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NASA CR-172,691

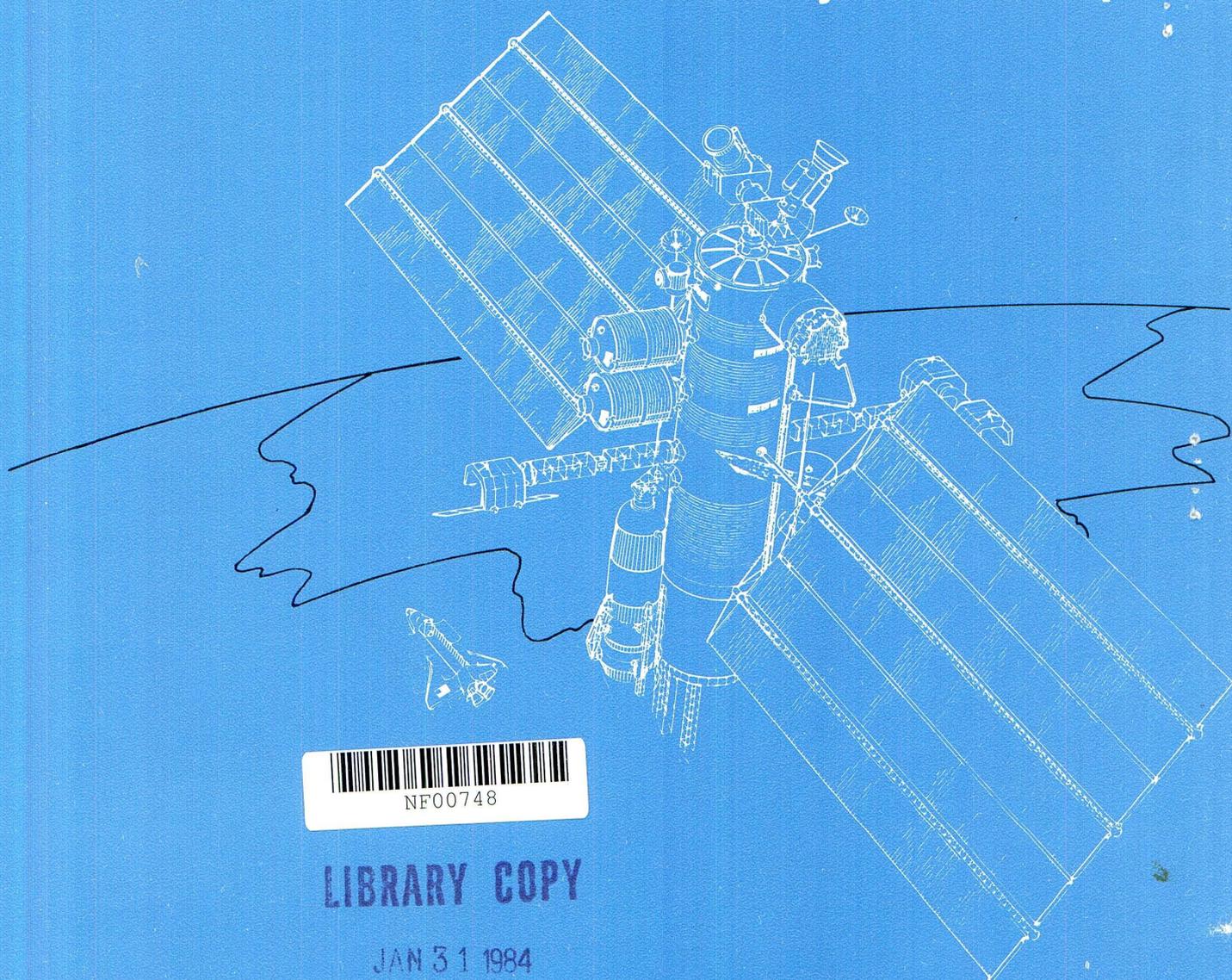
NASA-CR-172691
19830019784

Volume I

Executive
Summary

April 1983

Space Station Needs, Attributes, and Architectural Options Study—Final Report



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FOREWORD

This final report, submitted to National Aeronautics and Space Administration (NASA) Headquarters, Washington, DC 20546, presents the results of the Space Station Needs, Attributes and Architectural Options Study performed by the Space and Electronics Systems Division of the Martin Marietta Corporation under NASA Contract NASW-3686.

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1.0 Introduction

1.0 INTRODUCTION

1.1 PURPOSE

The primary objectives of the Space Station Needs, Attributes and Architectural Options study are to--identify user missions that are enhanced or enabled by a permanent manned space station in low earth orbit; characterize the attributes and capabilities that will be necessary to satisfy these mission requirements; recommend space station implementation approaches, architecture options, and evolutionary growth; and define the programmatic/cost implications.

1.2 SCOPE

This study identified, collected, and analyzed the science, applications, commercial, U.S. national security and space operations missions that would require or be materially benefited by the availability of a permanent manned space station in low earth orbit and identified and characterized the space station attributes and capabilities which will be necessary to satisfy these mission requirements. Emphasis was placed on the identification and validation of potential users, their requirements, and the benefits accruing to them from the existence of a space station, and the programmatic and cost implications of a space station program. Less emphasis was placed on the detailed design beyond that necessary for the identification of system attributes, characteristics, implementation approaches, architecture options, and ROM costs.

The study results are presented in six volumes as follows:

Volume I, Executive Summary, highlights the specific results obtained during each phase of the study as described in Volumes II through VI (classified information excepted).

Volume II, Mission Definition, presents the results of our mission definition activities including the identification, modeling and validation of potential user missions, their requirements and the benefits that could accrue to the users from the existence of a space station.

Volume III, Mission Requirements, presents the space station user requirements, their integration and time phasing, and the derivation of system and user accommodation requirements. The derivations of user requirements and space station accommodations encompassed a traceability analysis, parametric studies, and an analysis of economic, performance, and social benefits afforded by the existence of a space station.

Volume IV, Mission Implementation Concepts, presents the results of our study efforts describing our analyses and defining our recommended space station implementation approaches, architecture options, and evolutionary growth.

Volume V, Cost Benefits and Programmatic Analysis, presents the affordability analysis conducted to determine the affordable mission model, quantification of economic benefits, estimate of the ROM costs for each of the architectural options and their associated program and element schedules.

Volume VI, DOD Mission Considerations, presents the results (classified) of our analysis for the DOD National Security mission. This volume was published under a separate cover and is available through the DOD Task Manager at Space Division (SDXR), Los Angeles, California.

1.3 APPROACH

Figure 1.3-1 illustrates the Space Station program study flow.

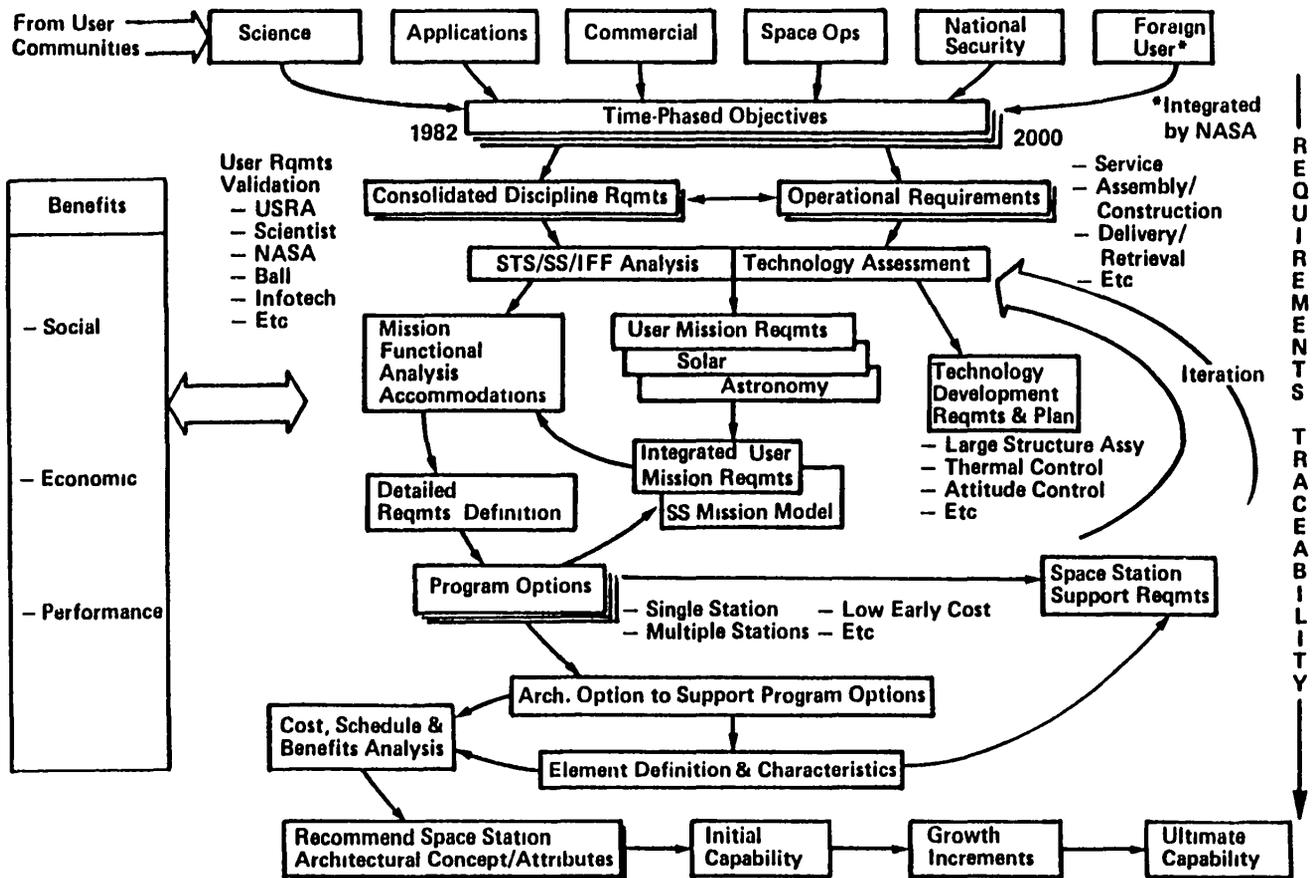


Figure 1.3-1 Study Task Flow and Relationships

Appendix A, Acronyms and Abbreviations, presents a reference list common to all volumes of this report.

