated, concepts and devices are available to meet the requirements foreseen at this time.

Question 7
WHERE SHOULD SPACE CONSTRUCTION PROJECTS BE ACCOMPLISHED – AT LOW EARTH ORBIT OR AT GEOSYNCHRONOUS ORBIT?

A comparative analysis of those potential program objectives which require mission hardware in order to operate in geosynchronous orbit (e.g., SPS TA-1 and TA-3, multibeam lens antennas, 3.75-km navigation antennas, and large radiotelescopes) indicated that construction of the mission hardware can be most effectively accomplished in low earth orbit. A number of factors were considered in arriving at this conclusion, but the primary factor was determined to be a transportation cost difference of $2.6 billion between two identical programs in which construction in low earth orbit or construction in geosynchronous orbit was the only variation. The two program options which provided the foundation for this evaluation were LG1 and LG2 (see Question 4) since they have the same goals, with the former requiring the construction of key objective elements at LEO and the latter at GEO. A time-phased comparison indicated that seven more SCB modules would be needed to accomplish Option LG2 (GEO construction) than for Option LG1 (LEO construction).

As seen in Figure 35, the major difference in the LEO and GEO construction sites lies in the orbital transport vehicle (OTV) propellant needed. Most of the propellant difference is due to the increased crew activity at geosynchronous orbit for Option LG2. For LG1, with construction at LEO, the major item produced, SPS (TA-3), can be self-powered to GEO using its solar array, thus reducing the OTV flights and corresponding OTV propellant needed.

The Shuttle flight history for each option is shown in Figure 36, with LG1 totaling 187 flights and LG2 408. This large difference of $19.1 million per flight represents a $4.2 billion total cost difference. The large number of Shuttle flights would warrant the use of a growth Shuttle which, in turn, would reduce the $4.2 billion differential by $1.1 billion. In addition, a low-g transfer system

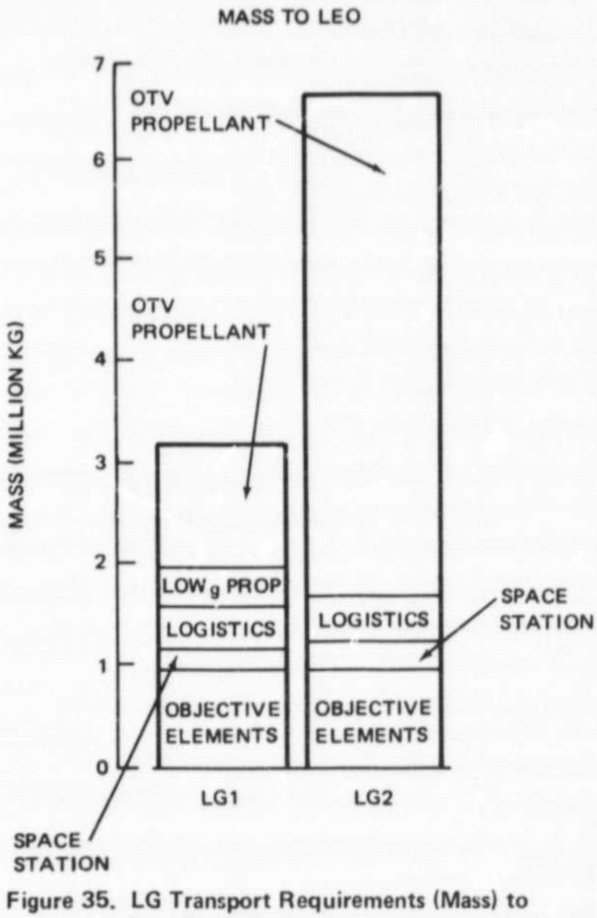
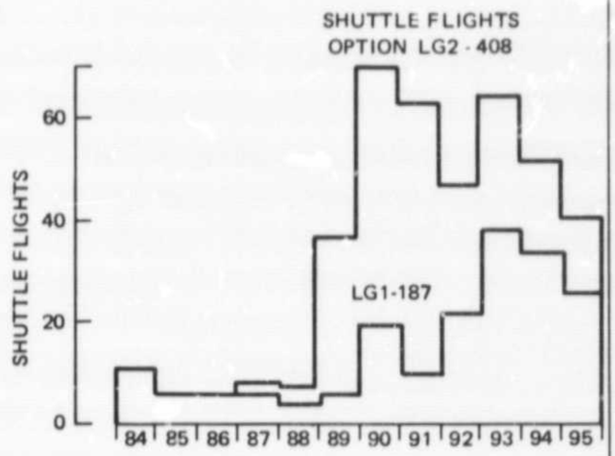


Figure 35. LG Transport Requirements (Mass) to Low Earth Orbit



	LEO CONSTRUCTION LG1	GEO CONSTRUCTION LG2	Δ COST
SHUTTLE FLIGHTS	187	408	$4.2 B
GROWTH SHUTTLE	MARGINAL	YES	$-1.1 B
OTV SIZING (KG/STAGE)	40,000	55,000	N.C.
LOW g SYSTEM	YES	NO	$-0.5 B
LOW g SYSTEM	GEO CONSTRUCTION PENALTY = $2.6 B		

Figure 36. LG Transport Requirements (Shuttle Flights) to Low Earth Orbit

for LG1 would be required. The development cost estimate for this system is $500 million. Based upon these considerations, the net difference between LG1 and LG2 due to LEO-GEO transportation was estimated to be $2.6 billion.

SPS (TA-3) was analyzed in greater depth to examine the factors that influence orbital transfer. The LEO-to-GEO orbit transfer is dependent upon the type of system used and the thrust level. The transfer time varies from 5.25 hours at 0.1 g to 70 days at 0.0001 g for continuous-thrust capability. For TA-3, the 21-MW array can be used to provide power for an ion engine thrust system. The resulting exposure of the solar cells in the lower Van Allen belt can cause significant degradation – up to 40%. In addition, large gimballing angles are needed and multiple engine systems are probably required. The yaw or out-of-plane angle variations become large and vary at orbital frequency to provide velocity where it is needed as the orbit inclination is depressed.

A low-thrust transfer using chemical systems (perhaps reusable or even expendable OTV's) could also be utilized. The orientation problem would be overcome and the transfer could be faster to reduce the solar cell degradation. The extra Shuttle flights needed are more than compensated for by not having to buy an electric propulsion system at a cost of about $500 million. Thus, from a transfer standpoint, the differences in LG2 and LG1 are nine Shuttle flights more for the GEO construction case if the recommended low-g chemical system is assumed for LG1.

Major issues, other than transportation costs that could influence construction locations, are discussed briefly below.

Orbit-Keeping

The objective elements being considered for LEO or GEO construction were analyzed to determine the relative orbit-keeping differences in terms of propellant required. It was found that LEO/GEO orbit-keeping differences do not appear to be a major influence on the selection of LEO or GEO as the construction site.

Orbital Forces and Moments

SPS (TA-3) was examined to calculate the forces that would be applied at LEO and GEO. Gravity gradient and aerodynamic torque differences are large from LEO to GEO. This would require an attitude control system for the LG1 option during LEO tests that would not be needed at geosynchronous orbit. The penalty may not be great, since the system used for orbit-keeping would probably suffice and uncontrolled excursions of a few degrees would probably be acceptable for a short-duration test.

Plasma Leakage

High-voltage equipment (particularly solar arrays) operating in space may be subject to substantial losses due to leakage caused by the space plasma. Figures 37 and 38 illustrate the nature of this potential problem for TA-2 and TA-3 (TA-1 uses a low-voltage solar array).

The curves plotted in Figure 37 show the power loss as a function of altitude due to electron and ion collection for a 90% insulated, 139 m^2 solar array operating at 2,000 and 16,000 V*. The potential for leakage exceeds the array output

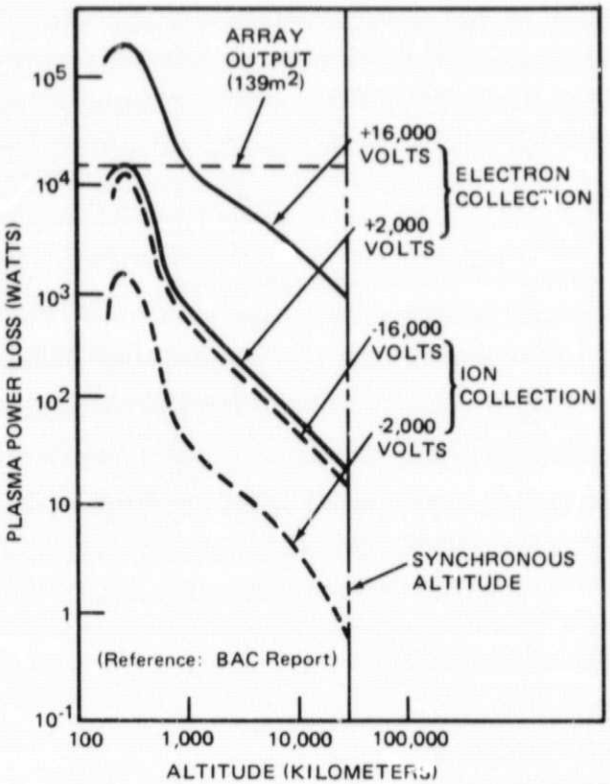


Figure 37. High-Voltage Solar Array—Plasma Leakage (Loss vs. Altitude)

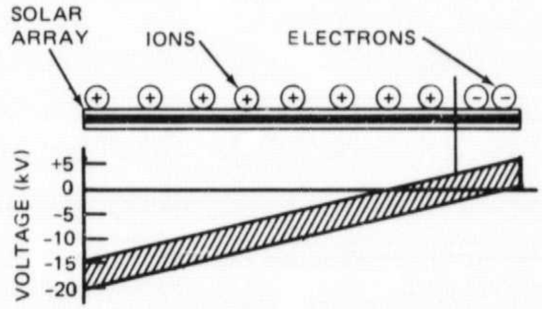


Figure 38. High-Voltage Solar Array—Plasma Leakage (Voltage Gradient)

capability at 16,000 V, and at altitudes below 1,000 km, the peak leakage occurs at 300 km. The leakage is a function of the plasma density, which is a function of altitude and the 11-year solar cycle. The curves are for the peak of the solar cycle (4×10^6 e/cm^2) and are conservative for TA-2, which will fly near the solar minimum (5×10^5 e/cm^2). These curves were calculated using Langmuir equations with constant-charge spheres used as a model.

