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REPORT NO. GDC-ASP-83-001
CONTRACT NASW-3682

A STUDY OF SPACE STATION NEEDS, ATTRIBUTES & ARCHITECTURAL OPTIONS

FINAL REPORT

VOLUME I • EXECUTIVE SUMMARY

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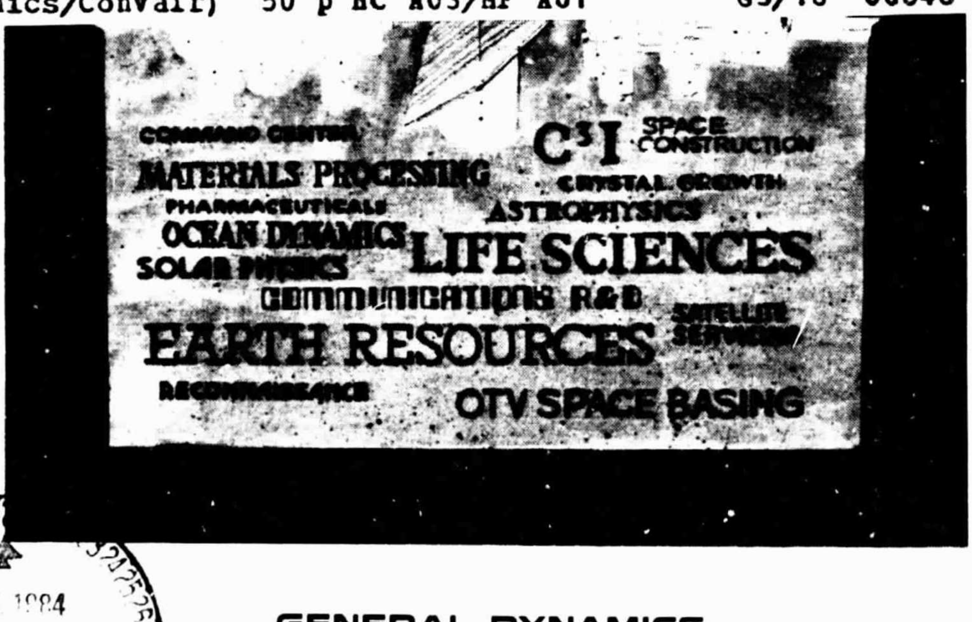

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GENERAL DYNAMICS
Convair Division

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A STUDY OF SPACE STATION NEEDS, ATTRIBUTES & ARCHITECTURAL OPTIONS

FINAL REPORT
VOLUME I • EXECUTIVE SUMMARY

22 April 1983

Submitted to
National Aeronautics and Space Administration
Washington, D.C. 20546

Prepared by
GENERAL DYNAMICS CONVAIR DIVISION
P.O. Box 85357
San Diego, California 92138

PREFACE

The U.S. progress toward a complete space transportation system (STS) for the exploration and exploitation of space achieved an important milestone when the Space Shuttle became operational. Other elements of the system, such as the Payload Assist Modules, Inertial Upper Stage, Spacelab, Extra vehicular Maneuvering System, and the Shuttle-Centaur Upper Stage are either in use or under development. However, there are other important STS elements that still require definition and development -- the major new element being a manned Space Station in low earth orbit. When available, a manned Space Station, plus the elements listed above, will provide the capability for a permanent manned presence in space.

The availability of a manned Space Station will:

a. Provide a versatile space system for an active space science program.

b. Stimulate development of advanced technologies.

c. Provide continuity to the civilian space program.

d. Stimulate commercial activities in space.

e. Enhance national security.

Through these, U.S. leadership in space will be maintained and our image abroad will be enhanced. The Space Station will provide:

a. A permanent manned presence.

b. Improved upper stage operations.

c. Maintenance of space systems through on-orbit checkout and repair.

d. Assembly and construction of large space elements.

It will also enhance Space Shuttle utilization as a transportation vehicle by releasing it from sortie missions that currently substitute for Space Station missions.

The Space Station will be a facility having the following general characteristics:

a. Support manned and unmanned elements.

b. User friendly.

c. Evolutionary in nature for size, capability, and technology.

d. High level of autonomous operations.

e. Shuttle compatible.

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The primary purpose of this study was to further identify, collect, and analyze the science, applications, commercial, technology, U.S. national security, and space operations missions that require or that will be materially benefited by the availability of a permanent manned Space Station and to identify and characterize the Space Station attributes and capabilities that will be necessary to satisfy those mission requirements.

NASA intends to integrate these data, recommendations, and insights developed under this contracted effort with those developed from in-house activities and other sources and then synthesize from this information a set of mission objectives and corresponding Space Station requirements that will be used in future phases of study and Space Station definition.

The study objectives as defined in the Request for Proposal (RFP) are:

a. Identify, collect, and analyze missions that require, or will materially benefit from, the availability of a Space Station:

   - Science
   - Applications
   - Commercial
   - Technology
   - Space operations
   - U.S. national security

b. Identify and characterize the Space Station attributes and capabilities that are necessary to meet these requirements.

c. Recommend mission implementation approaches and architectural options.

d. Recommend time phasing of implementation concepts.

e. Define the rough order of magnitude ogrammatic/cost implications.

Book 1 will address the first objective and provide the realistic, time-phased set of mission requirements upon which the balance of the study was based. Accomplishments of objectives b, c, and d are documented in Book 2, and objective e is addressed in Book 3. Book 4 contains a definition and an analysis of national security missions (classified).

FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA Headquarters under Contract Number NASW-3682.

The study was conducted from 20 August 1982 through 22 April 1983. A mid-term briefing was presented at NASA Headquarters on 17 November 1982; a final briefing was presented on 5 April 1983, also at NASA Headquarters.

The study was conducted within the Space Programs Organization at General Dynamics Convair Division, headed by W. F. Rector, III, Space Vice President and Program Director. D. E. Charhut, Director of Advanced Space Programs, was assigned specific responsibility for the study. The NASA COR is Brian Pritchard of the Space Station Task Force headed by John Hodge.

General Dynamics Convair Division personnel who significantly contributed to the study include

Study Manager	Otto Steinbronn
Mission Requirements	Warren Hardy - Manager
	Jim Peterson
	Charlie Hyde
Mission Implementation	John Bodle - Manager
	Earl Davis
	Tom Kessler
	Norm Gray
Cost and Programmatics	Bob Bradley - Manager
	Michael Simon
	Sam Wagner
Nation Security Missions	Al Phillips
	Clint James

Subcontract support was obtained from Space Communications Co. (SPACECOM) in the area of communication spacecraft and related technologies, and from Advanced Technology, Inc. in the area of life science and life support systems.