Appendix B, Reference Bibliography, presents a listing of all primary references used to develop the data presented throughout this report.

Appendix C, Mission Concept Reference Data, presents the detailed mission definition and user mission requirements for each mission defined in the Space Station Mission Model presented in Volume II.

1.4 GROUND RULES AND GUIDELINES

Throughout the study the following ground rules and guidelines are adhered to:

- o All facilities will be Shuttle launched and tended;
- o Potential missions of interest will include domestic and foreign science, applications and commercial users as well as U.S. national security and space operations missions,
- o All missions included in the study results will include the specific source of user input;
- o Primary consideration should be given to the requirements for a permanent manned space station in low earth orbit;
- o The Tracking Data Relay Satellite System (TDRSS) will be the primary space-to-ground communications interface for space station operations;
- o Development of space station options should consider a single space station in the 1990 time frame while the evolutionary growth could require consideration of multiple stations or platforms;
- o Department of Defense (DOD) Task Assignment - Consider space station interaction with the total DOD space infrastructure envisioned to be in use in the later 1980s through the year 2000;

(A mission model delineating the military space missions for the time period specified above was provided by DOD.)

- o The contractor has the responsibility to obtain all information and data necessary to conduct the study;
- o NASA will provide the results of appropriate in-house studies as a primary source of information on science and applications missions;
- o NASA will provide relevant results of mission analysis studies conducted in other countries.

2.0 Mission Definition

2.0 MISSION DEFINITION

The purpose of the Mission Definition phase of the study was to survey the space applications and science programs appropriate to the era beyond 1990 and select those user missions which can use the Space Station to an advantage, and further to define user mission concepts so that requirements which would drive the Space Station design could be developed.

The following paragraphs summarize the results of Volume II which define our mission definition activities including the identification, modeling and validation of potential user missions, their requirements and the benefits that could accrue to the users from the existence of a space station.

2.1 PLANETARY EXPLORATIONS

The affordable missions selected for planetary science application are as follows:

- o Galileo Jupiter and Saturn Probes
- o Comet Rendezvous and Sample Return
- o Venus Radar Mapper
- o Mars GeoChemistry, Climatology and Aeronomy Orbiter
- o Venus Probe

These missions are based on a systematic long range strategy of exploration, reconnaissance and missions to bodies in the solar system. The mission model also builds upon the experience gained from previous explorations.

The role of the SS in supporting planetary explorations of the near term will be limited to providing a launch/boost to the higher energy trajectories, if the orbital phasing can be provided, and quarantine and decontamination of samples returned from other solar system bodies.

2.2 EARTH OBSERVATIONS

The affordable mission sets selected for Earth Observations are as follows:

Initial Complement

Imaging Spectrometer
Microwave Radiometer
Synthetic Aperture Radar
Geosynchronous Satellite Sensor Intercalibration

Evolutionary Complement

LIDAR - Light Detection and Ranging
CLIR - Color Scanner Cryogenic Limb Scanning Interferometer and Radiometer
Thermal Infrared Multispectral Imager
Scatterometer

Ocean Microwave Package
Stereo Visual Imager
LAMMR - Large Antenna Multifrequency Microwave Radiometer
Advanced Meteorological Infrared and Microwave Sounder

Ultimate Facility (2000+)

Microwave Sounder (Geosynchronous)

The potential capability for space station support to earth observations, i.e., operations/control, subsystems, and initial activation, are only possible while on-board the space station and even the repair/resupply needs would require an orbit inclination separation of no more than 30°. Since the majority of earth observations missions require near-polar orbits the support of these may have to be on a platform without service from the main space station.

2.3 SPACE PHYSICS

The affordable missions selected for space physics are as follows:

Initial Complement

Space Plasma Effects Upon Large Spacecraft
Large Spacecraft Impact Upon Proximate Space Plasma
Initial Solar Terrestrial Observatory (STO)
Upper Atmosphere Research Satellite (UARS)
Origin of Plasma in Earth's Neighborhood (OPEN)
SL-X - X Experiments
Chemical Release Module Facility (CRM)
AMPTE

Evolutionary Complement

Active Plasma Facility
Advanced Solar Terrestrial Observatory (ASTO)
Plasma Turbulence Explorer (PTE)
Advanced Interplanetary Explorer

Ultimate Phase Complement

Very Large Radar (VLR)
Geostationary Solar Terrestrial Observatory (GEO-STO)
Advanced Active Plasma Facility

The rationale for selection is based upon the general objective of understanding the fundamental physical processes involved in man's global and universal environment. This mission complement has been subjected to the limitations of the budget projections.

2.4 ASTRONOMY - ASTROPHYSICS

The affordable missions selected for astronomy are as follows:

Initial Complement

EUVE - Extreme Ultraviolet Explorer
COBE - Cosmic Background Explorer
XTE - X-Ray Timing Explorer
GRO - Gamma Ray Observatory
ST - Space Telescope
Starlab
SIRTF - Shuttle IR Telescope Facility

Evolutionary Complement

AXAF - Advanced X-Ray Astrophysics Facility
OVLBI - Orbiting Very Baseline Interferometer
GTE - Gamma Ray Timing Explorer
FUSE - Far Ultraviolet Spectroscopy Explorer
LAMAR - Large Area Modular Array of Reflectors
HNE - Heavy Nuclei Explorer
OIST - Orbiting IR Submillimeter Telescope
XRO - X-Ray Facility
CRO - Cosmic Ray Facility
LDR - Large Deployable Reflector

Ultimate Complement (2000+)

COSMIC - Coherent Optical Sys. of Modular Imaging Collectors
TAT - Thinned Aperture Telescope
LWA - Long Wavelength Antenna

This complement was selected based on scientific priorities identified in the "Astronomy Survey Committee Report (1982)". The combination addresses the major scientific questions and objectives as defined in this report. It provides a broadbased approach using the full electromagnetic spectrum for both exploration and detailed study. Many of the programs are currently funded and will be developed during the 1980s, and it is felt that the entire complement can be accommodated by projected funding through the 1990s. These mission sets are in accord with the recommendations of several astronomers actively pursuing major work in key areas.

2.5 SOLAR PHYSICS

The affordable missions selected for the solar physics program are as follows:

Initial Complement

SSF - Solar Shuttle Facility
SIS - Solar Interplanetary Satellite
SIDM - Solar Internal Dynamics Missions
SCDM - Solar Coronal Diagnostic Mission

Evolutionary Complement

ASO - Advanced Solar Observatory
SOT - Solar Optical Telescope
P/OF - Pinhole Occulter Facility
SSXTF - Solar Soft X-Ray Telescope Facility
SEXTF - Solar EUV/XUV Telescope Facility

This proposed program essentially builds on the STS/Spacelab programs which precede the SS. The individual instruments would be flown as they are available and eventually integrated into the Advanced Solar Observatory (ASO). The ASO will have the flexibility to evolve through configurations of increasing capability as new instruments become available. With the SS support, these changes can be accomplished on-orbit.

The support which the SS has the potential to provide to solar astronomy would be to be attached and operate much as ATM did on Skylab including the use of film for some data, and direct support from SS subsystems. Solar astronomy could best benefit from an orbit which maximizes sun view time, the ultimate being sun synchronous at the terminator. This would not be a likely orbit for space station and would require a platform facility. The viewing time advantages of this will have to be traded against the advantages of long duration and high level support available at the SS in a less desirable orbit.

2.6 LIFE/BIOLOGICAL/MEDICAL SCIENCES

All of the conceptual experiments proposed by the investigator contacts and resource documents were considered to be affordable and were grouped as follows:

Initial Complement

Health Maintenance Facility Category II
Analysis & Diagnostics Laboratory
Computer Diagnostics System, Recompression

Evolutionary Complement

Health Maintenance Facility Category III
Expanded Medical and Exercise Instrumentation
Expanded Research; Quarantine

Life Sciences Research Module
Vivarium - Small Animals, Large and Small Primates, Plants
Life Sciences Laboratory Facility
Large General Purpose Centrifuge

Ultimate Complement (2000+)

Health Maintenance Facility Category IV
Controlled Environment Life Support System Demonstration
Large Plant Growth Module

All of the human research will be performed in the Health Maintenance Facility (HMF) which is to be located in the crew habitability module. A number of the equipment items required for routine and contingency medical support will have dual utility in basic biomedical research. The HMF is anticipated to evolve through four levels of support capability. Category I is provided by the Shuttle during buildup. Category II will be fully operational when longer duration manned missions are implemented. Categories III and IV (2000+) will be characterized by expanded research and medical support capabilities.

The non-human research activities will require a vivarium for non-human specimen support and a Life Sciences Laboratory Facility (LSLF) both of which will be contained in the Life Sciences Research Module (LSRM).

A number of the equipment items for the non-human research, such as the Large General Purpose Centrifuge and the Large Primate Holding Facility, are planned or are currently being developed for Shuttle Spacelab.

While it has been shown that man can effectively live and work in the space environment, a number of potentially health threatening physiological effects have been documented in previous spaceflights. Recent data on Shuttle have indicated that the vestibular-induced sickness and perceptual changes may prove to be hazardous with changes in the acceleration forces during landing of the craft. In addition, the postflight orthostatic intolerance has been more severe in both astronauts and cosmonauts than previously believed. With the longer missions proposed for SS, it is necessary to determine the extent of these effects as well as the nature and extent of the musculoskeletal deconditioning in order to establish the limitations of human habitation and operational efficiency for the SS era. Physiological effects which require greater than 30 days to manifest cannot be adequately studied on shuttle. The SS will provide the research capability and mission durations necessary to study the etiological mechanisms of these effects and to assess appropriate countermeasures including the potential need for a means of inducing artificial gravity in future SS architecture.