A solar array generating a 20,000-V differential is expected to assume the voltage levels depicted in

*H. Oman, "Cost of Earth Power from Photovoltaic Power Satellite," Boeing Aircraft Co.

Figure 38. The resulting low voltages (with the voltage gradient depicted) will attract relatively few electrons and ions compared to the constant high-voltage case (e.g., a uniform 16,000 V across the entire array) assumed in Figure 37. The leakage loss for the low-voltage case will be much less than that depicted in the figure.

Other factors mitigating the severity of the TA-2 and TA-3 problem in LEO relate to (1) operations at SCB altitudes greater than 300 km, which puts the losses to the right of the peak values, (2) the fact that large solar arrays are less affected than smaller ones, and (3) operations during or near solar minimum. It is believed that the latter will not be a severe problem for TA-2 and TA-3, but should this prove incorrect, options to resolve the problem include (1) development of substrate and solar cover insulation free of pinholes (which rapidly enlarge and cause leakage) or electrically biased screens, (2) reduction of array voltages using a step-up transformer, and (3) shifting test operations to GEO.

Based on the mitigating factors stated and the worst-case modeling used for the calculations, it is felt that the leakage problem will be substantially reduced after thorough analysis and test, thus will impose no penalty on the LEO/GEO construction issue.

Radiation Environment Influences

The radiation environment at LEO is different from that at GEO and could have some effects on the LEO/GEO construction issue. The allowable dose guidelines (REM) for crewmen are as follows:

Exposure (Days)	REM Skin	REM Eyes	REM Marrow
30	75	37	25
90	105	52	35
180	210	104	70

The skin dose data shown in Figure 39 are usually the limiting dose; this is the most difficult dose against which to provide shielding. At LEO or GEO, a ~ 1 gm/cm^2 Space Station wall would reduce the dose to well below the allowable limit.

The requirements for EVA radiation shielding at LEO were determined by comparing the allowable

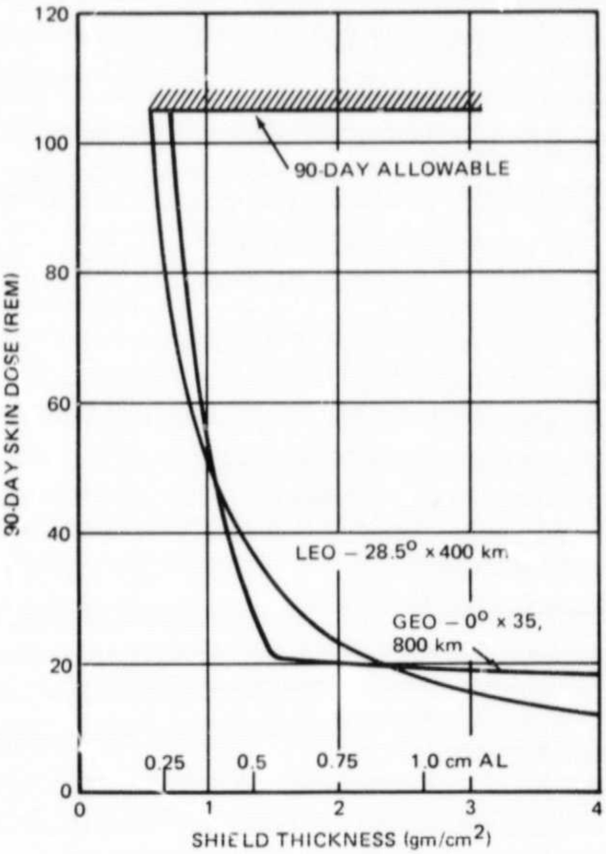


Figure 39. Radiation Environment Influences (Trapped Radiation Dose)

dose to that received inside a 1 gm/cm^2 Space Station, then allowing the difference to be the allowable EVA exposure dose. The relationship of mission duration, EVA exposure, and required suit thickness is shown in Figure 40 for LEO (28.5 deg x 400 km) using skin dose as the limit. A 30-day mission, with a total of 2 days spent on EVA, would require a suit thickness of 0.31 gm/cm^2. The suit thickness drops off with mission duration for constant EVA exposure because the total allowable dose increases. Planned EVA and mission-duration points for the SCB mission are shown by the data points at 30, 90, and 180 days. A suit thickness requirement of from 0.31 to 0.49 gm/cm^2 is required. The potentially available suit thicknesses range from 0.1 gm/cm (STS suit) to 0.3 gm/cm^2 (1985 EVA suit). An increase in thickness appears needed to stay within the overall allowable dose criteria.

The increased electron environment at small shield thicknesses would require a thicker suit at GEO. The previous requirement range would be extended to 0.5 to 0.67 gm/cm^2. This comparison is for trapped radiation only.

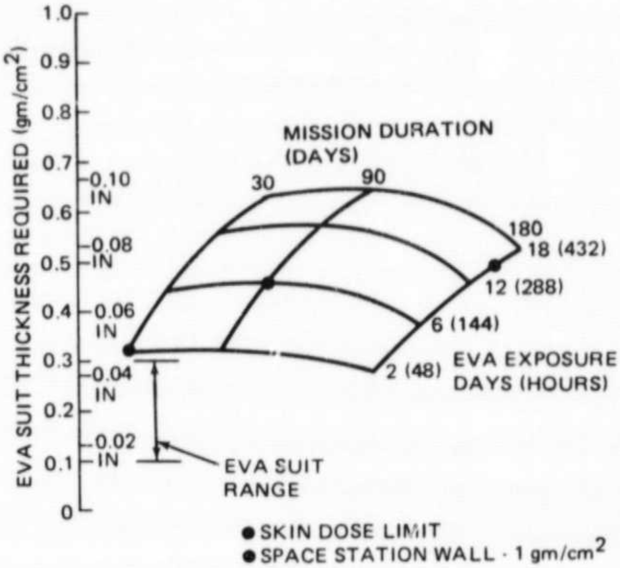


Figure 40. Radiation Shielding, Low Earth Orbit

The solar cosmic ray (SCR) exposure is primarily a problem in GEO since, at a 28.5-deg LEO, the earth's magnetic field would shield the SCR protons. The SCR dose at GEO is dependent on the size of flare received. The range of dose shown in Figure 41 as a function of shield thickness is for expected rates of 5 to 9 flares per year. A biowell is needed at GEO with a thickness of ~21 gm/cm^2. For aluminum. this would require a biowell 8 cm thick which, for a 6-man capacity, would have a mass of about 3,640 kg. At GEO, the intense environment during an SCR event would preclude any EVA activity during the period of the event. The SCR dose effect at GEO would require further increase in the EVA suit thickness of a few more gm/cm^2.

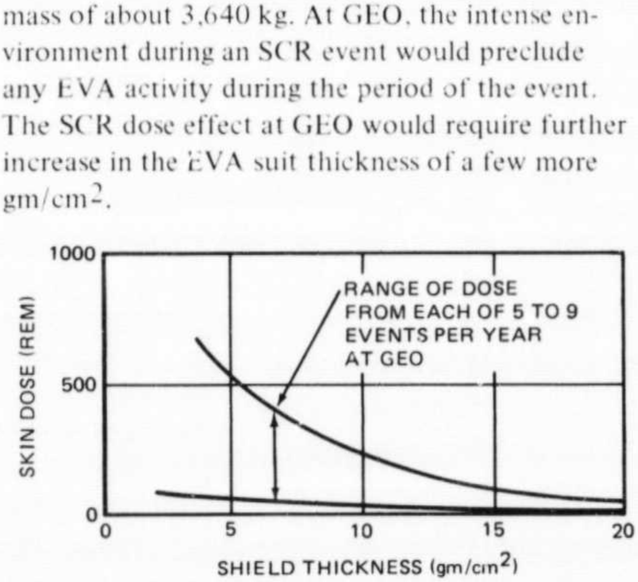


Figure 41. Radiation Environment Influences (Solar Cosmic Ray Dose)

Clearly there is a radiation penalty associated with extended-duration missions and with EVA exposure at GEO compared to LEO. In both cases, the EVA suit requirements appear to exceed the planned suit thicknesses. It should be remembered, however, that these calculations are for a thin shield in a region of the environment where dose is changing very rapidly with thickness. It should be cautioned that the results are sensitive to theoretical and calculation error and changes in the environment and, although design solutions are available to protect the crew, thorough analysis of the radiation environment appears warranted before firm EVA suit requirements are developed.

The evaluation of the major LEO/GEO construction issues resulted in the summary comparison shown in Figure 42. These conclusions are based on the objective elements analyzed, primarily as influenced by SPS (TA-3).

LEO construction is preferred because it would save at least \$2.6 billion over the GEO construction approach. In addition, the current shuttle is adequate to support the operations for the LEO construction case and the logistics are simpler.

The GEO construction technique does offer some advantages but the greater cost, the need to commit to a growth Shuttle, and the added radiation hazard make it less desirable.