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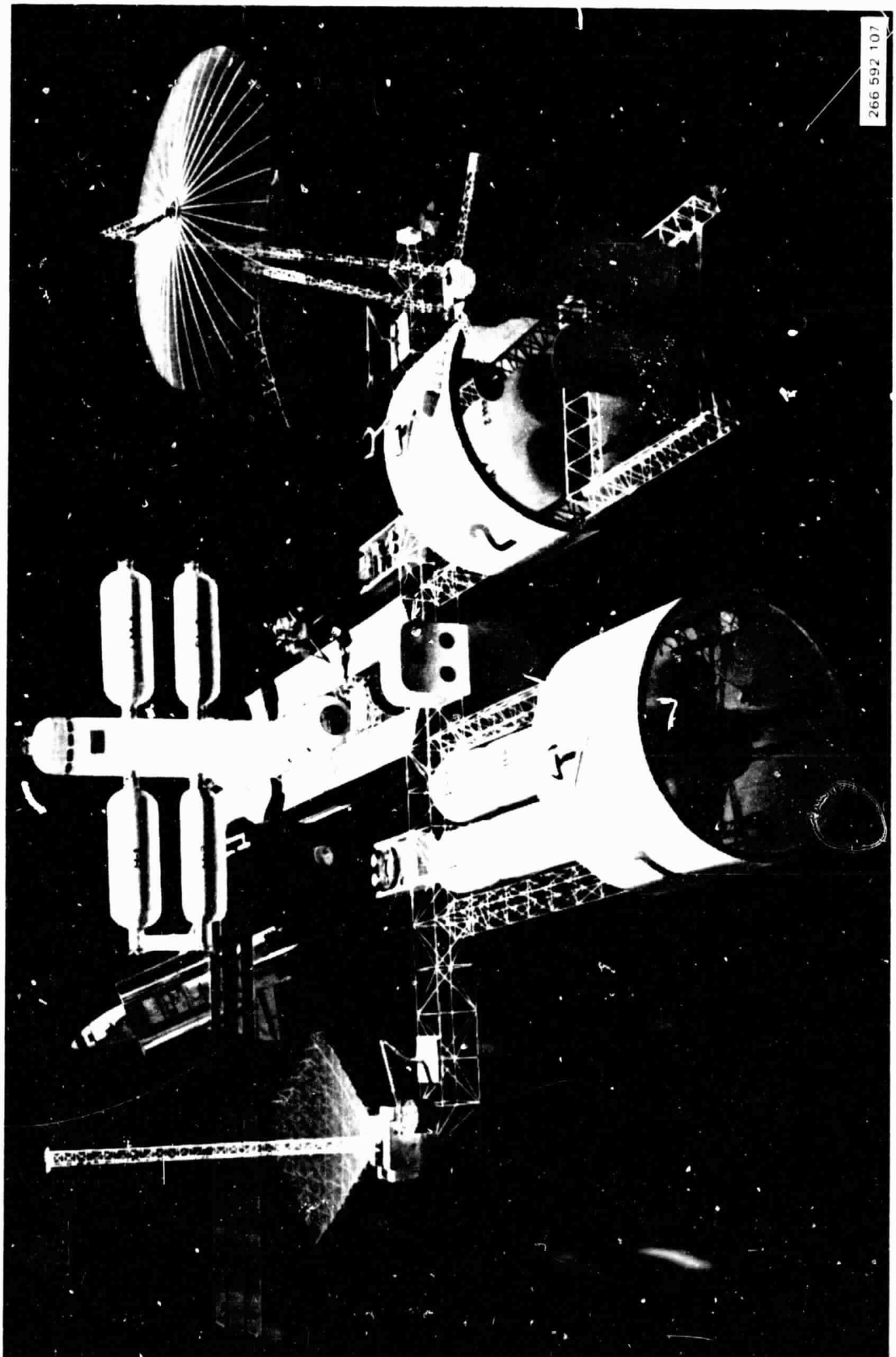

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SECTION 1
INTRODUCTION AND SUMMARY

The primary purpose of this study was to identify, collect, and analyse the science, applications, commercial, technology, National Security, and space operations missions that require or will materially benefit from the availability of a permanent manned presence in space, and from these findings, to identify and characterize the Space Station attributes and capabilities necessary to satisfy these mission requirements. The General Dynamics Convair Division (GDC) study team has carried out this study in compliance with this primary purpose, and in fulfillment of the study objectives defined in RFP/W 10-286471 HWC-2. The results of our analyses are contained in Volume II of this final report:

- Book 1 - Mission Requirements
- Book 2 - Mission Implementation Options
- Book 3 - Economic Benefits, Costs, and Programmatics
- Book 4 - National Security Missions and Analysis (Classified)

This Executive Summary presents the major study results and conclusions.

1.1 ORGANIZATION

The GDC team, Figure 1-1, was comprised of experienced personnel from our Advanced Space Systems department, supplemented in the areas shown below to provide both specific technical expertise, and broad space scientific overview:

a. Space Communications Company (SPACECOM) provided input and analyses of commercial communication spacecraft and related technology, in particular, definition of how a Space Station would enhance this thriving business.
b. Advanced Technologies, Inc. was responsible for all activities related to Life Sciences experimentation, development, and processes, and also provided major support in areas of life support systems.
c. Science Applications, Inc. provided support in the area of national security and in the preparation of our Space Station Prospectus.
d. Spar Aerospace Limited provided significant advice in the area of remote manipulator systems and their potential application to Space Station systems.

The Space Station Advisory Board was established to review the progress of our work, and the conclusions reached prior to each NASA review. This proved to be of significant benefit to our study.

1.2 APPROACH

We accomplished the study in the seven major steps shown in Figure 1-2.

In conducting these tasks, major emphasis was placed on establishing a realistic set of missions and requirements through extensive user contacts and involvement, and careful analyses of their responses. Emphasis was also placed on developing architectural concepts representing necessary and achievable facilities, and quantifying economic benefits that are realizable. Throughout the study, we attempted to focus efforts on those areas that appeared to derive the highest payoff from the availability of a manned Space Station.