2.7 MATERIALS PROCESSING IN SPACE

The affordable missions selected for Materials Processing in space are as follows:

Initial Phase

SS Materials Processing Laboratory

Acoustic Containerless Furnace	Directional Solidification Furnace
Electrostatic Containerless Furnace	Gradient Furnace
Electromagnetic Containerless Furnace	Isothermal Furnace
Vapor Crystal Growth Facility	Fluids/Chemical Process Facility
Crystals From Solution Facility	Fluid Experiment System
Floating Zone Furnace	Electrophoresis Separation Facility
	Combustion Research Chamber

MDAC/J&J Electrophoresis (EOS)
Lehigh Monodisperse Latex Reactor

Evolutionary Phase

Commercial Development Units

Ultimate Phase

Commercial Production Units

We are convinced that the early emphasis of space station in the area of Materials Processing should be basic research. This country's knowledge base of processing phenomena in low-gravity environments is not broad enough to allow accurate prediction of those commercial processes that might prove effective in space. We have, therefore, proposed an extensive complement of research facilities to be included within the laboratory, and have included the laboratory module as one of the early components in the space station buildup.

Also included in the MPS Initial Phase complement are the two commercial ventures that are farthest along in their development. We have not excluded other commercial applications from the initial phase, and some could well be ready by the early 1990s.

The Evolutionary Phase complement consists of commercial development hardware for the processes whose feasibility will have been demonstrated by STS-based system and SS laboratory experimentation. These are hardware units provided by private industry intended to develop a successful experiment process into a large scale production capability. The generic title is used because we cannot predict which of the processes might exhibit the best commercial viability.

The ultimate phase complement consists of commercial production units. These have been included in the mission set to assure that SS planning includes the servicing capabilities that will be required by successful MPS manufacturing operations.

2.8 COMMUNICATIONS

The affordable missions selected for communications are as follows:

Initial Phase

Search and Rescue Program (SARSAT)
Commercial Communication Satellite Launches

Evolutionary Phase

Experimental Geostationary Platform (XGP)

The search and rescue program payload can be easily accommodated by either the initial SS or on a polar-orbiting Earth Observations Platform. Commercial communication satellites launch operations can be accomplished after the implementation of SS reusable Orbital Transfer Vehicle (OTV) capabilities. The OTV launch operations become a significant SS benefit and are therefore incorporated into this mission set as early as possible. The Experimental Geostationary Platform (XGP) is shown in the Evolutionary Phase because of its additional SS operational requirements for antenna alignment along with launch operations. The Orbiting Deep Space Relay Station was omitted because it is not presently considered to be affordable nor technically advantageous.

Reusable OTV geosynchronous orbit transfer and servicing operations are the important contributions for Space Station to the communications community. These benefits include the reduced launch costs associated with the reusable OTV, the extended mission life gained from GEO satellite servicing and refueling, and the operational advantages gained by deploying and aligning antennas at the SS. The eventual development of communications antenna platforms will provide yet another demonstration of the SS's utility in meeting the world's communications needs.

2.9 TECHNOLOGY DEVELOPMENT

The affordable technology development missions selected are as follows:

<u>Technology Area</u>	<u>Title</u>
Structures	- Large Structures Technology - Structural Strain Monitoring - Thermal Driven Shape Control
Power Systems	- Large Space Power System Technology Demonstration - Low Cost Solar Panel Technology - Solar Array Plasma Effects
Attitude Control	- Attitude Control System Development - Tether Dynamics Technology
Propulsion Systems	- Fluid Management Technology - Low Thrust Propulsion
Communications/Tracking	- Laser Communications and Tracking - Antenna Range Facility - Large Antenna Development
Materials	- Spacecraft Materials Technology
Servicing Technology	- Satellite Servicing - OTV Servicing

<u>Technology Area</u>	<u>Title</u>
Safety	- Fire Safety
Advanced Energetics	- Large Solar Concentrator - Solar Pumped Lasers - Laser-to-Electric Energy Conversion - Laser Propulsion Test - Solar Sustained Plasmas

These missions have been selected to cover a variety of space technology disciplines to illustrate the range of adaptability of the SS to these development endeavors.

The missions selected for the technology development discipline are based on the inputs to the set of Candidate Technology Development Missions compiled by S. V. Manson of NASA Headquarters staff.

The role of the SS in support of technology development can be very broad in scope. The generalized benefits are derived from the availability of a test bed approach which permits alternate design approaches to be evaluated before commitment to a program. Most of the technology missions selected can only be demonstrated and studied in the space environment and with the operational capabilities provided by the SS. Some of the unique capabilities are: zero gravity environment; human operator participation prior to automation; extended duration operations; space exposure environment; and the capability to assemble and to accommodate large unwieldy objects. These unique capabilities will support the development of a wide range of space technologies and can substantially reduce development schedules and costs.

2.10 MISSION DEFINITION SUMMARY AND CONCLUSIONS

Long duration operation is probably the most significant single element. Many missions are currently planned for STS/Spacelab with its extremely limited time on orbit. Most of these concepts can be used on the SS with orders of magnitude improvement in results. Most free-flyers are limited by random failure and consumables and these missions also can be greatly extended.

Man can contribute most in his capacity to repair, replace, resupply and refurbish or modify systems. Many feel he has limited use in the role of observer and operator, and prefer to keep these functions for ground control, but in some areas, such as life sciences and materials processing, he can be invaluable in this role.

On orbit assembly and checkout will be critical for many large payloads of the future. Only the SS can maintain adequate crew and equipment to support this kind of operation.

Materials processing needs the kind of research laboratory facility that only the SS can provide. Industry lacks confidence in current operations but participation could be achieved through education and understanding of space station capability.

Earth observations could benefit very much from on-board SS support, but they generally need a near-polar orbit which is not likely to be directly supportable from space station.

The communications industry has a highly developed satellite system. The SS capability to reduce launch costs and prolong lifetime through repair and resupply has potential for high payoff.

Astronomy missions can generally derive very large benefits from long duration and maintenance and resupply support. Astronomers are apprehensive about their mission being onboard because of unknown levels of contamination and disturbances. Analysis of these factors, and the capability to control them are needed so that it can be determined if missions would have to be relegated to separate platforms.

A summary of potential SS support for missions in each discipline is shown in Figure 2.10-1. The numbers indicate how many missions could benefit from the support functions listed. It can be seen, for example, that the main benefit for communications and planetary missions is the launch to orbit assist while nearly all missions can benefit from repair and resupply. Many can potentially benefit from operations control and subsystems support. This generally requires them to be attached to the SS. This may not be possible since considerations of orbit preference preclude being aboard.

SS Support Functions	Astronomy	Solar Astronomy	Space Physics	Earth Observations	Life Sciences	Materials Processing	Communications	Planetary Explorations	Technology Development	Total
Launch	2	1	6	1	0	0	62	11	0	83
Repair & Resupply	20	7	7	14	14	20	13	0	0	95
Operate, Control, Data Mgmt	4	7	4	13	14	20	1	0	23	86
SS Subsystems - Attached	4	7	3	13	14	19	2	0	23	85
Initial Activation Checkout	6	0	6	14	14	20	4	0	22	86
Assembly-Large Structures	7	0	1	1	0	0	1	0	5	15
Total	43	22	27	56	56	79	83	11	73	450
No. of Missions	20	8	11	14	14	20	64	11	23	162

Figure 2.10-1 SS Potential Support by Missions

Figure 2.10-2 is more subjective in its evaluation of the SS support potential but shows the extent to which it is felt that the user missions will benefit. The light shading indicates improvements in performance and reductions in cost over what could likely be obtained by other means. The dark shading indicates the additional, major improvements beyond what is practical by any alternate mission

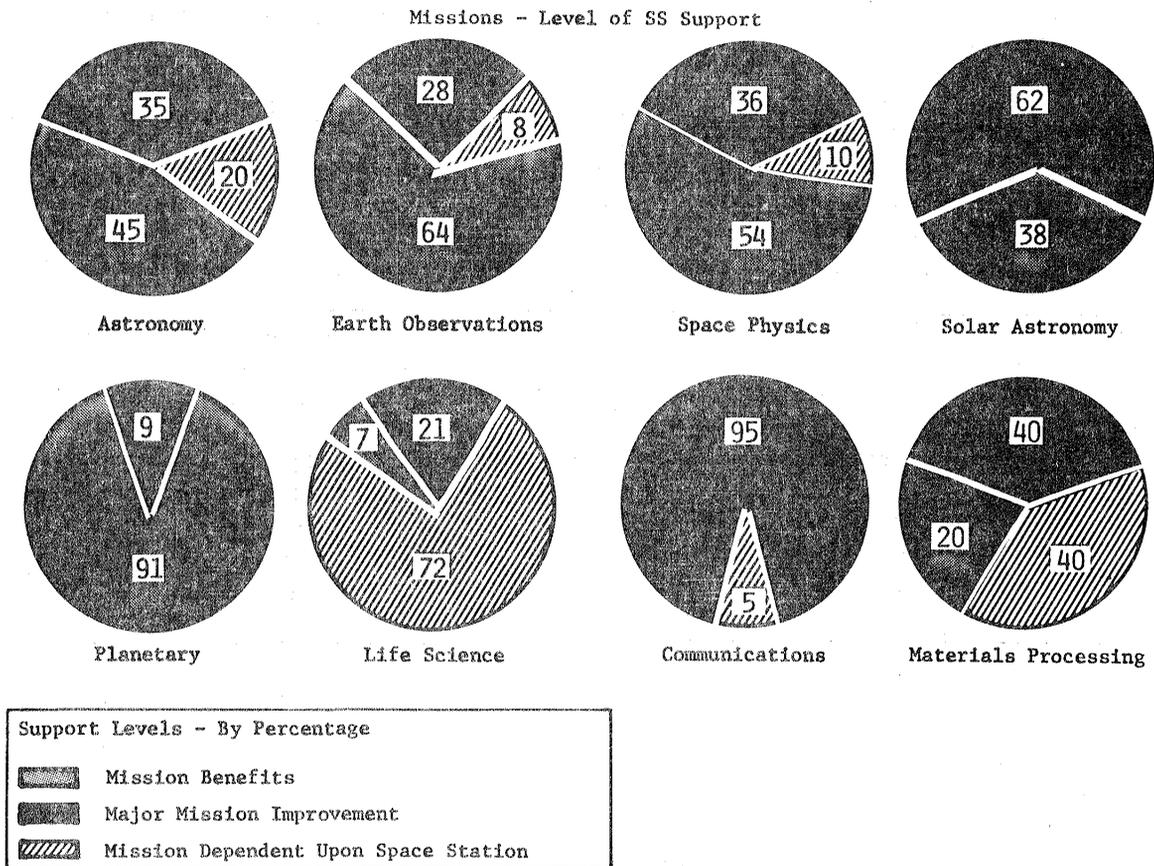


Figure 2.10-2 Mission Support Potential-Space Station

concepts. The cross hatched area indicates mission concepts which could not be performed without significantly reducing their objectives, except with space station support. Life science and materials processing have large cross hatch areas because their dependence upon long durations with manned involvement is not possible by other means. Other cross hatch areas are mostly due to vital assembly on-orbit functions. Communications has large dark shading since it is felt that the boost to higher orbit and the repair and resupply capability is very important. Likewise solar astronomy could significantly benefit from film changes and on-board data storage and processing and therefore also has a large dark shaded area. Overall, the chart expresses our belief that space station has the potential to enhance operations and reduce costs over a large majority of space missions.