	LEO CONSTRUCTION	GEO CONSTRUCTION
ADVANTAGES	LOWER SYSTEM COST	CONSTRUCTED IN SITU
	CURRENT SHUTTLE ADEQUATE	STOWED TRANSFER TO GEO
	SIMPLER LOGISTICS	
DISADVANTAGES	LOW 'g' TRANSFER NEEDED (USE CHEMICAL OTV)	TRANSPORTATION COSTS \$2.6 BILLION MORE
	ADDITIONAL ATTITUDE/ ORBIT CONTROL	REQUIRE MORE SCB ELEMENTS
	SOLAR CELL DEGRADATION DURING TRANSFER	REQUIRES GROWTH SHUTTLE
	POTENTIAL PLASMA LEAKAGE	GREATER RADIATION HAZARD

Figure 42. LEO vs GEO Construction Summary

Question 8

WHAT ARE THE TRANSPORTATION REQUIREMENTS FOR THE POTENTIAL PROGRAM OPTIONS?

The transportation systems analyses conducted as part of the Space Station study have included transportation requirements in terms of mass to be carried to orbit and number of flights for each program option.

For the Low Earth Orbit option about 500,000 kg was required to be delivered to LEO over the operational periods. The specific objective elements accounted for about one-third of this, and the Space Station elements represented about one-fifth. The remainder reflected logistics support requirements.

For those program options requiring GEO operations, additional mass was required for OTV (orbital transport vehicle) propellants, and in these cases the total mass requirements to LEO ranged from 3 to 7 million kg. The variance in the required mass reflected such factors as the use of high I_{sp} electric systems vs chemical systems and whether or not more manned sortie modes to GEO were required because of construction at GEO rather than LEO.

The annual number of flights needed to support the LEO options are shown in Figure 43. For operations limited to low earth orbit during the years 1984 to 2000, the minimum number of Shuttle flights required (not considering crew rotation requirements) varied from 44 for a program option which called for the initial activation of a 7-man permanently manned space construction base (Option L), to 62 for a program option that was based upon a Shuttle-tended program option (i.e., work proceeded only when the Shuttle Orbiter was docked to the construction platform). When geosynchronous options were introduced, the Shuttle flights needed varied from a low of 113 to a high of 408 (see Figure 44). Peak annual flight requirements varied from 39 for LG1, to 70 for LG2, 38 for g (permanently manned facility at GEO) and 55 for G' (sortie missions initially, – later growth to permanently manned at GEO). Clearly, these high rates would tax the Shuttle capabilities. A major portion of the flights were for OTV propellant delivery, thus, when GEO options are introduced, the development of a LEO delivery system of larger capability might be warranted to reduce the number of flights, to transport propellant more efficiently, and generally to reduce costs.

As an example of the factors considered, in defining the OTV requirements, the requirements for Program Option LG1 are shown in Figure 45 by year for both the delivery and round-trip missions. The payload for the delivery mission consists of the items identified, while the round-trip payload consists of the crew module and some objective element material. As can be seen, there are large items to be delivered, e.g., the cross-phased array and the multibeam lens.

The numerical distribution of delivery and round-trip flights for the payloads for Option LG1 is shown in Figure 46. As seen, most of the payloads are under 20,000 kg for the delivery mission and 7,000 kg or under for the round-trip mission.

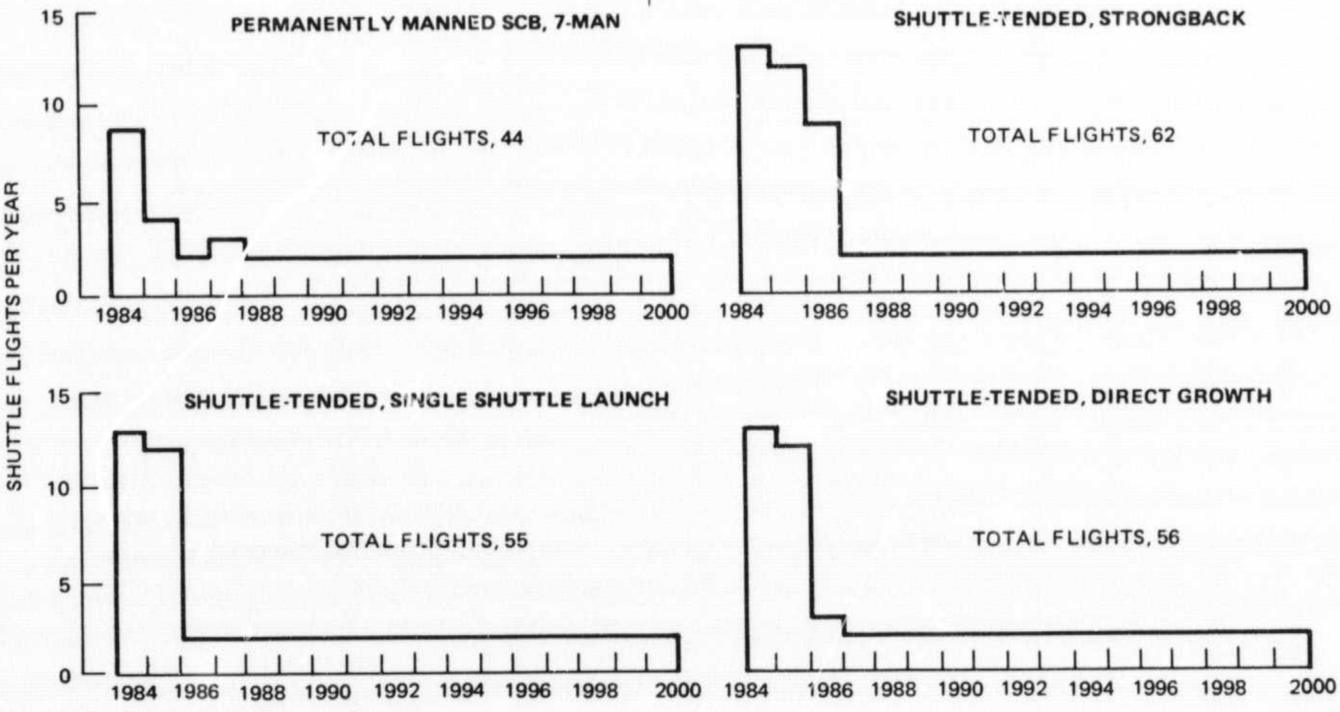


Figure 43. LEO Option Shuttle Flights

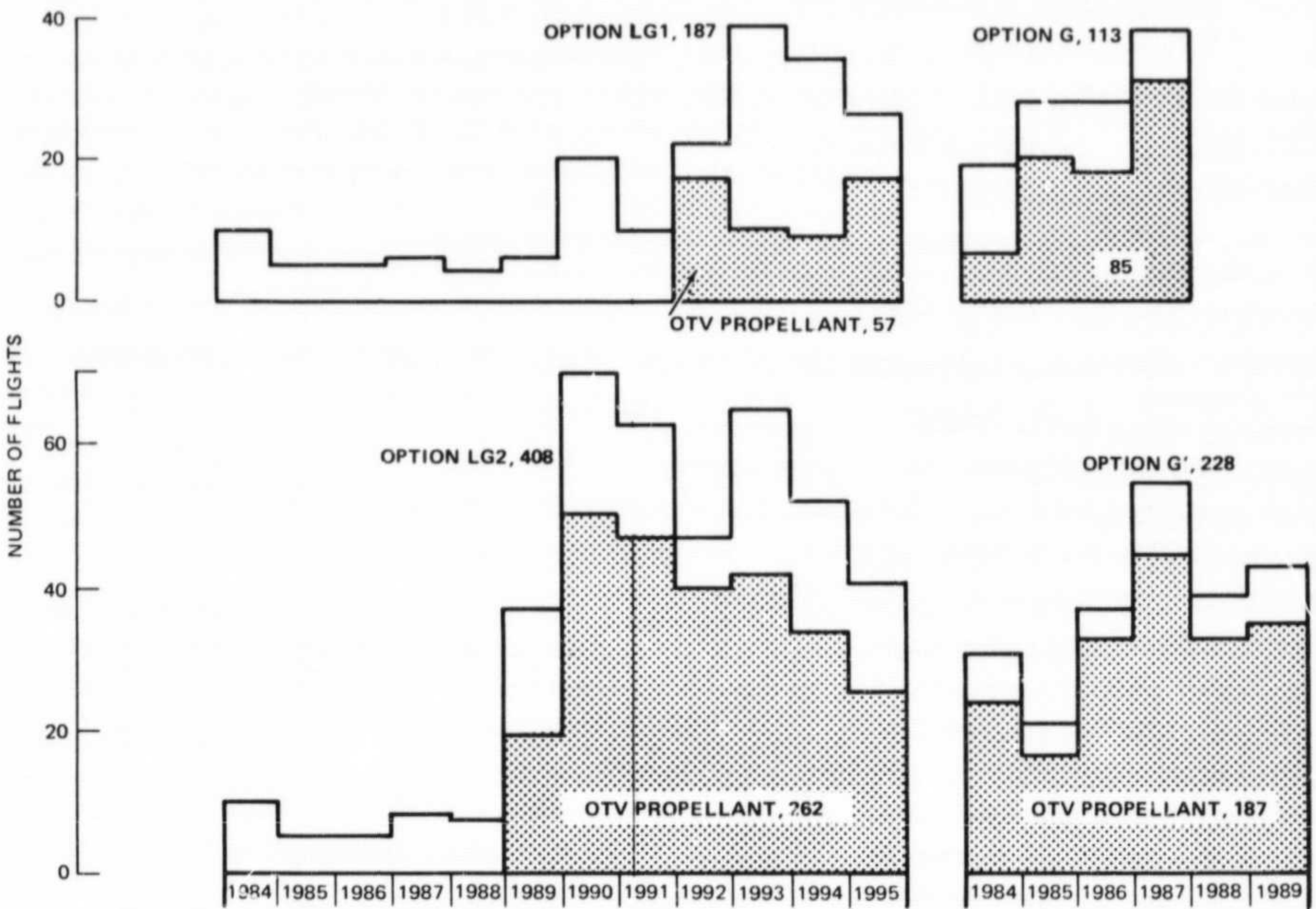


Figure 44. Shuttle Flights for LG1, LG2, G, and G' Program Options

These requirements were tabulated for each GEO program option. The delivery or round-trip value at which the OTV should be designed was then determined. These data suggest that the OTV design capability should be 20,000 kg for delivery and 7,000 kg for the round-trip.