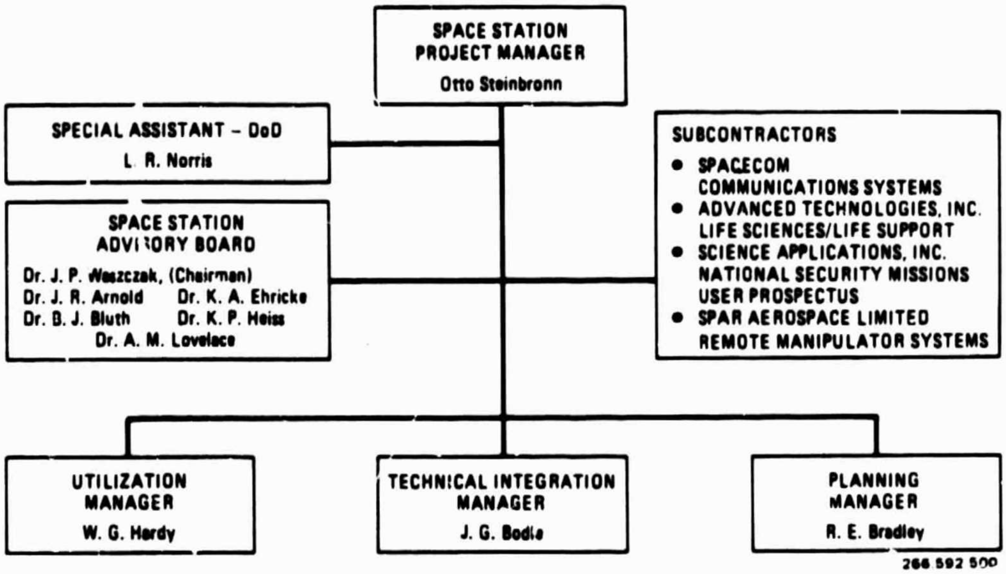

Figure 1-1. General Dynamics Space Station Study Team

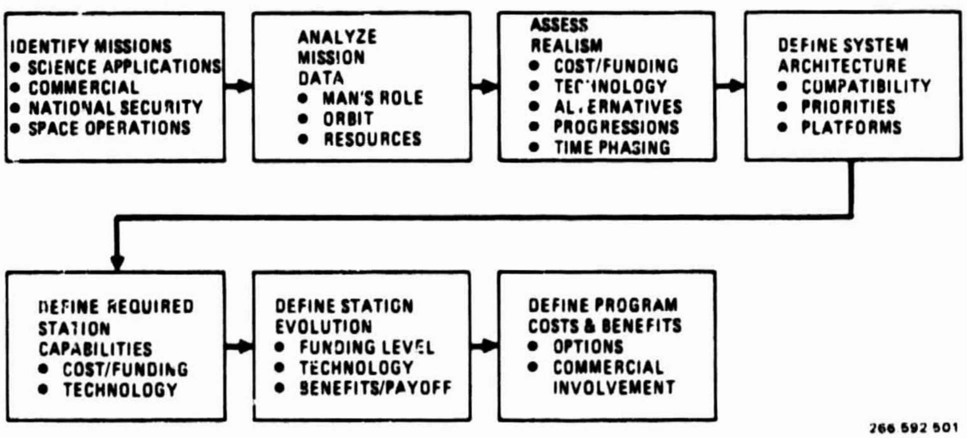

Figure 1-2. Study Approach

1.3 SUMMARY OF RESULTS

The overall products of this study, as summarized below, are a set of realistic missions and their time-phased requirements, that are sufficiently well defined and supported to provide a sound basis for developing Space Station architectural options; an analysis of these options and a recommended architecture and evolution; and quantified economic benefits, ROM costs, and programmatic options.

1.3.1 MISSION REQUIREMENTS ANALYSIS. As a result of our direct contacts with prospective users of the Space Station, a total of 149 missions were identified and defined in sufficient detail to provide requirements for architectural and cost/benefit studies. These missions covered the spectrum of user areas discussed earlier, and comprise both single and multiple flight missions, e.g., one communication satellite mission may have as many as 79 satellites emplaced over the decade. The missions are defined as attached to a Space Station, or operating as free-flyers separate from the station, with the free-flying satellites operating in low Earth orbit, high Earth orbit, and geosynchronous orbit (LEO, HEO, and GEO) locations, or inserted into escape trajectory for the planetary exploration missions.

The missions defined as attached to the station require man's presence for direct involvement in R&D activities, or his intervention on a scheduled, or unscheduled basis. These missions are predominantly satisfied by a low inclination 28-1/2-degree orbit, within a 400 to 500 km altitude LEO. Those missions desiring a higher 57-degree inclination, are few in number, and all can be satisfied by either the 28.5-degree or polar orbits, or are operable in a free-flyer mode, and, therefore, do not justify a station at the 57-degree inclination. Similarly, only seven missions require a polar orbit, with start dates after mid-1990s, which suggests a station in polar orbit be considered as growth capability required at the end of the decade or later.

It is concluded from this that the missions defined are best satisfied by and greatly support the need for a manned Space Station placed in a 28.5-degree x 400 km LEO.

A Space Station placed in this orbit can provide the necessary service to accessable free-flyers, and can support staging operations for high energy missions.

Those missions operating as free-flyers in unaccessable orbits, or injected into high-energy orbits from nonstation orbits, can continue to be delivered and serviced by the shuttle.

1.3.2 MISSION IMPLEMENTATION CONCEPTS. From analyses of the baseline mission set and related requirements, and analyses of various architectural options of manned and unmanned facilities at the three LEO inclinations of value to users, we have concluded that the mission needs are best satisfied by the Space Station architecture depicted in Figure 1-3, and as follows:

a. Manned Space Station located at 28.5-degree inclination LEO, with capability to support the following operations:
   1. Man-conducted research, development, and production.
   2. Servicing of co-orbital free-flying satellites and platforms.
   3. Staging and servicing base for a space-based Orbital Transfer Vehicle (OTV) and it's assigned payloads/satellites.
   4. Assembly, construction, and test for large structures and payloads.
b. Unmanned platforms in LEO at 57-degree and polar orbits.
c. Growth potential for a manned Space Station in polar orbit after the end of the decade.

The overall evolution of this space system is recommended to start with the required initial research, development and production capabilities for the manned station in 1990, with growth to meet mission needs throughout the decade. A satellite servicing capability is added in 1992. In the mid-1990s, when a space-based OTV is available, the capability for staging is added. Platforms would be placed in the 1992 to 1995 timeframe as dictated by user needs.

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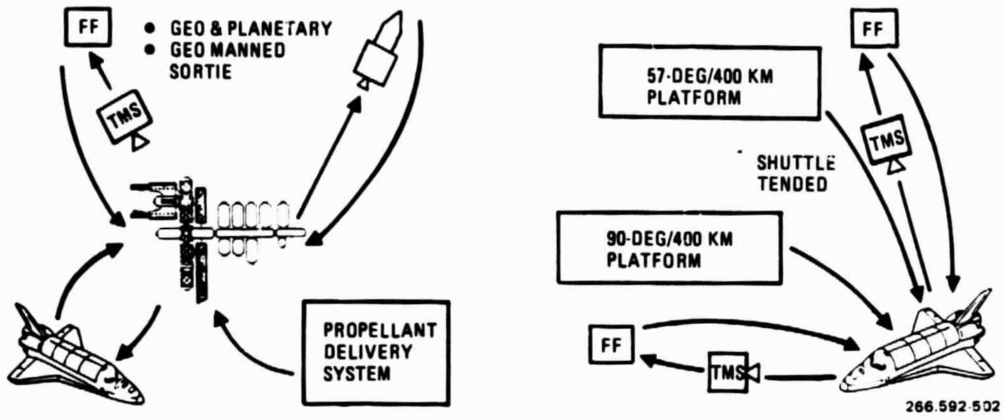

Figure 1-3. Recommended Space Station Architecture At Mid-1990s

1.3.3 COST AND PROGRAMMMATIC ANALYSIS. The primary result of the economic analysis is the definition of the very significant economic benefit provided by the inclusion of a space-based OTV in the overall Space Station system. Based on this capability being available by 1994, and with the GEO/HEO traffic levels projected from our studies, this economic benefit is expected to reach over $1 billion annually by the mid-1990s.