3.0 Mission Requirements

3.0 MISSION REQUIREMENTS

3.1 INTEGRATED USER REQUIREMENTS

Derivation of space station capability requirements began with an assessment of the requirements imposed by individual missions. Initially, we considered some 327 missions; this number was reduced to 159 missions by applying affordability criteria, capture analysis, and combining missions with similar objectives. Individual requirements were then combined, integrated, and time-phased into a unified set of user requirements.

User requirements were divided into five broad classes of user support requirements:

- In-Space Assembly and Checkout
- Orbit Transfer and Retrieval
- Propellant and Consumables Resupply
- Maintenance and Repair
- Operational Support

We found that in-space assembly and operational support requirements were only a small fraction of the total requirements (Fig. 3.1-1). Orbit transfer and retrieval accounted for 32% of the requirements, propellant and consumables resupply accounted for 36%, and maintenance and repair accounted for 26%. The mission category with the most requirements was commercial communications. This category, along with astronomy and earth observations, accounted for two thirds of the total requirements in the time period between 1991 and 2000.

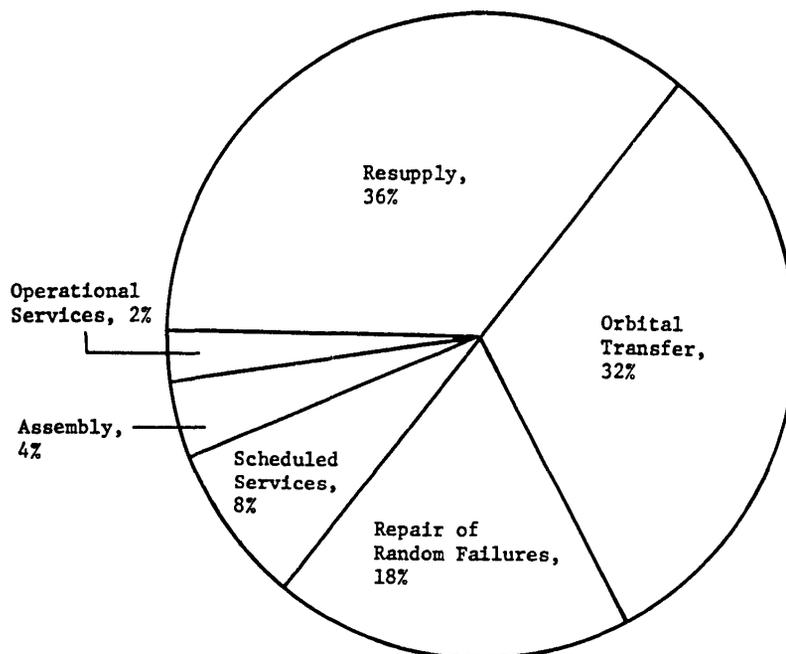


Figure 3.1-1 Distribution of Space Station Logistics Requirements

The time phasing of requirements, shown in Figure 3.1-2, a rapid buildup in the first two years, followed by a relatively level period, and then a gradual decline. (We believe the decline is more probably due to uncertainty in estimating the out-year requirements than to an actual reduction.) Peak activity is 95 services per year, in 1997.

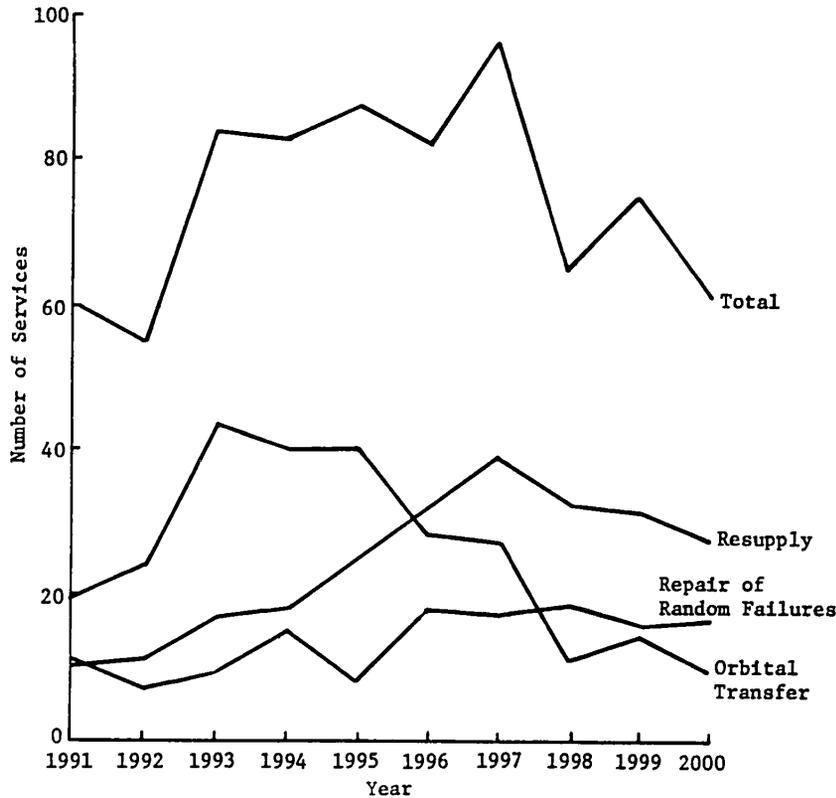


Figure 3.1-2 User Requirements Timeline Distribution by Type

In the early years, the principal service required is orbit transfer and retrieval, while resupply requirements gradually increase to represent the majority of requirements in later years. Maintenance and repair requirements increase very gradually throughout the decade.

3.2 SPACE STATION USER ACCOMMODATION REQUIREMENTS

Space Station capability requirements originate from two sources: accommodation of users, and the operational capabilities required of the space station itself. User accommodation and space station operational requirements were derived from consideration of a series of eighteen operational scenarios representing space station and user support activities. These scenarios were subjected to functional analysis in order to identify the ground rules, functional capabilities, and support equipment required to accomplish each scenario. Subelements of the top-level functional flows were further analyzed where it was evident that additional capabilities and support equipment could be identified. Finally, all requirements were collected, collated, and categorized by subsystem into a set of integrated facility, hardware, and software requirements. Figure 3.2-1 illustrates a few of the important requirements that resulted from this task.