Delivery round trip and expendable mode parametric OTV capabilities were compared to the mission requirements to determine the vehicle sizes needed (Figure 47). Performance capabilities include single- and two-stage OTV's, with the latter considered in both optimum and common-stage configurations. The optimum design consists of sizing the two stages for a propellant loading ratio between Stages 1 and 2 of about 2 : 1 for delivery missions and 55 : 45 for round-trip missions (optimum velocity split). For the common-stage design, both stages are the same size. The capabilities for delivery in an expendable mode were also calculated to investigate the capability to deliver outsized payloads.

The solid-dashed line variances on each performance curve indicate the transition points from integral stages to separate LO_2 and LH_2 tank designs as limited by Shuttle bay length. The center ordinate of the chart is the total OTV propellant loading common to both the delivery and round trip performance lines.

The bulk to the delivery missions (15 of 17) require a capability of less than 20,000 kg. This could be accomplished by both single- and two-stage OTV's, the single stage requiring 65,000 kg of propellant, and the two-stage requiring about 50,000 kg. When the round-trip requirements (7,000 kg) are considered, a propellant loading of 100,000 and 80,000 kg would be required for the single- and two stage OTV's, respectively. Note that the single-stage version would have to be launched in two sections (LH_2 tank and LO_2 tank/engine) and assembled in orbit. Also note that the 80,000-kg two-stage OTV could accommodate the 28,000-kg delivery mission. Clearly, the 64,000-kg payload would size an OTV beyond that which would be used efficiently for 34 of the 35 LG1 flights. This mission could be accomplished by special means – probably multiple OTV elements

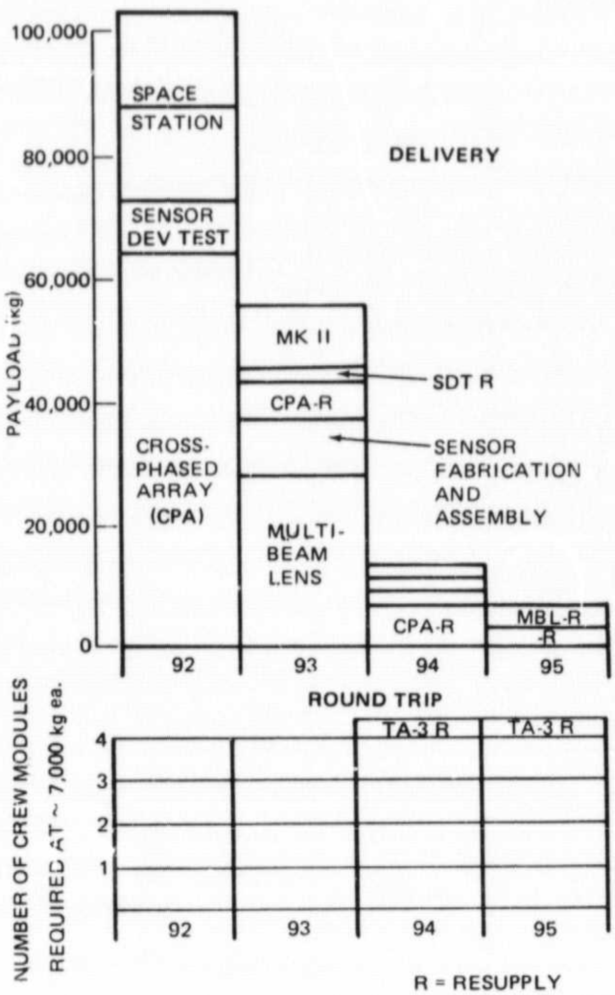


Figure 45. OTV Weight Requirements for Option LG1

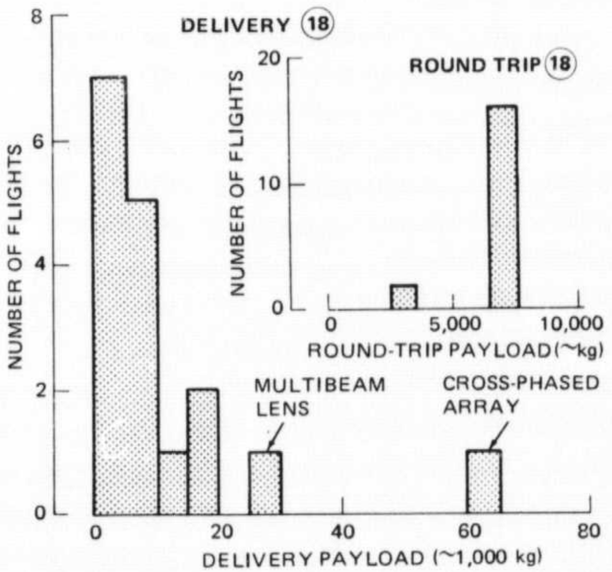


Figure 46. OTV Flight Requirements for Option LG1

used in an expendable mode. The propellant savings and flexibility of the two-stage OTV over that of the single stage resulted in recommendation of the two-stage for Option LG1. The reduced OTV propellant alone would result in a savings of \$340M, due to decreased Shuttle flights (17 x \$18.9 million). The common-stage design is recommended over the optimum concept for commonality reasons, the performance difference being small. Thus, an 80,000-kg propellant, common two-stage OTV (two 40,000-kg stages) would appear desirable for LG1.

The analytic process for sizing an OTV was performed for all four program options per the previous example. The types selected, sizes, and major influence for each option are shown in Figure 48.

The two-stage common-design OTV is recommended for all options, based on the reduced logistics costs for propellant delivery and the commonality of design. The respective logistics cost savings of the two-stage OTV over the single stage were LG1-\$340 million, LG2-\$1.6 billion, G-\$560 million, and G'-\$880 million. The individual sizes for each option were selected by considering the delivery and retrieval requirements for each. The 40,000 kg of propellant per stage for LG1 was discussed previously.

The OTV size recommended for LG2 was 55,000 kg of propellant per stage. The basic requirement of 53,000 kg to meet the 10,000-kg round-trip requirement was raised to 55,000 kg to accommodate the delivery of the 64,000-kg cross-phased array. (In this latter case, the OTV would be expended on this mission.)

Option G analysis resulted in an OTV of 53,000 kg of propellant per stage to meet the 10,000-kg round-trip requirements. For Option G', a 55,000-kg OTV stage was recommended. With this size, a two-stage OTV would be used to satisfy the round-trip mission requirement of 11,000 kg, and one of the two common stages could be used for the 15,000-kg delivery mission.

The above selections are meant to be illustrative only; final recommendations will be dependent upon the specific programs which NASA elects to pursue in the decade ahead.

The major results obtained from the transportation analyses indicate that the Shuttle can support all program options, though LG2 requires a large number of flights and high flight rate (70 per year maximum). A growth Shuttle concept appears needed for this option. In addition, a two-stage common-stage OTV design was selected for all options based on reduced propellant requirements and commonality of design. The basic size requires from 40,000 to 55,000 kg of propellants per stage – consequently 55,000 kg per stage was selected for conceptual design.