Other economic benefits appear possible from the free-flyer servicing operations, and the man-conducted R&D activities, projected at about $285 and $240 million per year, respectively, by the mid-1990s.

The cost of the Space Station following the above evolutionary build-up of capability appears to be within the projected budget available to NASA and is estimated at approximately $5.5 billion for the IOC capability, and $6.3 billion for the full research, development, and production facility. The delta cost for the OTV base is estimated at $3.2 billion.

Programmatic options were defined that focus on commercial/industrial funding and operation of Space Station elements, a concept that we conclude is quite feasible.

1.4 MAJOR STUDY CONCLUSIONS

As a result of the analyses conducted during the course of this study, and based on our contacts with the user community, there are several conclusions we have reached regarding the overall Space Station system:

a. Missions and requirements exist that both support and provide a sound basis for Space Station definition.
b. The initial station should be a joint R&D and operations facility located in a 28-1/2-degree inclination LEO.
c. The mission set does not support a station at a 57-degree inclination.
d. Although earlier requirements do exist, delay of a polar orbit station past the end of the next decade is recommended.
e. Operations and science/application missions can co-exist on the same station.
f. A space-based OTV launch capability is the major quantifiable economic benefit of a space station ($1 billion per year) and should be developed as rapidly as technology allows.

g. Cost of the initial recommended Space Station research, development, and production facility is approximately $5.5 billion at IOC, and $6.3 billion at full capability (1984 $).
h. The space-based OTV function incremental cost is approximately $3.2 billion for the station element, plus $2.7 billion for the space-based OTV and ET tanker for delivery of propellant to the station.
i. Build-up, supply and operations with the station can be accomplished within the shuttle annual flight capabilities, while still performing the required deliveries of nonstation missions.
j. Commercial interest in station capabilities exist and missions have been defined for these activities; however, long-term involvement with these users, and special incentives, appear to be required to fully develop this market.
k. Realistic opportunities exist for private investment in Space Station development - a potential investment scheme is outlined in our Space Station Prospectus included as Appendix I of Volume II Book 3.

1.5 RECOMMENDATIONS

The following recommendations are focused towards near term activities that we believe are necessary to further advance and develop a Space Station capability:

a. Expand user involvement, particularly in commercial areas, to stimulate and encourage and as necessary, educate, users to the benefits and uses of space -- both to encourage increased use of station capability, and to better define and establish the realism of projected commercial uses, particularly in the out years.
b. Pursue development of critical technologies, and develop plans to establish the technology level that is necessary and will be available for design into the initial station capability.
c. Conduct preliminary timeline analyses of station activities to better understand the extent of resource sharing possible, and the extent of operational conflicts that may exist, so that station requirements and characteristics may be better predicted.
d. Recognizing the potentially large economic benefits, continue to investigate means to advance development of the Space Station OTV base capability.

SECTION 2
MISSION REQUIREMENTS ANALYSIS

The overall objective of the mission requirements analysis was to produce a realistic time-phased set of missions and requirements that could be used as a basis for the Space Station architectural option studies and related benefits, cost, and programmatic evaluations. The GDC approach was to solicit Space Station user information, augment as necessary, and integrate into a cohesive whole (Figure 2-1). Two dominant mission characteristics were used as discriminators to evaluate applicability of each mission for Space Station attached accommodation: man's role in accomplishing mission objectives, and the required or acceptable orbit parameters. As the data was developed, particular attention was paid to defining the Space Station functions in support of free-flying satellites and platforms.

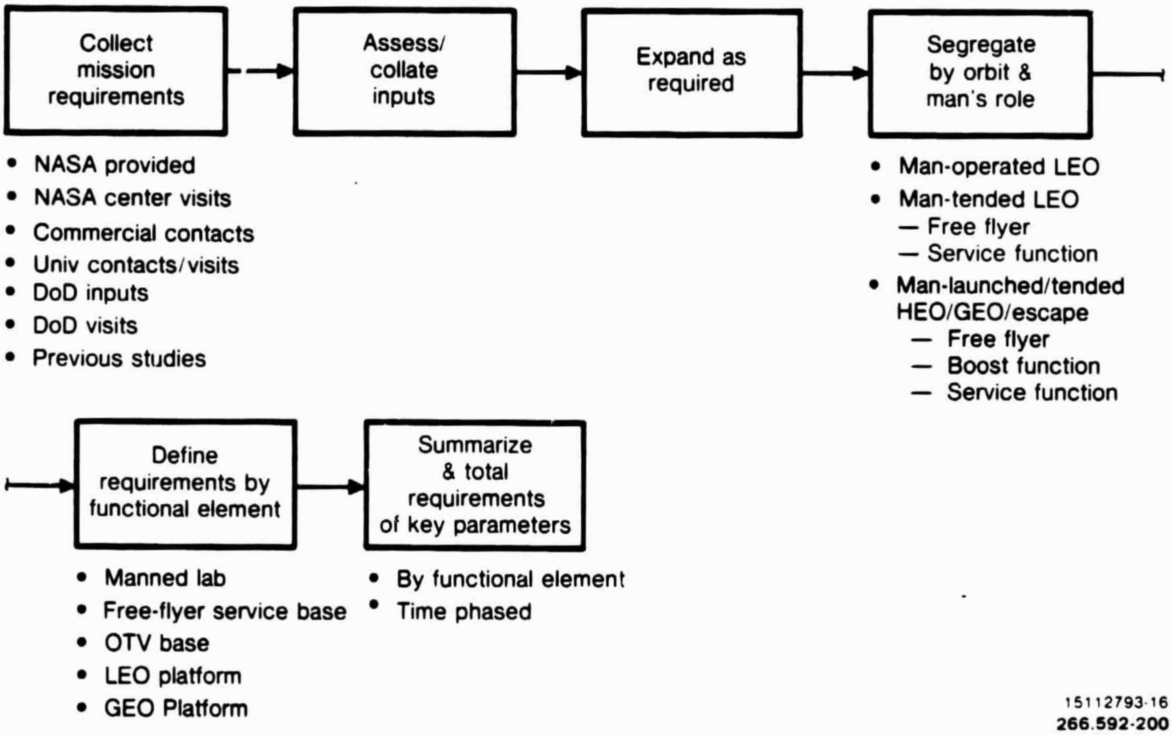

Figure 2-1. Mission Requirements Approach

2.1 DATA SOURCES, SURVEYS, AND RESPONSES

GDC placed particular emphasis on direct contacts with potential users to obtain valid definition of planned or proposed Space Station missions. Scientific and commercial mission requirements were compiled from a combination of NASA reports, personal visits to user facilities, telephone and personal industry contacts with questionnaire follow-up, and information derived by subcontractors. Data for national security missions were obtained from a traffic model, and reports supplied by DOD and by personal visits to various commands. Foreign mission data were obtained by personal visits to European firms augmented by reports from MBB/ERNO and Dornier Systems. The mission requirements were validated by reference to corollary reports and personal interviews. A total of 149 missions were defined and documented (Table 2-1).