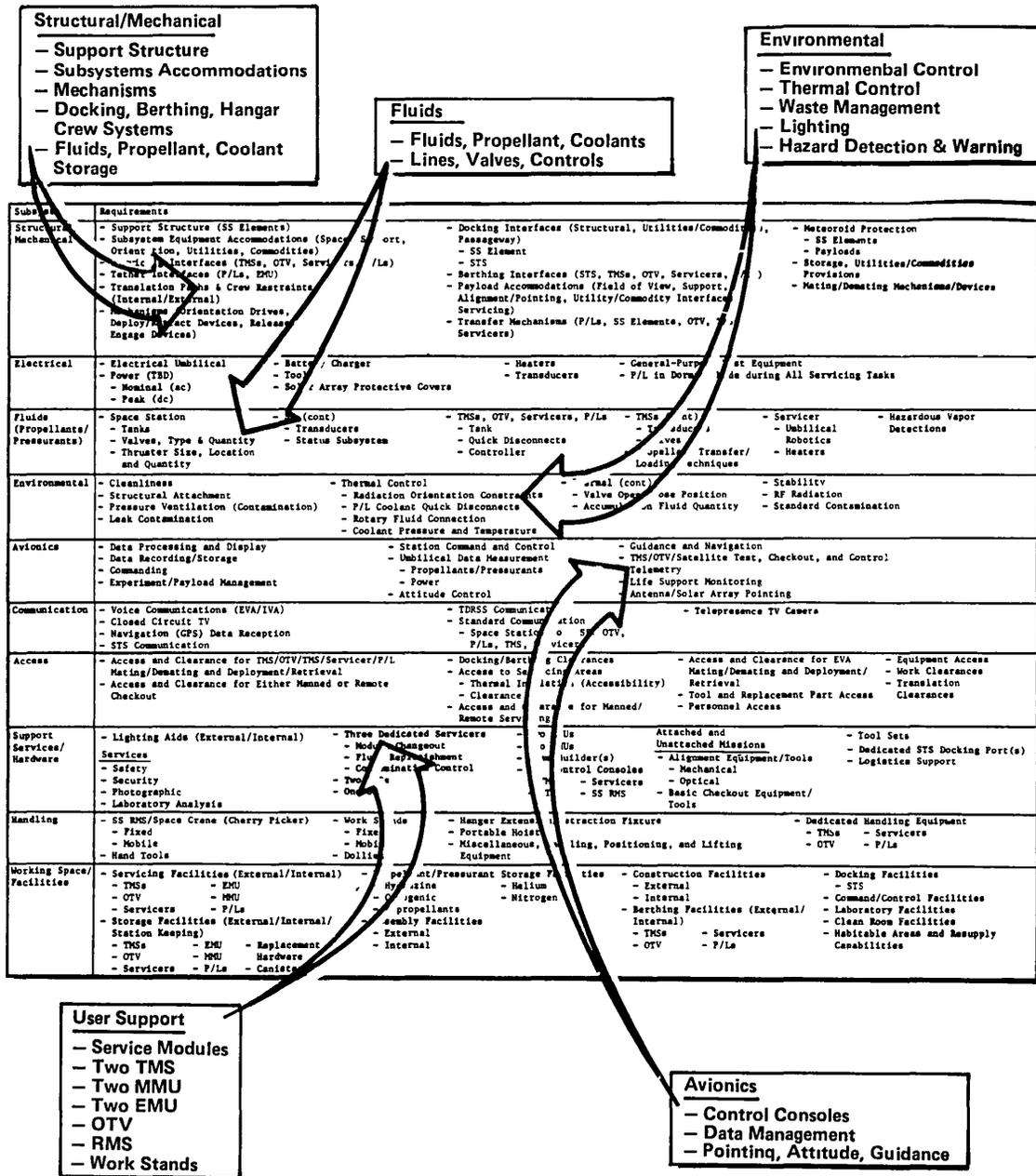


Figure 3.2-1 Space Station Capability Requirements

For the most part, numerical performance requirements have not yet been determined, because many of the underlying user support requirements, as well as the characteristics of the space station itself, are insufficiently defined. These requirements and characteristics should be subjects for additional study as the space station program matures.

3.3 REQUIREMENTS TRACEABILITY

During the course of this study, the basic mission model has evolved from a compilation of missions from several sources (MMC Composite Mission Model), through the application of affordability, capture criteria, and combination of related or redundant objectives, to a Space Station Mission Model. At each step, a unique identification

code has been assigned to each mission so it can be traced to its original source for validation. In addition, the service and support capability requirements associated with each mission are indexed so each requirement can be traced to its user mission. In this way, space station capability requirements can be updated quickly to reflect mission model changes.

3.4 MISSION ANALYSIS AND PARAMETRIC STUDIES

The primary purpose of the parametric studies was to determine the optimum space station orbit altitude and inclination. Additional analyses were performed to determine orbit transfer vehicle performance requirements, launch window penalties, and concepts for station-keeping platforms. All orbit performance analyses were based on Hohmann transfer ellipses and impulsive velocity changes.

The recommended orbit altitude is nominally 250 nautical miles, based primarily on the requirement that the Space Station have at least a 90 day orbit lifetime without makeup of velocity lost due to drag decay. This altitude is also well above the traffic hazards posed by short-lifetime satellites and other low-altitude space debris.

The optimum space station orbit inclination appears to be 28.5 degrees, this is optimum both from the standpoint of minimizing the number of STS flights and capturing the largest number of user missions. As shown in Figure 3.4-1, the space station reduces the number of STS flights for delivery by about one third at the optimum orbit. When additional STS flights required to support the space station are considered, the net benefit is about one flight in six.

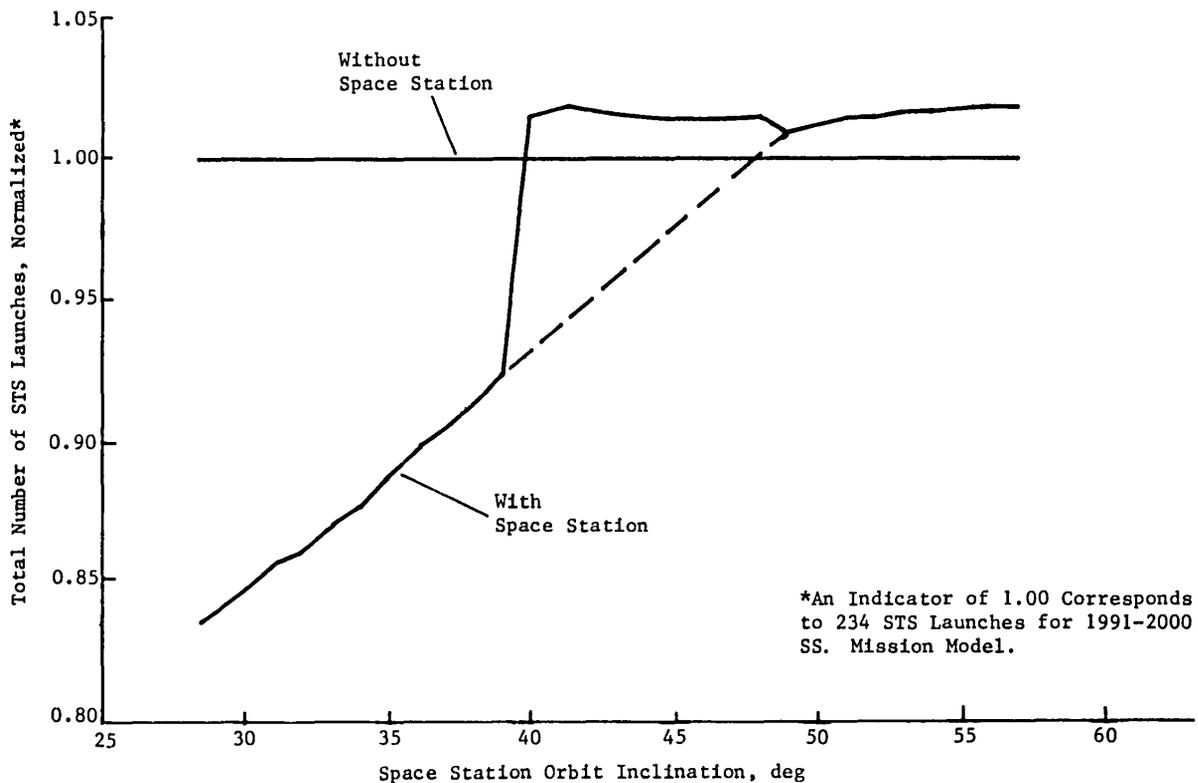


Figure 3.4-1 Sensitivity of STS Launch Requirements to SS Orbit Inclination

A reusable, aerobraked, cryogenic-fueled orbit transfer vehicle with a 16,000 kg propellant capacity captures approximately 80% of all missions considered; this size OTV can also be carried to the space station in a single STS flight.

For minimum propellant expenditure, an optimum time exists for orbit transfer involving a plane change; additional propellant is required for launch times before or after that optimum. The propellant requirements decrease as the target orbit altitude increases; however, the additional velocity capability required for a launch window enabling launch at any time exceeds two kilometers per second even for geosynchronous altitude, and is probably unacceptable except in extreme cases.

Unmanned platforms separated from the space station by a few tens of kilometers confer significant benefits on the overall space station and mission user program. Several concepts have been identified for maintaining this separation so that regular visits between a platform and the space station can occur. Among these are station-keeping propulsion systems, utilization of drag-decay differences, and utilization of tethers between the vehicles. These concepts are still under study, and no recommendation can yet be made.

3.5 MISSION ALTERNATIVES AND BENEFITS

The purpose of this analysis was to identify the economic, performance, and social benefits accruing to science and commercial missions using the space station as an alternative to the STS for mission implementation and support. To accomplish this, we compared each mission in the Space Station Mission Model against a series of 26 potential benefits in the areas of operations, basing, servicing, assembly, and orbit transfer. For each potential benefit, we determined whether the mission was uniquely enabled by the space station, equally served by the space station or the STS, or favored by the STS alone. The analysis assumed the space station in orbit at 28.5 degrees and 250 nautical miles, with unmanned platforms at 28.5 degrees, 57 degrees, and 90° degrees; note that this is an ultimate, not an initial, space station complex.

Of the 2065 benefit assessments made, 22% were uniquely enabled by the space station, an additional 56% were favored by the space station, and only 14% were more favorable to STS or STS-launched free flying satellites as an operational mode. These results were input to the Mission Implementation Concepts (Volume IV) and the Cost and Programmatic Analysis (Volume V) volumes of this report.

4.0 Mission Implementation Concepts

4.0 MISSION IMPLEMENTATION CONCEPTS

4.1 PROGRAM OPTIONS

Eight top level program options for implementing and evolving space station capabilities were defined and subjected to analyses in the areas of user support, space station evolution, life cycle cost, and schedule compatibility. The eight varied in terms of the number of manned space stations, either one or two, operating in conjunction with appropriate payload platforms, and the inclination angle at which the stations were placed.

The initial program options were:

- 1) Option A-1, single station at 28.5° with early OTV capability;
- 2) Option A-2, single station at 28.5° with delayed OTV capability;
- 3) Option A-3, single station at 57° with early OTV;
- 4) Option A-4, single station at polar orbit with early OTV;
- 5) Option B-1, early station at 28.5° followed by station at polar orbit in mid 1990's;
- 6) Option B-2, early polar orbit station followed by 28.5° station in mid 1990's;
- 7) Option B-3, an early shuttle derived vehicle station at 28.5° followed by polar orbit station; and
- 8) Option C-1, low front end cost approach.

Cost analyses showed that the four lowest cost options were A-1, A-2, A-3 and C-1. By comparison, the four options providing the highest level of user support were options A-1, A-3, B-1, and B-3. This naturally focused attention on options A-1 and A-3 as those considered to be the most viable approaches. In depth user support and evolution analyses were continued with these two options.

The user support analyses indicated that option A-1 will support 79% of the non DOD user missions while option A-3 will support 64% of these missions. Another important factor considered was the fact that option A-1 provided more cost effective support to the largest user class, commercial communications satellites operating at GEO orbit. The results of those analyses and trade studies led to our recommendation that program option A-1 was the optimum space station approach. An important factor in that recommendation is the early availability of the proposed retrievable and space maintainable OTV.

4.2 ARCHITECTURAL OPTIONS

Two modular space station configurations were developed, one based on STS cargo bay delivery, and the other making use of the cargo bay plus the additional volume afforded by the external tank (ET)/aft cargo carrier (ACC). A third configuration is based on the shuttle derived vehicle (SDV) concept.