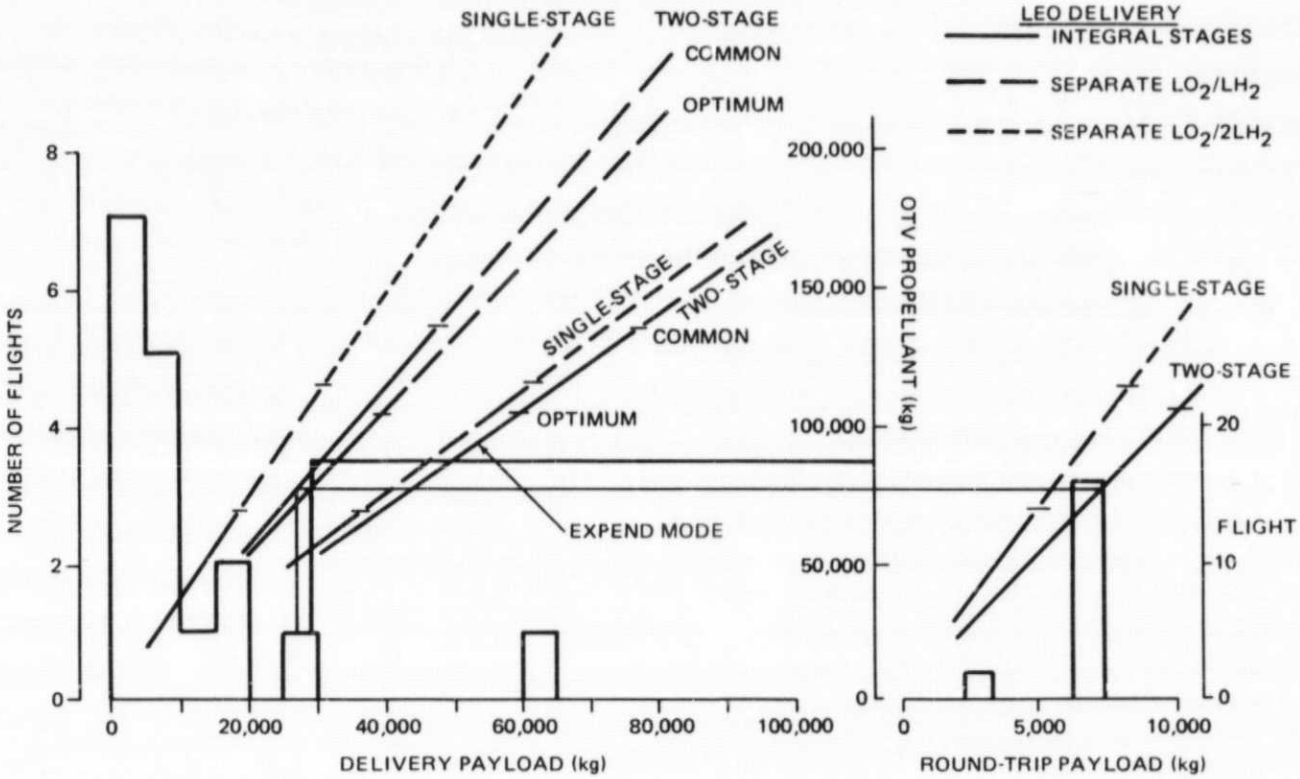


Figure 47. OTV Requirements and Capabilities for Option LG1

OPTION	TYPE	PROPELLANT/ STAGE (kg)	PAYLOAD (kg) DELIVERY	ROUND TRIP	EXPEND	MAJOR INFLUENCE
LG1	2-C*	40,000	28,000	7,500	46,000	DELIVERY PAYLOAD
LG2	2-C*	55,000	39,000	11,000	64,000	EXPEND PAYLOAD
G	2-C*	53,000	37,000	10,000	60,000	ROUND-TRIP PAYLOAD
G'	2-C*	55,000	39,000 15,000	11,000	60,000	ROUND-TRIP PAYLOAD AND DELIVERY (1 STAGE)

*2-C = 2-STAGE COMMON DESIGN

Figure 48. Initial OTV Selections

Question 9
WHAT TECHNOLOGICAL STEPS, DEVELOPMENTS, OR BREAKTHROUGHS ARE REQUIRED?

Although no major breakthroughs are required for initial implementation of the programs described, continual technological growth is anticipated and new research and development requirements will continue to be identified as specific mission objectives are defined. Some of the key technology areas which have been identified to date as warranting further emphasis are described in the following paragraphs.

Solar Power Satellite

Development of lightweight packaging concepts and low-cost designs are mandatory in establishing the commercial feasibility of solar power satellites. Other areas for research and development include techniques for the space fabrication of solar collectors and microwave antennas, and large-scale energy collection and distribution systems, and low-cost lightweight, flexible and radiation-resistant solar cell blankets. Precision pointing and control represents an area for continuing emphasis, as well as problems related to microwave power transmission systems and components, radio-frequency generators, accurate and stable waveguide/structure systems, phase control systems (including ionosphere interaction), and radio-frequency interference effects.

Materials and Design for Large Space Structures

Control of thermal distortion in large space structures through development of materials and improvement in design technology represents an area for continued research and development. Structural joining techniques and the dynamic interaction of large structures with stabilization and control systems will also be areas of continuing investigation.

Large Antennas for Communications and Radiometers

A better theoretical and practical understanding is required of the scaling effects between small and large antenna concepts. The feasibility of implementing theoretical electrical design concepts for multibeam lens antennas and maintaining structural precision tolerances must be investigated. Microwave transmission problems as noted above also require continuing attention.

Space Processing

Further research is required to provide a better understanding of the impact of environmental changes (vibration, acceleration, temperature, pressure, etc.) on the processing of various materials (metals, glasses, pharmaceuticals) in a basically zero-g environment. Conversely, a better understanding of the potential effects (environmental and otherwise) which the space processing or manufacturing procedures may have on the space base and the crew is required.

Stability and Control

The major stability and control problems which must be addressed are those associated with adaptive system concepts and component development including actuators capable of controlling a range of masses from individual Shuttle-delivered modules to large, complex mass distributions, and inertias created by many modular units structurally linked together. The stability and control systems must be able to also accommodate dynamic interactions of short periods with such elements as moving cranes, manipulators, and Shuttle docking kinetics.

Extravehicular Activity

A better definition and understanding of true extravehicular capability is required before optimal workloads, schedules, and manning requirements (crew sizes) can be completed. In addition, supporting equipment tools, and environmental protection (radiation) devices and techniques require development.

Fabrication and Assembly

The development of remote manipulators and crane systems with flexible dynamic characteristics including aided control networks, and advanced display techniques will be required in space fabrication and assembly operations. Teleoperators, robotics, and crew augmentation devices may require further development as specific missions are defined.

Interaction with the Space Environment

The interaction of systems and components with the space environment is still not completely understood. Plasma leakage effects, radiation protection, etc., represent continuing areas for concern. Operations will require high-voltage circuits in space where conditions such as arcing, insulation breakdown, plasma currents, ion bombardment, electron bombardment, and x-ray and gamma ray radiation effects can be anticipated. Electromagnetic and electrostatic force field interactions and coupling effects, particularly of high-power density systems, would impact mechanical design as well as stability and control of space system elements.

Electrical Power System

System concepts that are efficient, easily maintainable, lightweight, low cost, and long lasting represent a continuing need in energy system development. Requirements exist for solar arrays with flexible substrates and advanced energy-storage devices (e.g., regenerative fuel cells, advanced nickel cadmium or nickel hydrogen batteries, etc.).

Long-Duration Environmental Control and Life Support Systems

The economic feasibility of long-duration missions in GEO will depend upon development of reliable closed-ECS concepts for water and oxygen. Generally improved habitability features of all space platforms represents a continuing need, whether in LEO or GEO.

Question 10
WHAT ARE THE EXPECTED MILESTONES AND SCHEDULES?

As the Shuttle becomes operational, the use of expendable launch vehicles will phase out and the Shuttle-Spacelab combination will provide the principal support for space research and operations especially during the early years of the 1980s (see Figure 49). As requirements for on-orbit construction facilities develop and requirements for longer stay times emerge, it can be anticipated that it will no longer be cost-effective to return all system elements to earth at the conclusion of each Shuttle flight. Many system elements will be left on orbit and will only be activated in a Shuttle-tended mode of operation while the Shuttle/Orbiter is on station. As demands grow, permanently manned space stations/bases will be required in order to provide continuous fabrication and/or assembly operations as well as more comprehensive research and development capabilities in orbit.

The key milestones in overall program development are summarized in Figure 50. The critical point of reference is the date to be established for the initial operating capability (IOC). Historical experience dictates a 52- to 60-month development cycle, and if it is desired to have IOC in 1984, a Phase B activity must be initiated in calendar 1978.

Figure 51 shows the schedule for the development of a permanently manned SCB. This schedule includes SCB buildup, and construction of two test articles for the solar power satellite program (TA-1 and TA-2), and the 30-m radiometer for a 7-man permanently manned option. This schedule assumes the DDT&E would begin at the start of FY 1980 and that the first launch of the SCB would be in December 1983. This allows the SCB to be in place and operational by mid-1984. The two SPS test articles may then be completed before the end of 1986 and the 30-m radiometer built and tested by early 1987.

The schedule to accomplish the major objectives examined in this study is shown in Figure 52 for three different SCB crew sizes (7, 14, and 21) for a permanently manned option. This schedule is referenced to the time the SCB is certified as ready for operational use.

In general, the 7- and 14-man cases cannot support simultaneously all of the potential research and development activities which have been identified to date; therefore, the total time required to accomplish all the objectives is long. Obviously, 21 men can accomplish more activities in parallel, and the time required to complete the objective items is much shorter.

Figure 53 shows the schedule for the development, SCB buildup, and construction and test of the TA-1, 30-m radiometer, and TA-2 for the construction part of the option which starts in the Shuttle-tended mode. In this program option model, the SCB would be operational in early 1984 in the Shuttle-tended mode and operational in early 1986 in the permanently manned mode.