Table 2-1. Mission Summary

Science and Applications		Commercial	
• Astrophysics	18	• Earth and Ocean Observations	4
• Earth Exploration	16	• Communications	11
• Planetary Exploration	12	• Materials Processing	15
• Environmental Observations	23	• Industrial Services	6
• Life Sciences	7		36
• Materials Processing	2		
	78	Technology Development	33
		Operations	2

2.2 SUMMARY OF MISSIONS

Two basic categories of missions were established: man-operated, which are accommodated directly on the Space Station, i.e., attached, and free-flyers, which are separate entities. Man's role in the mission was used as the basic evaluation criterion. Therefore, in those cases where man's involvement was vital to the mission or would enhance the mission by a significant contribution on a continuing basis, the missions were classified as attached. The 149 missions were divided into the three NASA classifications (Figure 2-2) to facilitate accommodations analyses in accordance with the peculiar requirements of each class. In some cases, e.g., commercial communication satellites, a single mission represents as many as 114 separate satellites requiring in-orbit placement. The majority of the missions are suitable for space station operation, of which 18% could be accommodated on a free-flying, man-tended platform. Of the free-flyers that were defined as separate satellites, 54% are compatible with a platform. The status of the missions range from operational or approved (4) to candidates (119). The value of the Space Station to the mission was rated on a scale of 1-10 (benefit to vital); 16 are in the lowest one-third and 78 in the highest one-third. In addition to defining the accommodation requirements within the Space Station, supporting functions of: 1) assembly and construction; 2) checkout and servicing; and, 3) transportation were derived for free-flyers.

2.2.1 <u>SCIENCE AND APPLICATIONS MISSIONS</u>. The Science and Applications missions are primarily those that have been conceived and developed through the activities sponsored or carried out by NASA's Office of Space Science and Applications (OSSA). These comprise about half of the missions identified and defined in our data base. These 78 missions would interface with the Space Station system during the 1990-2000 timeframe, either as attached payloads or as payloads that could be launched from or be serviced by the station (reference Table 2-2). Operational or planned missions that will be completed before the Space Station era or that have unique orbit requirements that dictate launch by shuttle or expendable launch vehicles have not been included in the data base. Many possible payloads were excluded because the proposed operational timeframe was before the station would be ready for use. If, as these payloads become fact, their operational timing moves into the station operational era, they would benefit from Space Station support also.

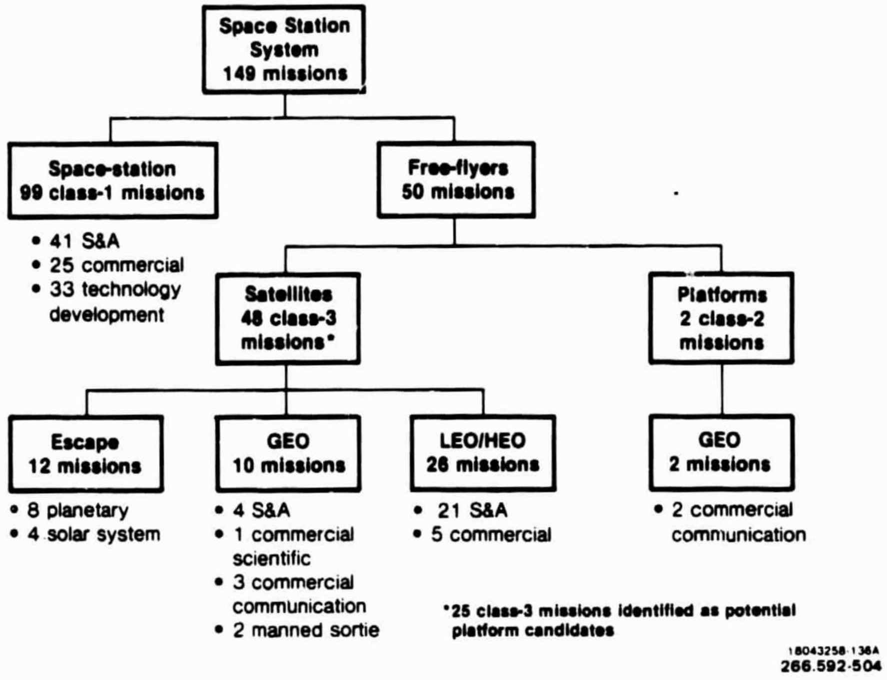

Figure 2-2. Mission Classifications

Table 2-2. Science and Applications Missions

	Station Attached	Free Flyers LEO/HEO	GEO	Escape	Total
Astrophysics	8	9	1		18
Earth and Planet Exploration	11	5		12	28
Environmental Observations	13	7	3		23
Life Sciences	7				7
Materials Processing	2				2
	41	21	4	12	78

Note: Mission orbit requirements range from LEO (28.5 degrees) to Polar for all accommodation modes; free-flyers range to GEO Orbits.

The Life Sciences and Material Processing missions establish the driving requirements for station crew size, power, and internal volume. The mission suitable for a 28.5-degree station with the heaviest externally mounted payload element is for Astrophysics. Earth Exploration and Environmental Observations have the largest external equipments. Requirements for a Space Station in polar orbit later in the decade are defined for Earth Exploration and Environmental Observations. Free-flyers at inclinations from 28.5-degrees (principally Astrophysics) through 100 degrees require servicing throughout the decade. A number of free-flyers, including 12 on escape trajectories, benefit from the station as a transportation node.

2.2.2 COMMERCIAL MISSIONS. Commercial missions could be some of the most important because of their unique characteristic of potential for cost sharing benefits and revenue sources to NASA through private sector involvement in the Space Station program. A total of 36 representative payload elements were defined (Table 2-3). Approximately one-half were provided by commercial firms in response to a GDC-developed user brochure and fact sheet; the balance were developed by GDC, with SPACECOM as a subcontractor.

Table 2-3. Commercial Missions

	Station Attached	Free Flyers LEO/HEO	Free Flyers GEO	Total
Earth and Ocean Observation		3	1	4
Communications	6		5	11
Materials Processing	14	1		15
Industrial Services	5	1		6
	25	5	6	36

Not all firms who responded provided specifics on potential commercial missions. The defined missions cover a range from research-type such as chemical reaction effects in microgravity, to MPS production, and monitoring the earth's atmosphere for pollution. Industry responses to inquiries on economic and planning factors are particularly important and unique to commercial missions. A broad interest was expressed in the potential for entering into JEAs with NASA. The most significant investment barriers are investment level, ROI Horizon, and a perception of uncertainty in Government commitment to a Space Station. Important incentives for industry participation include: nonmonetary cost shuttle flights, Government-sponsored R&D, reduced STS costs, and tax provisions.