Our cargo bay (14' diameter) modular design is based on the premise of maximizing commonality between elements and the logic of phased growth. Figure 4.2-1 illustrates the modular design at a mature development stage (approximately 1995). Highlights of the approach include, STS compatibility, commonality, a phased growth approach, and provisions for unplanned future growth. The major disadvantages associated with this design are the number of STS flights required to reach a mature configuration, and the complexity involved with the build up and assembly.

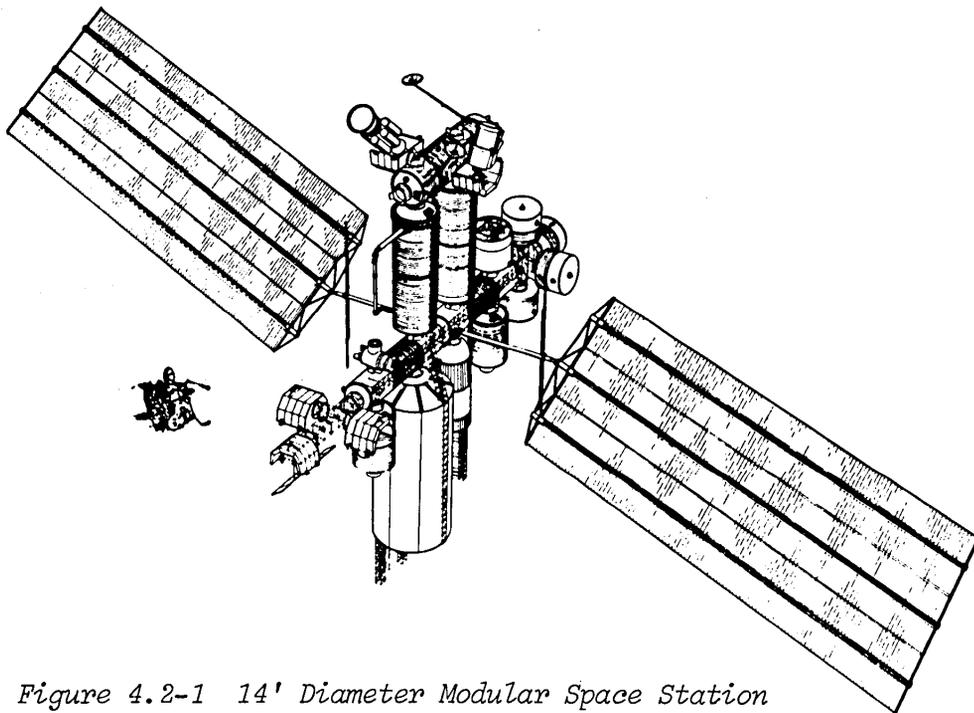


Figure 4.2-1 14' Diameter Modular Space Station

The ACC concept was developed after it became apparent that the STS transportation costs involved with building the station were appreciable, and that many of the STS payloads are volume limited. The ACC approach provides additional volume (12,000 ft³) which not only permits the transportation of extra elements on a single STS flight, but also allows for elements up to 25 feet in diameter. Figure 4.2-2 presents this configuration. With this approach at least two STS flights involved with building the station can be saved. Other advantages include the use of larger diameter building blocks while retaining the phased growth approach. This configuration also provides for future growth. ACC disadvantages include the build up complexity previously mentioned, and the cost of developing a new module size.

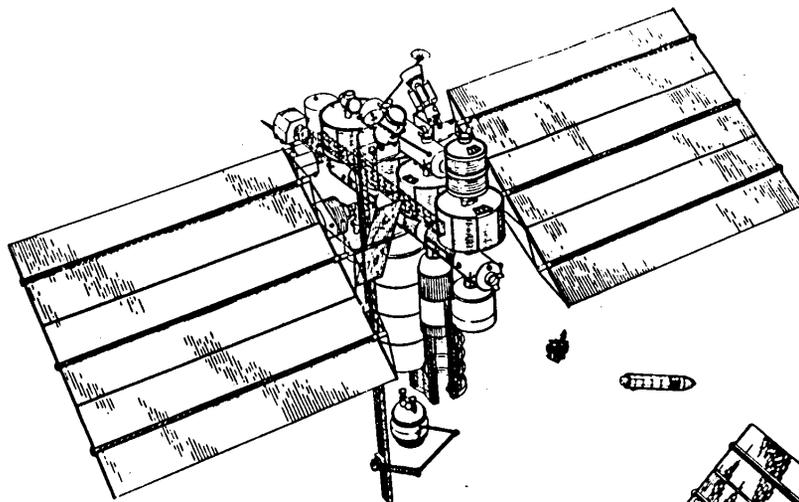


Figure 4.2-2 Modular Aft Cargo
Carrier Space Station

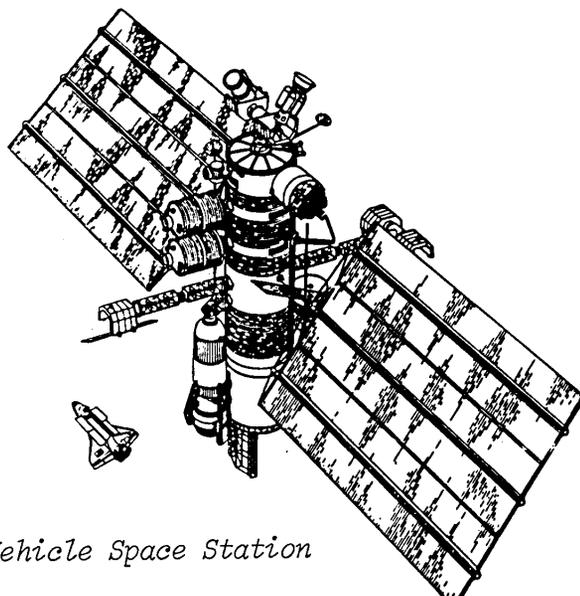


Figure 4.2-3 Shuttle-Derived Vehicle Space Station

A space station configuration based on the shuttle derived vehicle payload carrier is illustrated in Figure 4.2-3. This unique approach permits a saving of 3-5 STS flights (build up phase), and achieves a large pressurized volume (mature station requirement) in a single launch. Advantages associated with the SDV station are reduced transportation costs, significant early capability, and crew safety at the initial phase. Reduced growth capability and a commitment to the launch era technology are potential disadvantages.

4.3 MAN/SYSTEMS INTEGRATION

This area of the implementation concepts task addressed such crew related areas as: (1) environmental control and life support (ECLS), (2) EVA operations, (3) social-psychological factors, (4) medical needs, (5) SS pressure, and (6) crew resupply quantities.

The early space station will include an ECLS based on current orbiter technology, and with a limited regenerative capability. This approach in the early years increases reliability, and reduces crew time required for maintenance of the ECLS. Early regenerative capability will be limited to a CO₂ removal system and a condensate water

clean-up system to provide hygiene water. Space station evolution and associated crew growth will drive an increasing regenerative capability to avoid sizable ECLS resupply launch costs. The next major evolutionary step will be to incorporate a waste water processing system to provide additional hygiene water for shower and clothes washing. Oxygen and water loop closure will be accomplished in a third major step by the addition of a CO₂ reduction system, an O₂ generation system, and additional waste water processing equipment to include water recovery from urine.

The anticipated level of crew EVA activities required for space station integration and maintenance, and for large structures payload assembly dictate that improvements in the current Orbiter extravehicular mobility unit (EMU) be implemented. The primary need is for a higher pressure suit which can avoid totally the need for prebreathing before an EVA, which would require 3.5 hours with the EMU. Based on a Space Station operating pressure of 12-14.7 PSIA, a 6 to 8 PSIA suit would eliminate the pre-breathing requirements. (The current EMU operates at 4.3 PSIA.) Another improvement would be the elimination of water discharge from the Portable Life Support System (PLSS). In the vicinity of the space station, this discharge, currently at the rate of 1.7 lbs/hours, would present a serious contamination problem for a number of scientific payloads. Finally, the EVA suit component and operational lifetime must be extended. The current EMU is refurbished after 5 EVAs and has a useable life of 30 EVA's. A more appropriate capability would be an operational life of 6000 EVA hours and provision for on-orbit refurbishment.

Considering the social-psychological factors, crew problems may arise for the following reasons: 1) duration of orbital stay, 2) crew inter-relationships, 3) heterogeneous nature of individual crew member backgrounds and assignments, and 4) constraining physical environment of the space station. These factors can result in adverse crew stress reactions leading eventually to decreased performance of assigned tasks. We have proposed a social-psychological design approach which recommends consideration of SS volume requirements, group organization, flexible activity scheduling, cross-training in assignments, and stress management techniques.

4.4 SUBSYSTEM CONCEPTS

Emphasis was placed during our subsystem analyses on identifying and sizing subsystems which had a direct influence on space station evolution, configuration, and/or stability. In addition the projected technological state-of-the-art required to satisfy a 1991 IOC date as well as future technology development was given serious consideration in all subsystem areas. The following data summarize the significant trade study results for the various subsystems.