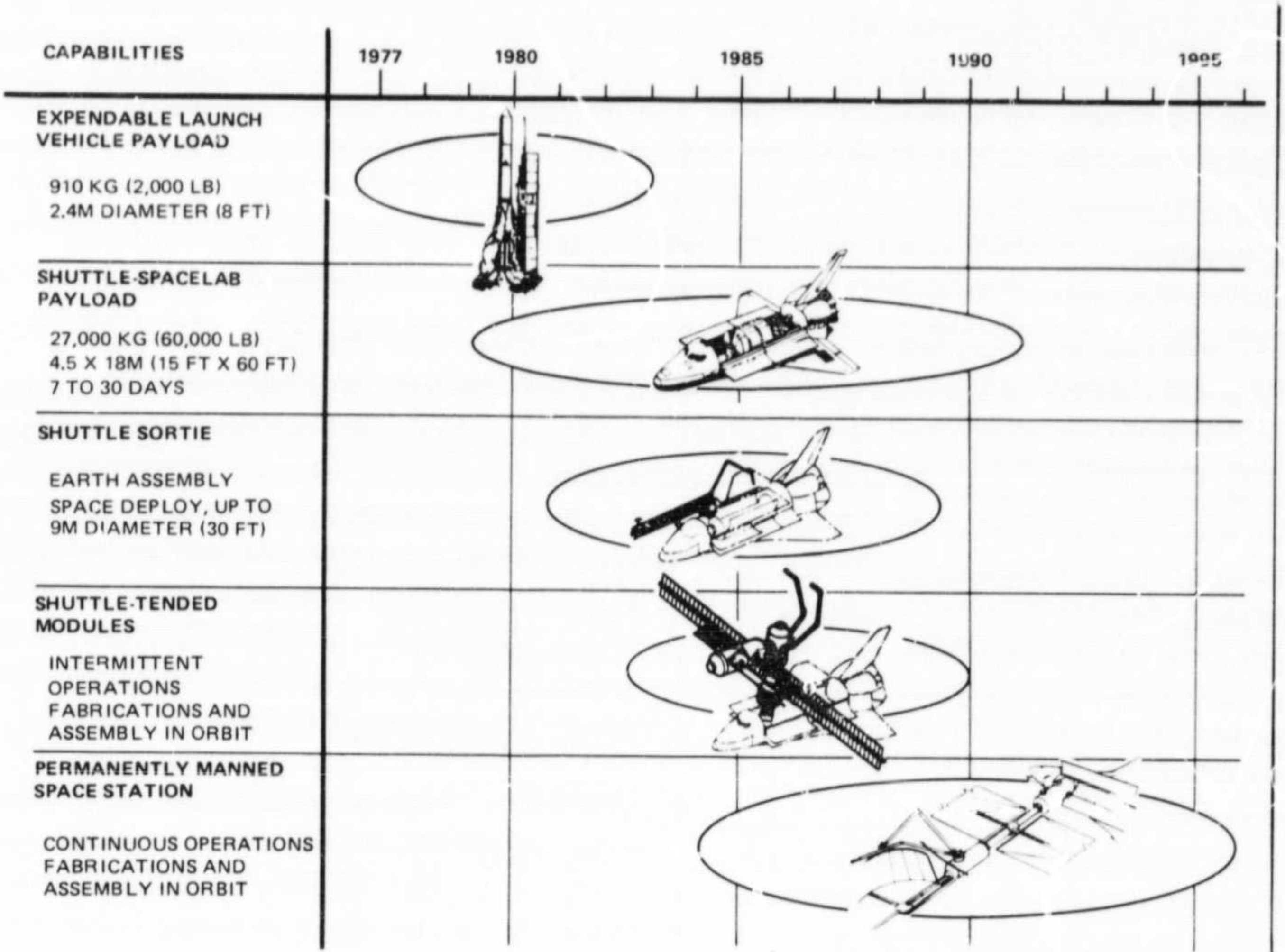


Figure 49. Space Program Evolution

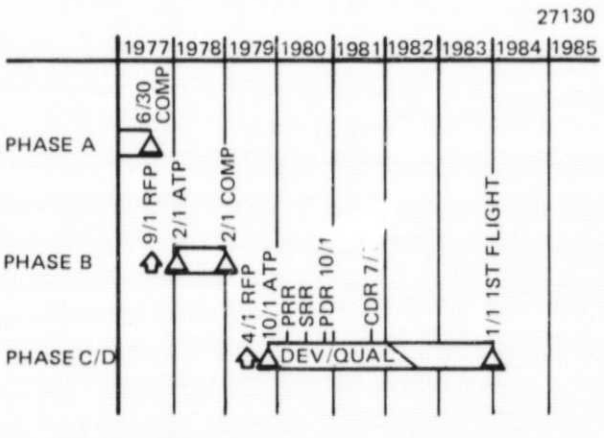


Figure 50. Key Milestones

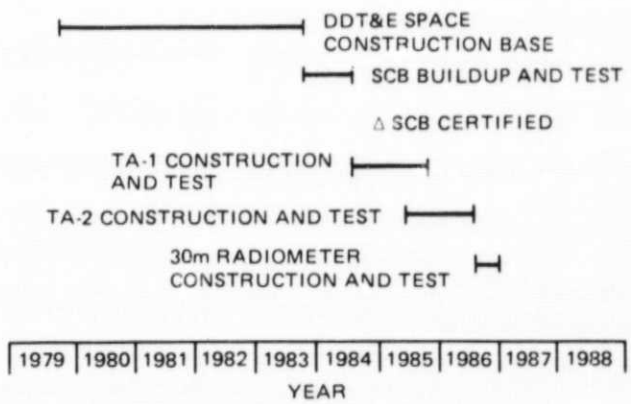


Figure 51. Development and Construction Schedule for 7-Man Permanently Manned Option

The schedule to accomplish the objectives is shown in Figure 54 for the three initial Shuttle-tended approaches. All versions have a 3-man crew during the Shuttle-tended portion of the option, and these particular schedules reflect a 7-man crew during the permanently manned period. However, a larger crew could be provided during the permanently manned period by adding additional crew modules. This would permit acceleration of the later activities, but at additional expense.

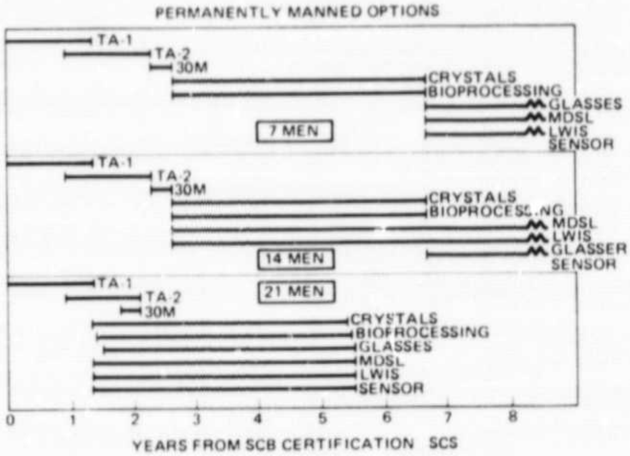


Figure 52. Objective Schedule

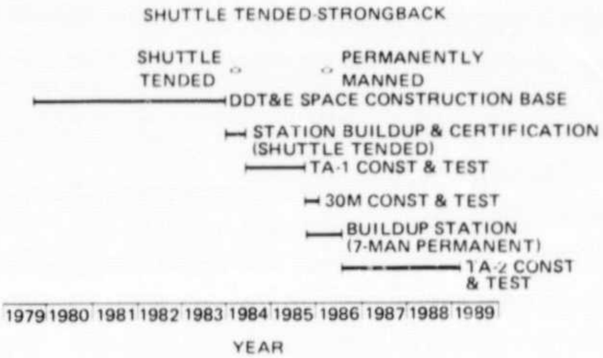


Figure 53. Development and Construction Schedule

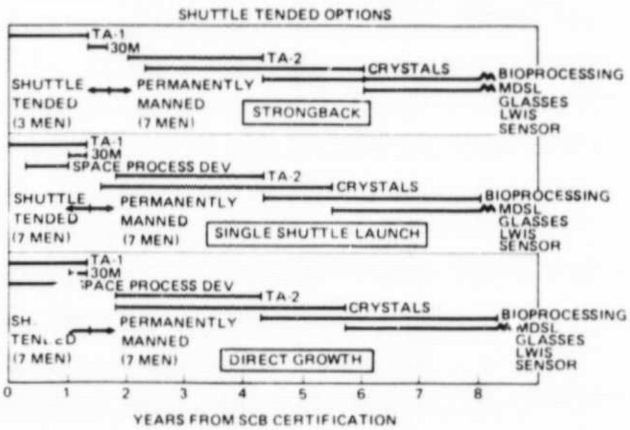


Figure 54. Objective Schedule

Question 11
WHAT ARE THE EXPECTED COSTS?

The cost estimates to develop, produce, place in orbit, and operate the station elements of a 7-man permanently manned space construction base (SCB) (Figure 23) are summarized in Figures 55 and 56. Figure 55 presents the yearly funding requirements and cumulative cost, segregated by major element, SCB, mission hardware, and transportation. Figure 56 presents a breakdown of the cost for each of the three major elements. For the SCB, the cost of the individual modules that comprise it, the cost of management and integration, the ground test and GSE costs, and the remaining ground support costs during the operational period are shown in the first bar in Figure 56. The mission hardware cost is divided into the cost of the individual objective elements as shown in the second bar of Figure 56. The transportation cost shown in the third bar reflects the cost required for placing the SCB and mission hardware into orbit, and the logistics transportation cost for the operational period.

In a similar fashion, the cost estimates for the various initially Shuttle-tended approaches are presented in Figures 57 through 62. To understand the cost data that is presented for the Shuttle-tended options, one must remember that each of the Shuttle-tended options grows into a permanently manned facility after about 1-1/2 years of operation. Accordingly, the cost data presented for these options encompasses the total cost of the Shuttle-tended option, including both the Shuttle-tended and permanently manned portions.

The annual and cumulative cost to accomplish the Shuttle-tended option by using the "strongback" configuration is given in Figure 57. The "strongback" configuration for the Shuttle-tended part of this option is relatively austere. It consists of only a rudimentary fabrication and assembly module, with a Shuttle-derived remote manipulator system (RMS), and it relies to a maximum extent on the basic Shuttle Orbiter for habitability, power, stability and control, communications, and data management. By comparing the annual funding on this figure with that of Figure 55 (the permanently manned option) a major advantage of the Shuttle-tended approach can be seen, namely, a reduction in the annual funding required during the early part of the program. This reduction results from the fact that the Shuttle-tended portion of the option is accomplished first and consequently the schedule for the development of the permanently manned elements can be delayed with a resultant postponement in the relatively higher funding required for these developments. This reduction in early year funding holds true for the other Shuttle-tended cases as well, although the magnitude varies somewhat with each program option.