The communication satellite traffic to GEO represents the principal transportation traffic for the Space Station and a space-based, reusable OTV. A total of 243 satellites and large platforms will be emplaced in the 1900-2000 period.

The following conclusions were drawn relative to commercial use of the space station:

a. A commercial satellite placement market exists.
b. A Space Station/OTV system will serve the market.
c. MPS and Earth Observation markets exist but need further development.
d. Special incentives may be required to induce significant commercial space investment.

2.2.3 TECHNOLOGY DEVELOPMENT MISSIONS. The technology missions cover a broad range of disciplines. Some missions call for very long exposure to the space environment, covering most of the decade. These are generally the investigations relating to long term effects on properties and performance, as exemplified by the experiments in materials and coatings, special sensors, and space component lifetimes. Other experiments, such as those in advanced energy conversion and controls technology, have span times on the order of one year.

All of the missions identified in this discipline prefer station-attached accommodations and many have large externally mounted elements. The station provides the necessary characteristics of low gravity, availability of power, man/experiment interaction, data processing, and long-term presence in the space environment to facilitate the technology development missions. These missions benefit all other categories of users and enhance capabilities for advanced missions and space systems. A representative set of 33 technology development missions were defined (Table 2-4). Most of these were based upon NASA provided themes; the balance were derived by GDC. Several missions were defined as part of the OTV development program.

Table 2-4. Technology Development Missions

Materials and Structures	7
Energy Conversion	7
Computer Science and Electronics	4
Propulsion	2
Controls and Human Factors	2
Space Station Systems/Operations	10
Fluid and Thermal Physics	1
	33

2.2.4 SPACE OPERATIONS MISSIONS. Space operations missions are of two distinct categories. Those that are conducted in support of, or are an integral part of an overall mission; and those that are separate specific missions having operational characteristics. Examples of the first category are: assembly and construction, servicing, and high energy staging of free-flyers. An example of the second category is a manned GEO sortie mission.

Requirements for operational support of the Science, Applications, Commercial, and Technology missions were derived and documented during the definition process. An analysis was made from these requirements to determine the OTV and TMS operations activities. Separate mission definitions in payload element terms were not prepared for each of the OTV and TMS operational actions because that did not advance the study objective of deriving a station architecture, and to do so would tend to confuse the data set. There are over 400 such operations.

Two specific missions of the second category have been identified by GDC as candidate space operations missions. Both missions involve development activity related to placing and supporting a manned presence at geosynchronous orbit altitude. The two missions are intimately linked together and can be described in terms of operations concepts. The first mission is a manned geosynchronous sortie capsule delivered by an OTV to GEO where manned operations are conducted for a short time, e.g., 1-2 days. Annual trips are scheduled. Approximately 3 years later, a manned support module is placed in GEO and visited by the sortie capsule. This provides the capability for extended, e.g., 1-2 week, manned operations in GEO.

2.2.5 FOREIGN MISSIONS. ESA has several Space Station studies in process whose objectives include to "identify European payload candidates that can be beneficially supported by a Space Station". The areas of interest include:

a. Material Science and Processing
b. Life Science

c. Space Science
d. Earth Observation
e. Space Technology and New Space Utilization Fields
f. Operational Support

We have received reports from MBB/ERNO and Dornier Systems that provide insight into potential European Space Station missions. A comparison of the missions and their characteristics such as size, mass, pointing requirements, power levels, and data rates disclose that most are similar to those derived for U.S. missions. Some missions have similar objectives but are sized differently. Reviewing this data provided two principal pieces of information. First, insight into the views and plans of scientists outside the U.S. Second, substantiation of the premise that a worldwide cooperative effort will have positive results.

2.2.6 NATIONAL SECURITY MISSIONS. The details of the DOD portion of the study are reported in Volume 11, Book 4 (Classified). In this volume we discuss how the National Security missions interface with the science and commercial Space Station. DOD operational missions generally require high inclination or GEO, and have stringent security and survivability requirements. Their requirements lead to dedicated, peculiar facilities as opposed to joint science/commercial/DOD facilities.

DOD RDT&E missions are derived from operational missions and directly support their evolution. When considered as two sets -- R&D and T&E, logical differences are evident. Verification T&E for operational missions either require or benefit from performance in the operational environment, in this case, orbit. On the other hand, R&D missions can usually be performed under different though comparable conditions and are candidates for a low inclination LEO such as that determined for science, technology, and commercial missions. Furthermore, the survivability requirements become progressively lower, progressing from operational to R&D. Security is less demanding but still of concern. The conclusions, therefore, are that R&D activities are suitable for a LEO low inclination orbit, even in a joint station. Some T&E missions may also be suitable, but many require operational mission orbits.

The high payoff technology areas for DOD missions were compared to the NASA and commercial missions, and a high level of correlation was observed. This analysis supported the conclusion that DOD R&D can be accomplished in the man-operated research and development facility. In fact, many of the objectives may be achieved jointly, and the level of station resources required for National Security missions are provided in the station architecture.

In addition to the R&D missions, there are a number of satellite placement missions each year which could use the station and OTV as a transportation node.

2.3 SELECTED TIME-PHASED MISSION SET

The work done throughout the study to identify users and their requirements, produced a mission set with validated requirements. This "user's set" provides a menu of representative missions suitable as a basis for architectural option studies. The missions are more concentrated in the early timeframe (Figure 2-3) because of the tendency to concentrate more on near term than long term planning. Although this did not create serious problems with accomodation analyses, it did lead to extreme NASA budget requirements. Some of the schedules may also be optimistic in terms of technology readiness for the timeframe. There was sufficient concern about the realism of the time-phased mission set requirements to direct further analyses.

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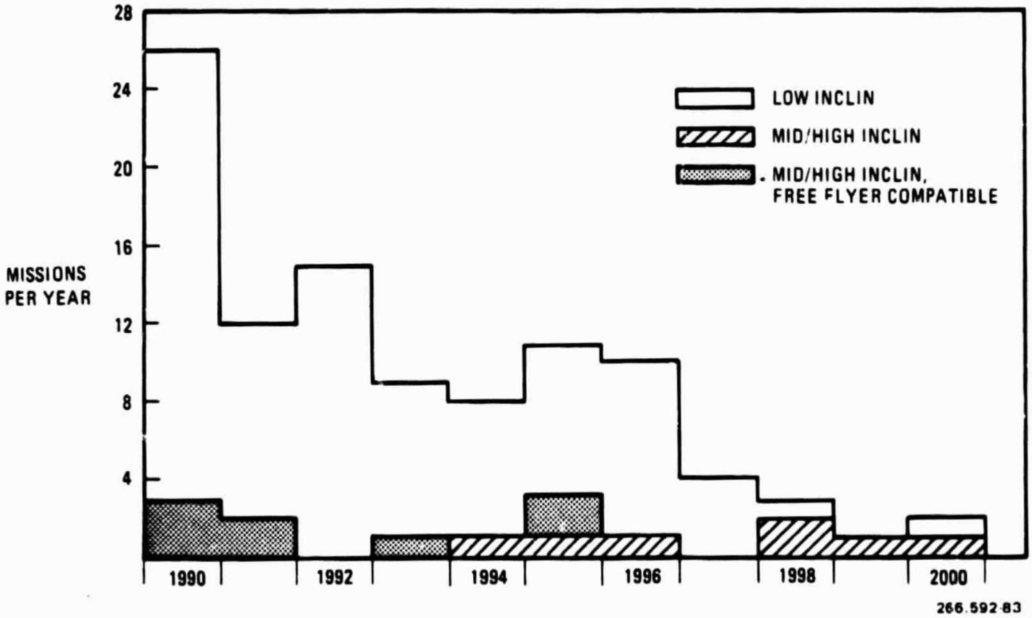