- 1) Electrical:
 - o Requirements range from 33.5 Kw (IOC) to 78 Kw (1995-2000) at the SS bus
 - o Solar array power required at beginning of life (BOL) is 75 Kw (IOC) and 187 Kw (1995) with an associated size of 6400 ft² (BOL) increasing to 17000 ft² (1995)

- o Silicon cells were selected over GaAs for IOC
 - o Modular design was selected using NiH₂ batteries and a 120-160 VDC bus.
- 2) Propulsion:
- o Hydrazine was selected for SS orbit maintenance and attitude control, using 8 boom-mounted 30 lbm thrusters
 - o Hydrazine storage (15000 lbs) in the logistics module would be used to resupply the TMS
 - o Cryogen storage of 70000 lbs would be provided to resupply the OTV
- 3) Thermal Control:
- o Conventional redundant, pumped heat transport loop (orbiter technology) with body-mounted heat pipe radiators was selected
 - o Augmentation would be provided by deployed heat pipe radiator panels if required
 - o Subsequent upgrading to two phase heat transport loop should be considered
- 4) Attitude Control:
- o Gravity gradient attitude control of pitch and roll axes:
 - Provides coarse stabilization,
 - Fine pointing provided by payloads
 - o Early configuration may augment the reaction control system (RCS) with control moment gyros (CMGs)
 - o Orbital rate (pitch axis) provides gyroscopic stabilization in both the yaw and roll axes
- 5) RF Communications:
- o RF links are possible at UHF, L, S, & Ku bands, at 40-60 GHz; and at laser wavelength
 - o Numerous interfaces are required with EVA, Orbiter, TMS, OTV, TDRSS, platforms, STDN and the DOD network
 - o Maximum antenna diameter would be less than 15 ft
- 6) Data Processing:
- o End-to-end system interfaces between the SS data bus and ground processor(s) data bus
 - o Uses distributed architecture
 - o Requires adaptation of commercial, ground systems/concepts to SS use
 - o Requires an estimated 50 Mbps data bus and 10⁶ FLOPS for some processors
 - o Dedicated signal processors and fiber optics interfaces for high data rates (in excess of 50 Mbps)

4.5 EVOLUTION APPROACH

An evolution approach was developed for each of the eight candidate program options to provide a basis for subsequent user support, cost and schedule analyses. Following selection of the 28.5° space station option, a more detailed evolution plan was defined, and is presented graphically in Figure 4.5-1.

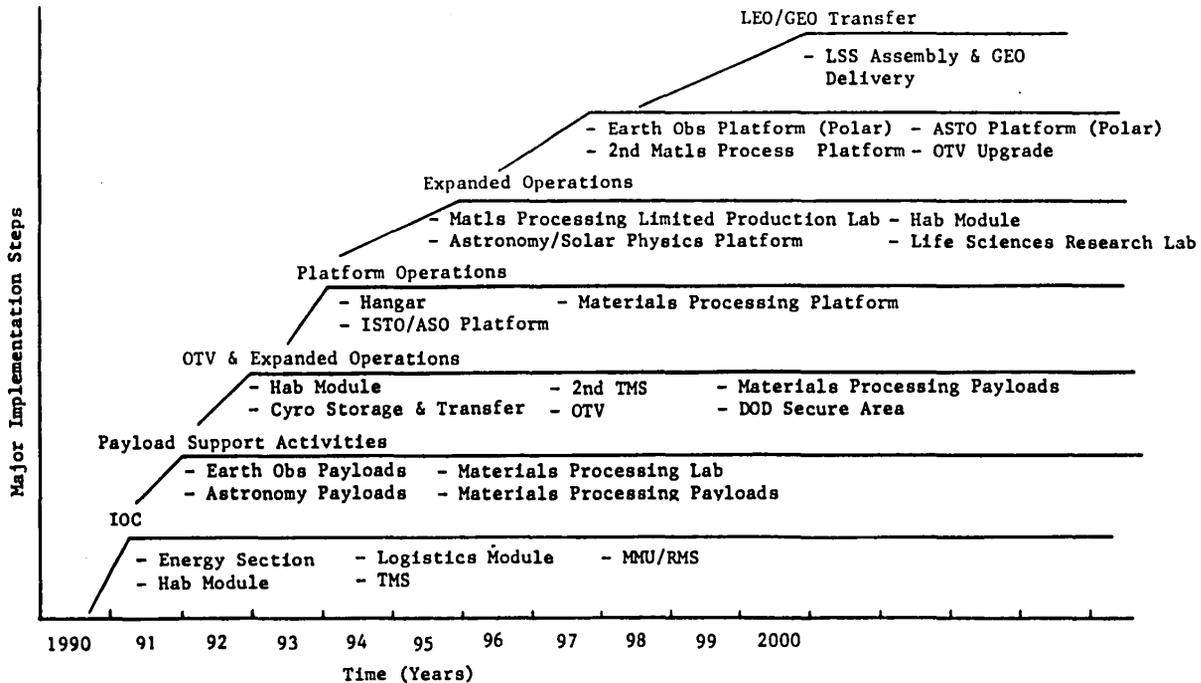


Figure 4.5-1 Recommended Evolution Plan

Significant characteristics of the evolution plan include:

- 1) Initial launch of unmanned elements about mid-1990;
- 2) Space station manned IOC occurs early in 1991;
- 3) As many as ten user payloads in five user categories will be located and operated from the station in its first year of operation;
- 4) Crew size will grow from four in 1991 to 10 or 11 by the year 2000;
- 5) OTV operations will be implemented as early as possible, presently scheduled for 1992, to capture sizable benefits gained from the delivery of commercial satellites to GEO;
- 6) Implementation of a materials processing platform (1993) and combined astronomy/solar physics platform (1994) in the vicinity of the station, and the ISTO/ASO platform (1993) at 57 degrees;
- 7) Special user support in the form of a materials processing laboratory and limited production facility, and a life sciences research laboratory supporting plant and animal research,
- 8) Large structure assembly at LEO and transfer by OTV to GEO occurring in the late 1990's;
- 9) Subsystem growth in terms of capability and technology to support space station growth and increasing user support.

5.0 Cost, Benefits and Programmatic Analysis

5.0 COST, BENEFITS AND PROGRAMMATIC ANALYSIS

5.1 PROGRAM AFFORDABILITY

Consideration of affordability is important in two major areas; the science missions that will occur in the 1990's and the development and building of the space station.

In order to develop realistic user requirements for a space station it was necessary to establish a realistic affordable mission model. We started with the Composite Mission Model presented at the mid-term review as the comprehensive set of missions that the user community desired to conduct given that no budget constraints exist. We then determined the subset of those missions that were affordable within the limits of projected NASA budget allocations.

The approach we used to determine an affordable mission model was to first review NASA budget history to determine the trend of both total budget and budget allocations to the continuing programs and new starts. We found that a ten year average NASA budget in fiscal year 1984 dollars was \$7.2 billion. We set \$7.2 billion as a target budget ceiling for our affordability analyses.

Our next step was to determine the budget allocations by major programs and extrapolate these into the future using the groundrules and assumptions presented at the end of this section. We used an early ROM estimate of a space station program cost as a strawman budget allocation and then refined it as our space station cost estimates matured. In this manner we determined the budget allocations by mission category out to the year 2000. These budget allocations are shown in Figure 5.1-1 NASA Budget Projection. We then matched the individual mission funding requirements to these budget allocations to determine an affordable mission set to the year 2000, and performed our analyses using the affordable mission set.

5.2 PROGRAM ECONOMIC BENEFITS

A permanent manned Space Station in low Earth orbit will provide cost-effective space operations as well as capabilities to support DOD missions and new space industries. Our economic benefits analysis indicates that in constant year dollars the break even point when cumulative economic benefits exceed cumulative costs occurs in the late 1990s as shown in Figure 5.2-1. Our studies have identified the following principal economic benefits:

- 1) A manned Space Station will enable the conduct of space missions and their respective operations with fewer Shuttle flights. Satellite servicing, for example, can be completed without scheduling a dedicated Shuttle flight for each servicing mission. Service equipment can be based at the Space Station instead of being transported to and from orbit for each use. In addition, automated systems for servicing of spacecraft in geosynchronous orbit will provide timely response in the event of unexpected spacecraft failures.