Figure 58 shows the cost breakdown for the "strongback" Shuttle-tended option, for the three

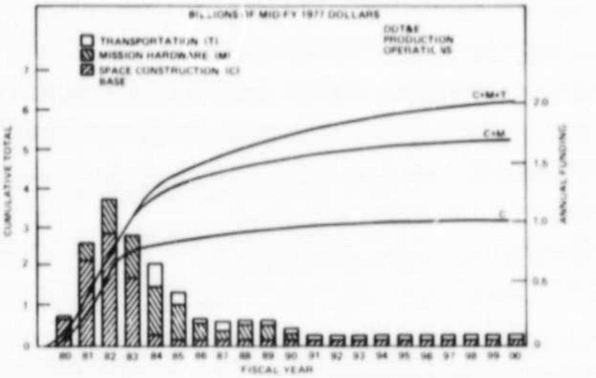


Figure 55. Permanently Manned Option Cost

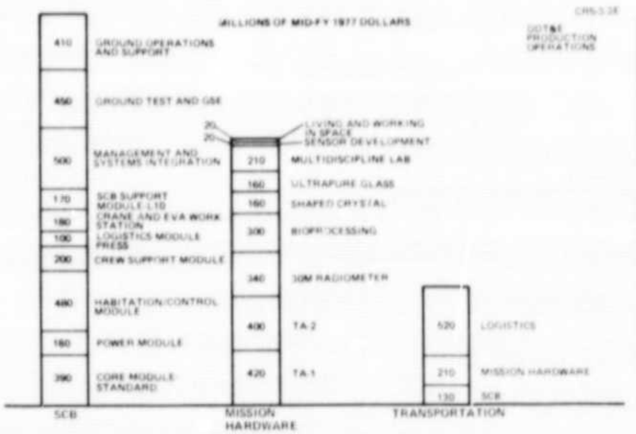


Figure 56. Permanently Manned Cost Breakdown

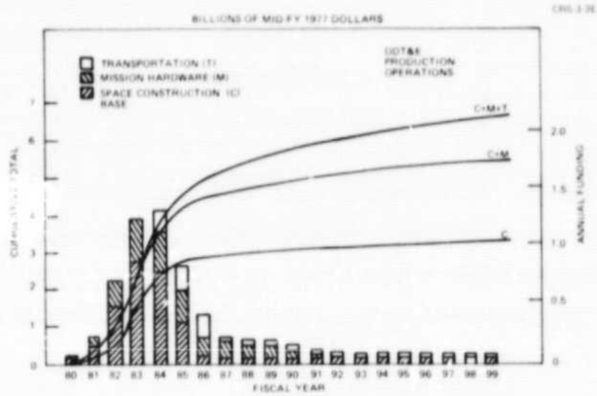


Figure 57. Strongback Option Cost

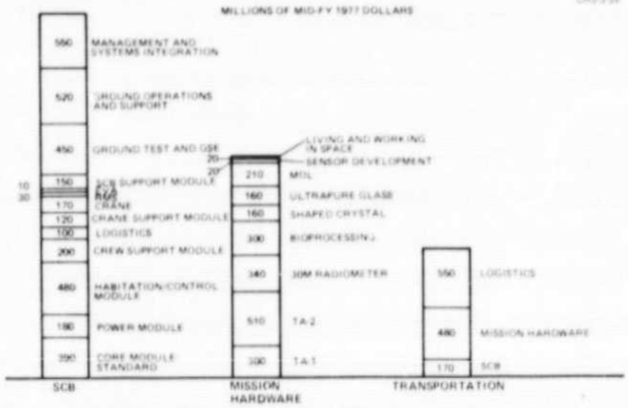


Figure 58. Strongback Cost Breakdown

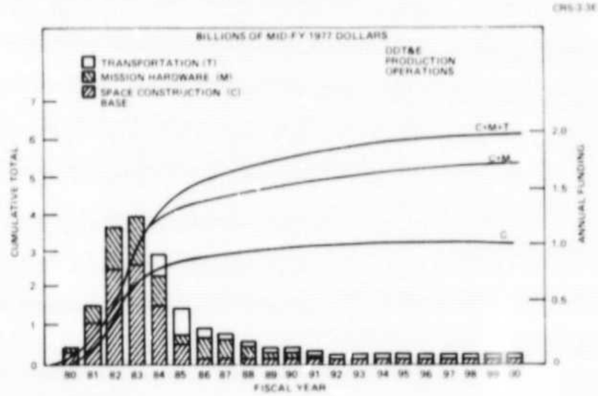


Figure 59. Single-Launch Option Cost

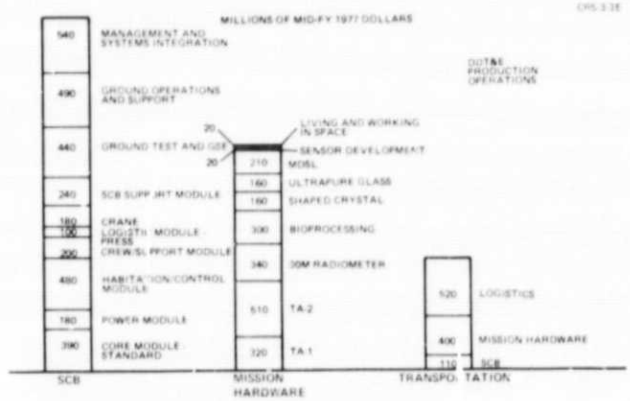


Figure 60. Single-Launch Option Cost Breakdown

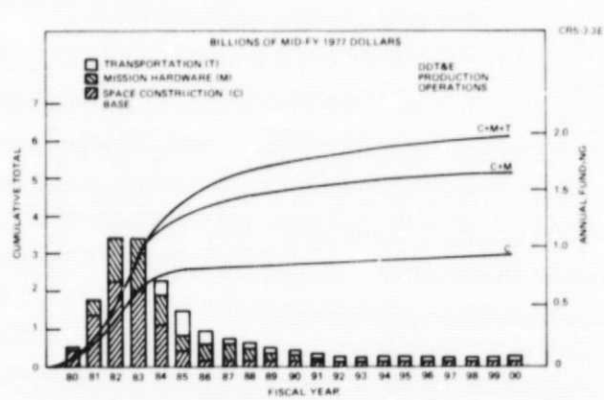


Figure 61. Direct-Growth Option Cost

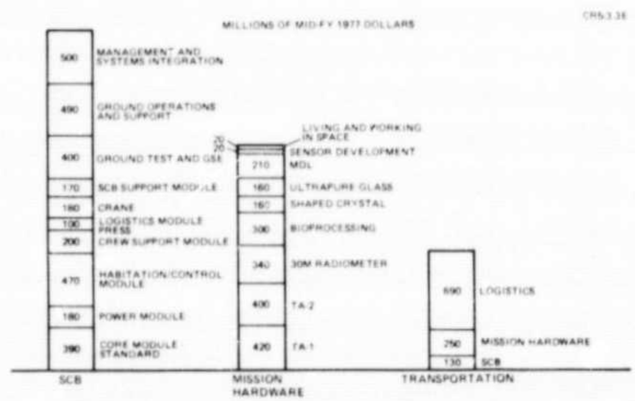


Figure 62. Direct Growth Cost Breakdown

major categories of SCB, mission hardware, and transportation. These are further divided to show the cost of the individual modules and elements of the SCB, the individual objective elements cost for the mission hardware, and the transportation costs for the SCB, mission hardware, and operational logistics support.

Figure 59 summarizes the yearly funding and cumulative cost for the "single launch" option. This configuration is somewhat more autonomous than the "strongback," principally in the areas of power and EVA capability, but it is still dependent on the Shuttle for many functions in addition to habitability. Figure 60 shows the cost breakdown for this option.

The cost for the last Shuttle-tended option, the "direct growth" case, is presented in Figure 61. For this option, the modules for the Shuttle-tended portion of the SCB are the same as those used during the permanently manned portion, except that the crew habitability and cargo functions are provided by the Shuttle. This option represents the most autonomous of the Shuttle-tended configurations. When growth to the permanently manned configuration takes place, all that must be added are the two crew modules and a cargo module. Figure 62 presents the cost breakdown for the direct growth option.

A comparative cost summary for all of the options is given in Figure 63. The data are divided into SCB costs, mission hardware costs, transportation costs, and the total for each option. For the three Shuttle-tended concepts, the costs are given for both the Shuttle-tended portion and the total for growth to a permanently manned configuration. In the Shuttle-tended modes the cost of design, development, test, and assembly of the SCB up to the time of initial operational capability ranges from \$400 million for the "strongback" approach to \$1460 million for the "direct growth" approach. This reflected the increase in the number and complexity of the modules needed to form the base in the "single launch" and "direct growth" approaches. The SCB has basically the same configuration in its final evolutionary state for each of the options.

The total cost figures of the SCB (including growth) were progressively greater for the "single launch" (\$3240 million) and the "strongback" approaches (\$3350 million) when compared with the "direct growth" approach (\$3100 million). This was due in part to the fact that some of the single launch (and still more of the strongback) modules were initially of limited capability as conceived, and needed to be augmented and/or replaced during the period of buildup to the permanent station capability.

The mission hardware for the Shuttle-tended approach also increased from the "strongback" option (\$640 million) to the direct growth option (\$760 million). This reflected the fact that the tooling for fabricating these items was determined to be considerably more sophisticated in the "direct growth" case than in the "strongback" option.

The total cost for mission hardware to accomplish all objectives was found to be about the same for each of the options. Slight variances in the costs occurred because of minor differences in the tooling approaches.

The transportation cost for the Shuttle-tended options varied from \$290 million for the "single launch" to \$420 million for the "strongback." These figures reflect the number of Shuttle flights required. The "strongback" required more flights because of the smaller crew size and the less sophis-

OPTION	SPACE CONSTRUCTION BASE	MISSION HARDWARE	TRANSPORTATION	TOTAL
STRONGBACK				
SHUTTLE-TENDED MODE	400	640	420	1460
TOTAL WITH GROWTH	3350	2020	1200	6570
SINGLE LAUNCH				
SHUTTLE-TENDED MODE	710	660	290	1660
TOTAL WITH GROWTH	3240	2040	1020	6310
DIRECT GROWTH				
SHUTTLE-TENDED MODE	1460	760	360	2580
TOTAL WITH GROWTH	3100	2030	1070	6200
PERMANENTLY MANNED	3060	2030	860	5950

Figure 63. Program Option Cost Comparison (\$ Millions)

ticated equipment used to build to TA-1 and 30-meter radiometer. With this approach, approximately 1-3/4 years at one launch per month (total 22 launches) were required before building of the permanent configuration is begun. The "single launch" option required only 1-1/4 years in the Shuttle-tended mode, still at one launch per month (total 15 launches), before building of the permanent configuration. The "direct growth" option required about four months longer or 1-1/2 years (a total of 19 launches) because more modules are launched, and the power module was not phased into the operation as early as in the "single launch" option.