Figure 2-3. User IOC Dates - Station-Attached Missions

2.3.1 SELECTION PROCESS. A key parameter in the accommodation determination process is orbit inclination. Both 28.5 and 57 degrees were evaluated for the low inclination station, using acceptable as well as preferred orbit data (Figure 2-4). These same data were useful in evaluating polar orbiting stations.

Another key element in the selection process involves basic questions related to realism of the basic set. To scope the problem in more manageable terms, the planetary/escape missions were excluded because of their limited involvement with the station. The commercial missions were excluded because they were not major contributors to the heavy early year traffic congestion and were not involved in the budget concerns.

The science, applications, and technology missions were evaluated using the following evaluation criteria:

a. Is mission planned or approved by NASA
b. Are requirements traceable
c. Is mission cost commensurate with need and benefit
d. Is required technology base available
e. Are alternate accommodation modes available
f. Is mission definition sufficiently mature
g. Is mission a logical progression in a series
h. Does mission accommodation imply a major station cost delta

None of the user defined missions was eliminated, but some changes were made in schedule, and alternate accommodations modes were employed. Eight missions were transferred from the station to free-flyers primarily because man's role was not vital and they required high inclination orbits early in the decade. Our architectural and programmatic studies indicated a polar station was not viable so early. In all, 36 man-operated and 19 free-flyers were rescheduled (Table 2-5).

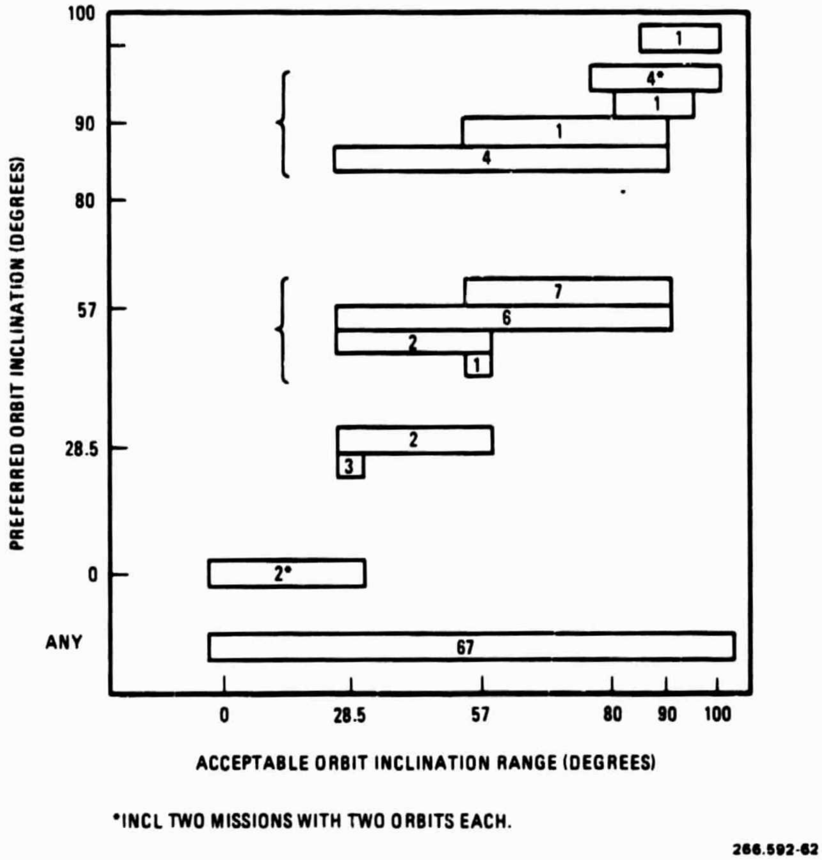

Figure 2-4. Orbit Inclination Requirements - Attached Missions/Payloads

Table 2-5. Distribution of Schedule Changes

Years Delayed	0	1	2	3	4
Station-attached	55	16	16	3	1
Free-flyers	39	7	8	3	1

Three missions moved beyond the year 2000: one free-flyer and two station-attached, one each of high and low inclination. As a result, the peak NASA budget requirements were relieved considerably. In conclusion, the selected baseline time-phased mission set is based on realistic technical progression, accommodation capability, benefits, mission maturity, and cost considerations.

2.3.2 BASELINE MISSION SET. The baseline mission set (Table 2-6) reflects decisions made in the accommodations and previously described evaluation process. Eight missions previously assigned to the Space Station became free-flyers and the man-operated missions were allocated to 28.5-degree and polar stations. No changes were made for GEO or escape-type satellites. Each of three Environmental Observation missions are unique in that they have payload elements at both low and polar orbit inclinations.

Table 2-6. Baseline Mission Set

	Station-Attached		Free-flyers				
			Degrees				
	28.5 deg	Polar	28.5	57	Polar	GEO	Escape
Science & Applications							
Astrophysics	7		6	3	1	1	
Earth & Planetary	5	3		1	7		12
Environmental Observations	7	4	1	7	4	3	
Life Sciences	7						
Materials Processes	2						
Commercial							
Earth & Ocean				1	2	1	
Communications	6					5	
Material Processs	14		1				
Industrial Services	5		1				
Technology Development	33						
Operations						2	
	86	7	9	12	14	12	12

The baseline time-phased mission set has been smoothed but still exhibits some reduction in new mission starts and station loading in the out-years (Figure 2-5). However, the early and mid years show reasonable planning. The level of station occupancy rises in the first few years and remains relatively constant in mid-decade.

An examination of the free-flyer distribution by orbit inclination and altitude (Figure 2-6) discloses several opportunities for combining individual satellites on larger platforms that will improve the operating efficiency. When time phasing and mission compatibility issues are considered, the 28.5-degree platform does not appear to be viable.

2.4 INTEGRATED REQUIREMENTS OF BASELINE MISSION SET

The Space Station provides resources and support for two basic mission classes: man-operated and free-flyers. The first class of missions establishes the driving requirements for pressurized volume, crew size, and power and data systems. The second class establishes the need for functional support in terms of satellite servicing, high energy staging, assembly, construction, and test (Table 2-7).