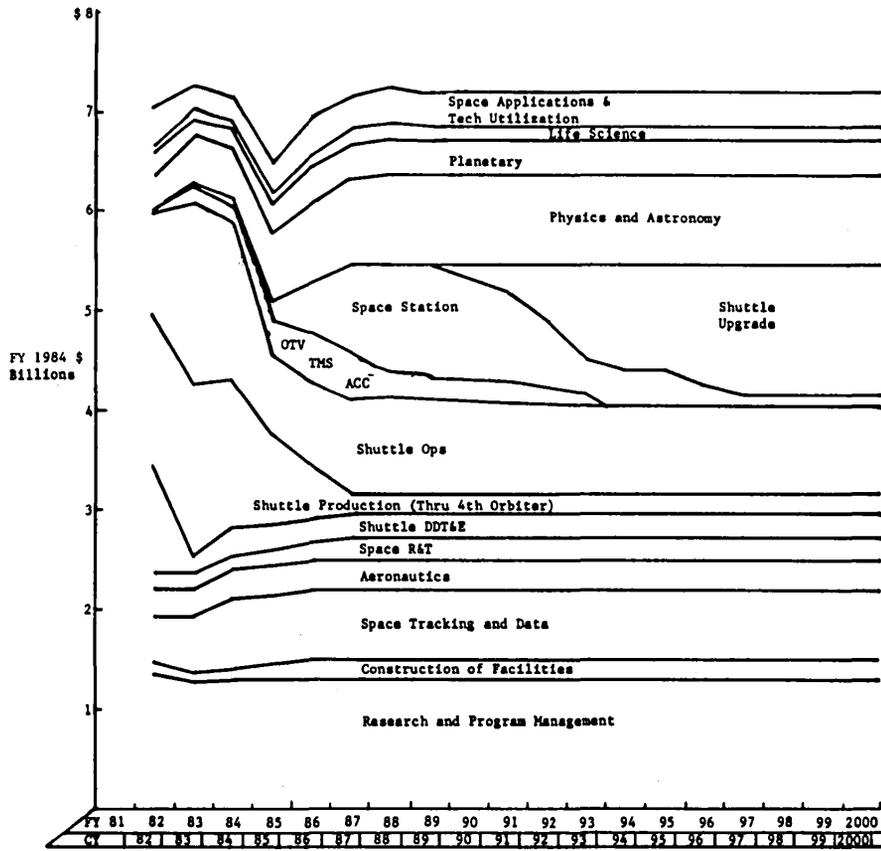


Figure 5.1-1 NASA Budget Projection

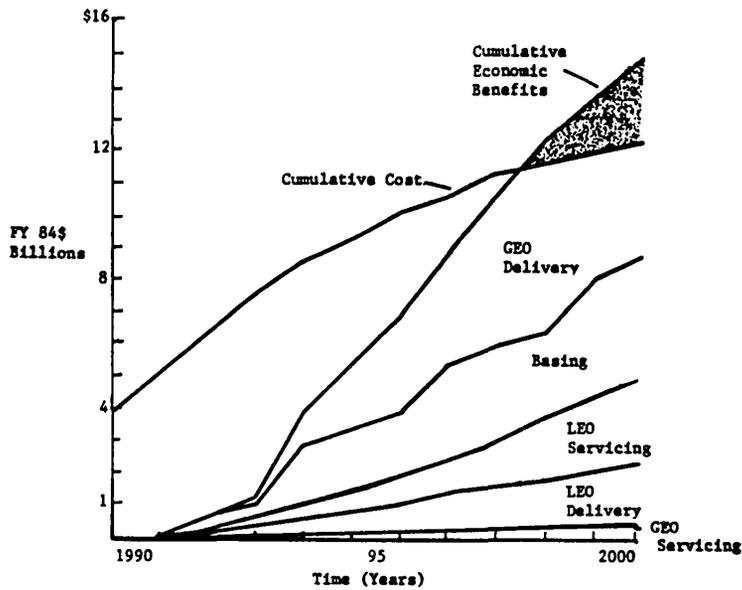


Figure 5.2-1 Cost/Benefit Breakeven Analysis-Modular Space Station 28.5°

- 2) The benefits derived from LEO and GEO delivery missions are potentially very significant. The combination of using Shuttle and Space Station will allow increased efficiency in manifesting compared to using the Shuttle alone. This improved manifesting will reduce the number of STS flights to deliver LEO and GEO payloads.
- 3) A Space Station will provide a cost effective basing mode for user payloads by providing utilities such as structure, attitude control, power and thermal control. This basing benefit results from either attachment to the manned Space Station or one of the platforms that are a part of the Space Station architecture. These services would otherwise be provided by free flyers that each user would have to design and build independently.

A major objective of the economic benefits analysis was to aid in the selection of program options and Space Station architectures. The benefit to cost ratios of each program option were compared and as a result we concluded that a single manned Space Station had a better benefit to cost ratio than multiple stations.

The next step in our selection process was to determine the most cost effective orbit inclination to locate the manned Space Station. Space Station mission analysis studies identified inclinations of 28.5°, 57° and 70° as the most promising inclinations (reference Volume III,). The optimal inclination of 28.5° was selected because it had the highest benefit/cost ratio as shown in Figure 5.2-2. Economic benefits from delivery, servicing, basing, assembly and operations were determined by comparing performance of the missions with Shuttle alone and with Space Station.

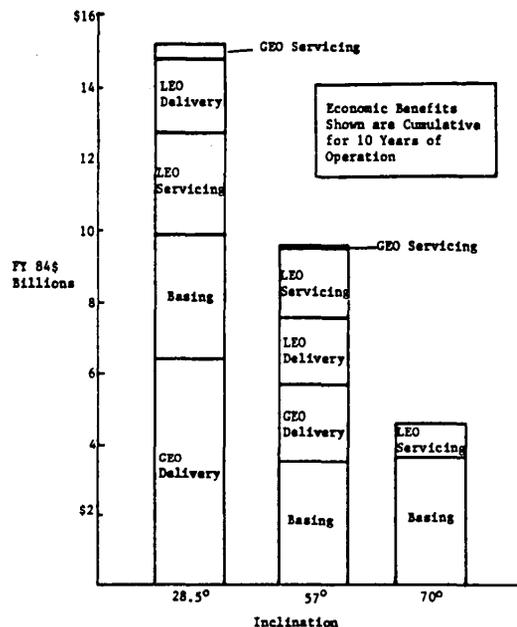


Figure 5.2-2 Economic Benefits by Inclination

5.3 PROGRAM COSTS

Our cost estimates of a modular space station from ATP through 10 years of evolution and operation are shown in Figure 5.3-1 as a function of cost by Fiscal Year.

The costs for a modular concept apply to either an STS orbiter modular concept or to an ACC modular concept. The preliminary ROM nature of the cost analysis combined with the early conceptual design data available at this time does not indicate a significant difference in the development or production cost of the modular options.

The SDV concept however does permit cost avoidance in the areas of structure design, fabrication, and assembly and system test and integration. A significant cost avoidance is realized in launch costs if an SDV vehicle is used to launch the SDV space station module.

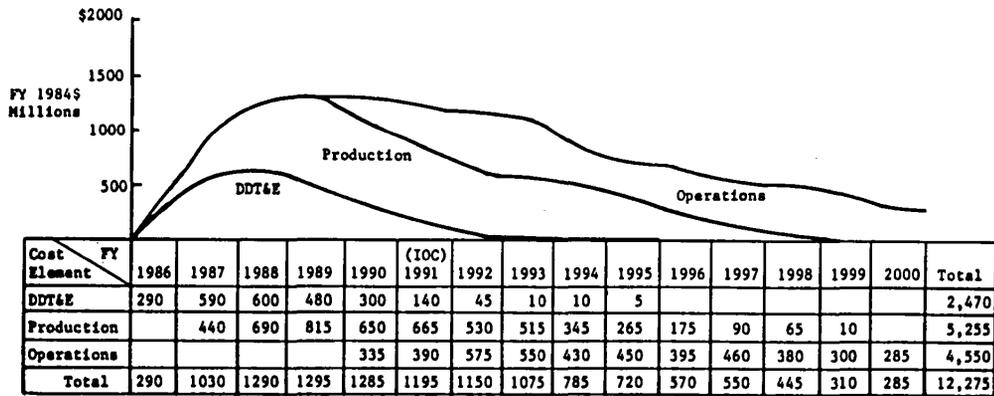


Figure 5.3-1 Cost by Fiscal Year - Modular Space Station

5.4 PROGRAM SCHEDULES

The Space Station program development schedule shown in Figure 5.4-1 summarizes the major activities and milestones required for space station development thru initial operational capability (IOC). The time spans from ATP to Preliminary Design Review (PDR) and Critical Design Review (CDR) are typical for a large scale program such as this. The span from CDR to IOC is longer than a program with separate development and flight articles due to the time required to refurbish or replace components after qualification and development tests.

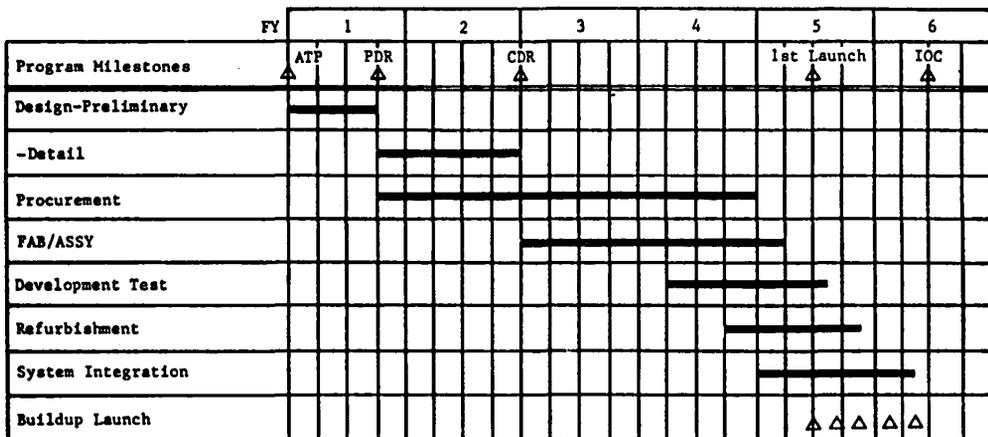


Figure 5.4-1 Space Station Program Development Schedule

6.0 Recommendations and Conclusions

6.0 RECOMMENDATIONS AND CONCLUSIONS

Our Space Station Needs, Attributes, and Architectural Options Study has resulted in several major conclusions concerning the development and evolution of a space station as described in the following paragraphs.

It is Affordable

We have found that both the acquisition of a space station and the accomplishment of NASA's science and technology objectives are affordable within the projected budget constraints. The affordability analysis was performed to determine an affordable mission set from the total complement of missions that the science community desired to accomplish. The budget constraints necessitated delaying lower priority science missions until funds would be available. The overall effect of including a space station as an orbiting NASA asset is to provide a greater return of science dollar spent by extending on-orbit data collection time.

It is Beneficial

The economic benefits analysis shows that the space station will be cost effective as a space launch base and as a platform for user missions. As a launch base, it has the potential to eliminate the need to buy two additional orbiters that would otherwise be required to handle the projected volume of affordable launches planned in the 1990s. By providing utilities and subsystems to users, the space station will eliminate the need to design and build approximately 40 independent free flying spacecraft. As an experimental laboratory it will provide low cost continuous time on orbit to shuttle sortie missions that would otherwise be limited to several days on orbit.

The space station as a repair base will enable quick response low cost repair and servicing of satellites to extend their useful life and improve their return on science and/or investment dollars.

It Pays for Itself

The cost/benefit breakeven analysis indicates that the space station will pay for its acquisition cost in the value it adds to the Space Transportation System. The potential economic advantage as a space transportation mode indicates that it can avoid as much as \$11.6 billion in FY 1984 dollars during a ten year period of operations. The potential avoidance of each user mission providing their own independent spacecraft bus shows a \$3.6 billion advantage to the space station and its associated platforms.

A Reusable OTV Is Needed

Our benefits analysis indicate that a significant advantage of space station is to serve as a launch base for high energy missions. A reusable, space maintained OTV is a necessary element of this scenario

to make it cost effective compared to expendable vehicles. The major advantage to a space reusable OTV is that it would not be launched to low earth orbit on each shuttle thus saving space for payloads and reducing total transportation cost to the user.

A Reusable TMS Is Needed

Just as the reusable OTV benefits the transportation of missions to high energy orbits, the TMS vehicle enables delivery and servicing of payloads in orbits near the space station at a significantly reduced cost over a TMS that accompanies the shuttle. Again, the major advantage is the launch weight and volume saved if a TMS remains based in orbit at a space station.

Recommendations

We recommend that limited near term NASA funds should be allocated not only to space station technology studies but also to studies to develop an on orbit based and maintained, reusable OTV and TMS vehicles. Our study results show these two elements of a space transportation system are necessary to the cost effective operation of the space station.

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