The transportation costs also reflect the fact that only three launches were necessary in the "direct growth" option to deliver the new modules required for the permanent stations. The "single launch" required five, and the "strongback" required seven. The number of launches required for mission hardware and logistics was the same for all the options once they evolved into the permanent seven-man configuration.

On the basis of the cost studies of the configurations analyzed during Part 2 of the SSSAS, the following conclusions may be drawn:

1. The use of a Shuttle-tended mode of operation that later evolves to a permanently manned station can lower the annual funding requirements for the initial years of the program as compared to a program based only on a permanently manned station.
2. However, the total cost of the program, including the growth required to accommodate all the objectives, will be higher for options that initially use the Shuttle-tended mode as compared to the option that is based on early activation of the permanently manned station.

Question 12
WHAT HAVE WE LEARNED SO FAR?

During the study, a number of points have emerged which are not only of general interest but serve to highlight factors which should be considered in future planning activities.

Briefly, the issue of space fabrication versus ground fabrication with orbital assembly remains an open issue. The resolution of this issue is highly dependent upon the dimensional requirements and the number of units to be constructed, and these factors in turn are dependent upon the objectives to be accomplished and the schedules established. As a general comment, it can be said that space construction appears to be an easier task than initially believed. Also, fewer manhours appear to be required for a given task than originally visualized, equipment requirements are modest and well within the Orbiter capability, and even the largest jobs can be broken into smaller segments for ease of accomplishment.

The one area where an increase in demand was noted was in the extravehicular crew operations. In construction tasks, approximately 50% of the working hours are spent in EVA. It also appears at this time that a single multipurpose construction facility is very expensive for value gained when compared with several construction facilities each dedicated to a specific task.

The procedures for amortizing costs of DDT&E and production for both ground and space facilities must be standardized across all program elements. A common philosophy must be developed for Shuttle (Orbiter) costs and other space platforms. This is essential if valid program costs and user cost policies are to be established.

From a program planning standpoint, specific goals are needed by both NASA and the aerospace industry. The initial Space Station/construction base will be the basic building block for all future development and to provide a 1984 initial operational capability, the development cycle must start in 1979 and the Phase B must occur in calendar 1978.

Of the many potential objectives examined to date, energy, telecommunications, and space processing appear to be the most promising areas of application, and the development of space construction technology will be key to the pursuit of each.

Finally, it must be remembered that the decisions we make today will determine what is accomplished in the 1980's and that the alternative courses of action which will be open to our nation in the future will be predicted upon the research and development steps implemented during the next 10 years.

Question 13
WHAT PLANNING AND ANALYSES REMAIN TO BE DONE?

In the current study, our next immediate step is to define further the program or system option which represents the most likely candidate for early implementation. Selected SCB concepts will be defined in terms of (1) *support systems* which provide the resources (crew habitability, power, communications, etc.) for the conduct of all on-orbit activities and (2) *construction systems* which provide the tooling and operational control for on-orbit construction efforts. We will focus on LEO operations. In this regard, the initial test articles for a satellite power system, earth services (communications and radiometric surveys), and space processing will represent the key mission elements.

The key issues which will be examined during the next phase of the current study will include both technical and programmatic considerations. From a technical standpoint, considerations will include development of a concept for on-orbit construction of the power supply as a first step in the SCB build up, better definition of EVA operations (optimal durations, mobility aids, work platforms, and radiation protection); examination of the stabilization, control, and orientation requirements for multiple combinations of modules; definition of crane-type operations, including dynamics and control and display requirements; and engineering definition of space construction tooling requirements. From a programmatic standpoint, comparative data on relative productivity and cost-effectiveness of system options will be prepared. In addition, recommendations for establishing the crossover points for the Shuttle-tended versus continuous manning, deployment versus assembly, and assembly versus fabrication and assembly operational modes will be developed.

When the SCB configurations have been designed and the various technical and programmatic issues resolved, the best SCB approaches will be selected and preliminary program plans written.

Question 14
AT THIS TIME, DOES THERE APPEAR TO BE SOUND JUSTIFICATION FOR A NATIONAL COMMITMENT TO PROCEED WITH THE DEVELOPMENT OF A SPACE STATION?

Based upon the work accomplished so far, and the wealth of information developed in previous studies the development of a continuously manned Space Station appears inevitable. It is our firm conviction that the next NASA-industry objective should be the development of a modular, low cost approach to a general-purpose space construction base. This SCB must be designed to support construction of the initial test articles essential to early decisions on the feasibility of solar power satellites, and it must be designed to support the construction in space of large antenna systems. In addition, the basic space platform must provide a facility for the development of space manufacturing and processing technology and for the continuing support of other emerging objectives.

As the costs of operations per available service hour in orbit are reduced, more industrial, commercial, and non-government institutions will find it practicable to invest venture capital to use space facilities for the development of new products and processes. By providing space platforms capable of supporting 6 to 12 crewmen for 90 days or more, the costs of orbital man-hours become much more attractive to potential industrial or commercial users of space (see Figure 64). When operating costs can be reduced to less than \$5,000 per hour, they will become comparable to those experienced in a wide variety of ground-based research and development operations*. In space processing, for example, facility operating costs of about \$2,000 per hour would appear to provide attractive inducements to many industrial users.

If it can be agreed that the development of a continuously manned Space Station is inevitable, whether accomplished through evolutionary steps from an initially Shuttle-tended mode of operation or whether accomplished directly, the only question remaining to be answered is, when? In committing our nation to proceed with the development of a

*Operating costs of DC-10 average \$1,065 per hour; of a Boeing 747, \$1,602 per hour (3rd quarter, 1976), the 4-foot wind tunnel at McDonnell Douglas Aerophysics Laboratory, \$1,125 per hour.

permanently manned Space Station, it is essential that the design development, and scheduling activities recognize realistic budgetary limitations and effectively use and build upon ongoing activities. With this in mind, it does appear that the costs of developing a permanently manned LEO facility are compatible with the Office of Space Flight/NASA budget (see Figure 65) and can be achieved with an initial operational capability in 1984. That capability data, is predicated, however, upon a 1978 Phase B and a 1979 Phase C/D go-ahead.

Remembering that the "longest journey starts with the first step," it is our recommendation that the first step be taken now.

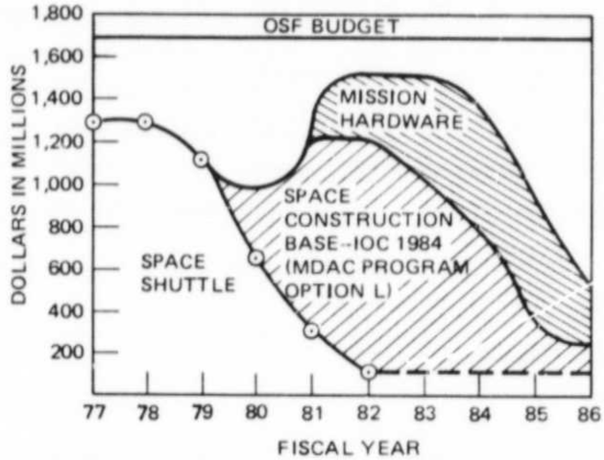
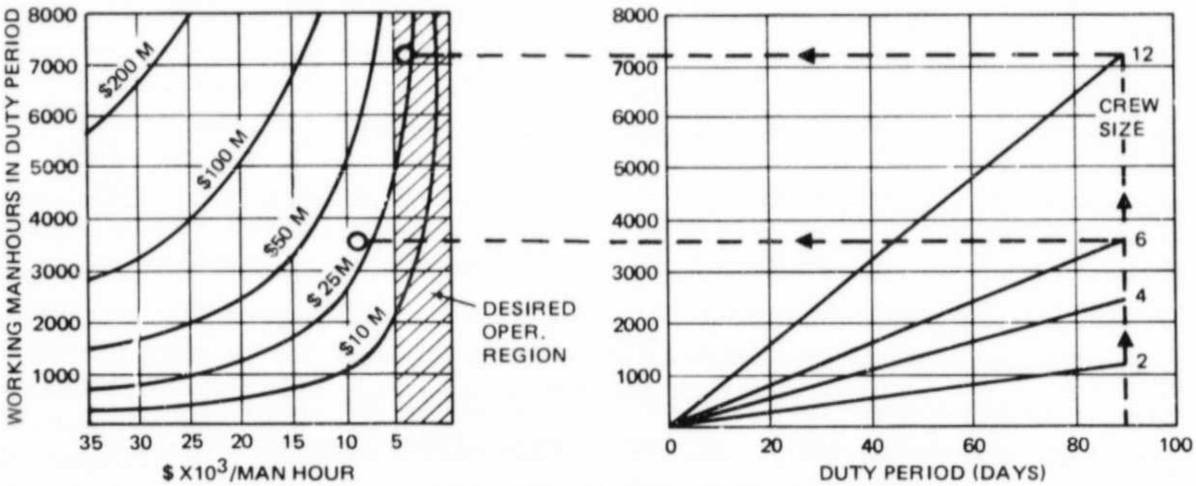


Figure 65. Space Station Development Costs are Compatible With Constant OSF Budget



AS AN EXAMPLE ASSUME ORBITER FLIGHTS AT $19M EA, OPERATIONS COSTS AT $50M/YR, ADDITIONAL STATION MODULE AT $200M WITH 5 YR LIFE, TO REPRESENT $19M + 12.5M + 10M OR $31.5M PER 90 DAY PERIOD

Figure 64. Crews of 6 to 12 Men for 90 Days or More Provide Attractive Orbital Costs