2.4.1 MAN-OPERATED MISSIONS. The time-phased station resource requirements were derived for a number of key parameters (Figure 2-7). Station resources requirements were derived by integrating the individual mission requirements on an annual basis. For example, the average crew hours were spread over the mission duration and summed for all payloads active during each year. Average power was derived similarly. No attempt was made to prepare detailed mission time lines during this study.

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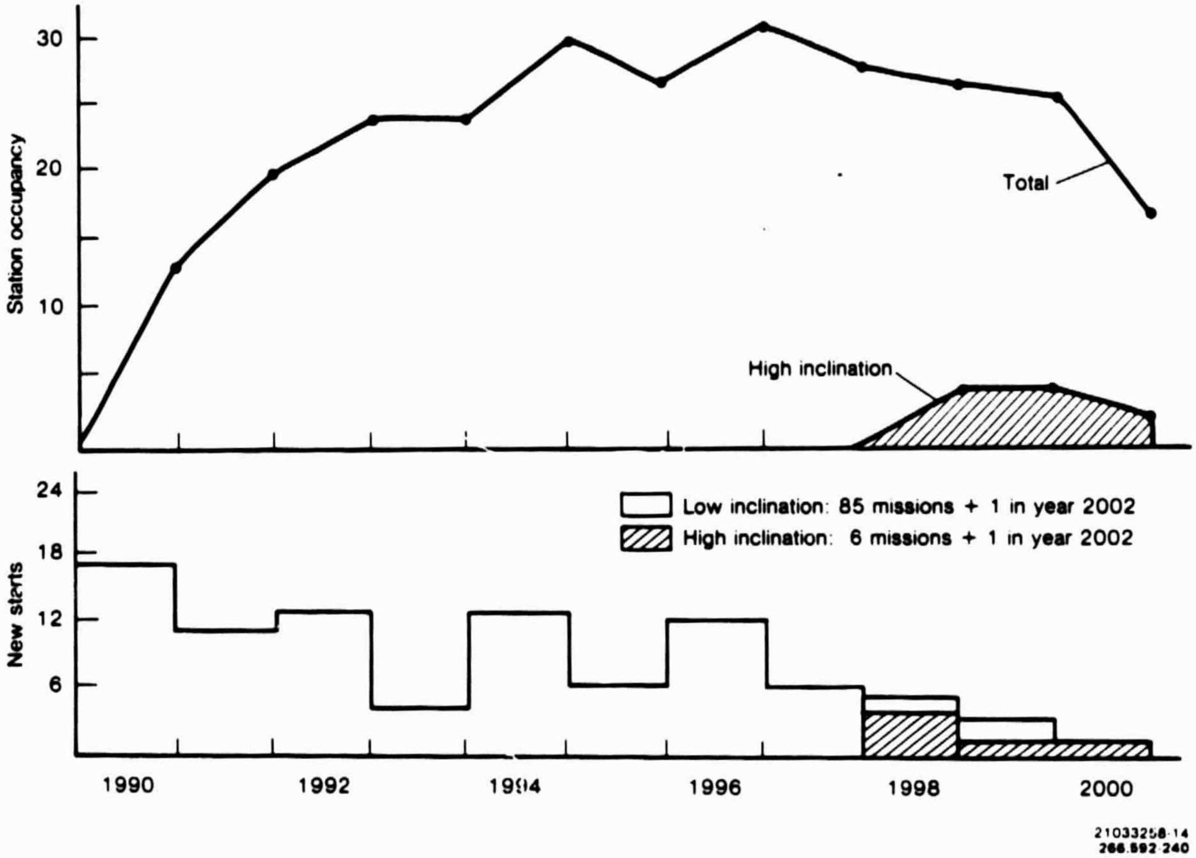

Figure 2-5. Baseline Man-Operated Missions

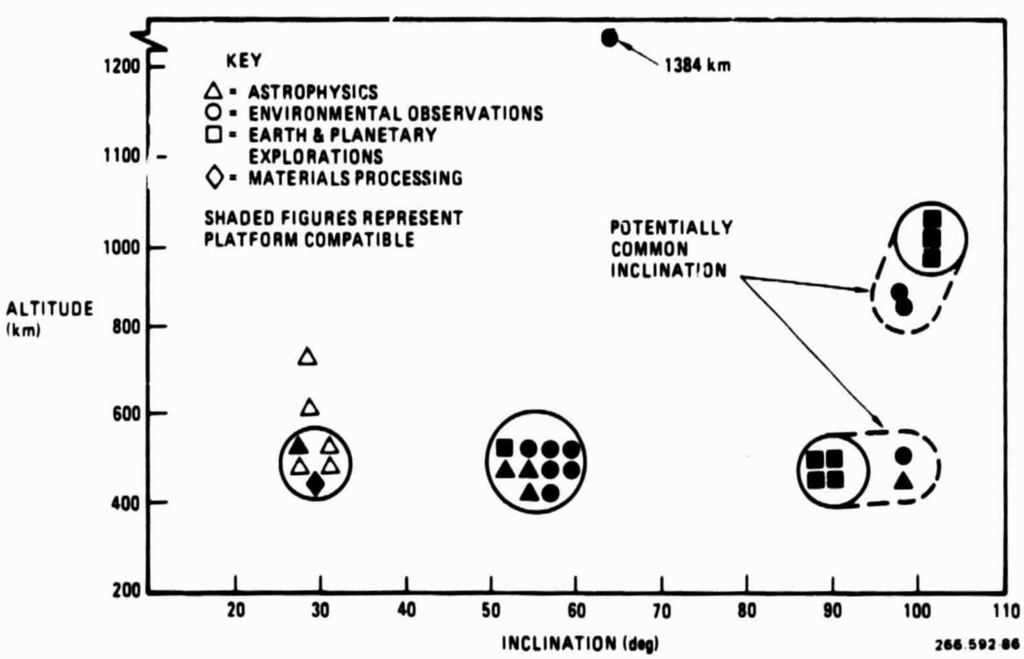

Figure 2-6. Baseline Free-Flyer Missions

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Table 2-7. Required Space Station Attributes

Accommodates man-operated missions
- Micro-gravity
  - -- Life sciences
  - -- Materials processing
  - -- Technology development
- Outward looking
  - -- Astrophysics
- Earth pointing
  - -- Earth exploration
  - -- Environmental observation

Supports free-flyer missions
- LEO/HEO satellites/platforms
  - -- Emplacement
  - -- Service
  - -- Retrieval
- GEO satellites/platforms
  - -- Emplacement
  - -- Service
- Planetary satellites
  - -- Boost

Provides resources
- Crew time
- Power
- Data processing
- Command & control
- Thermal control
- Stable platform
- Pressurized volume
- Exterior mounting

Provides functions
- Assembly & construction
- Checkout
- Service
- Reconfiguration
- Maintenance & repair
- Transportation
- Storage

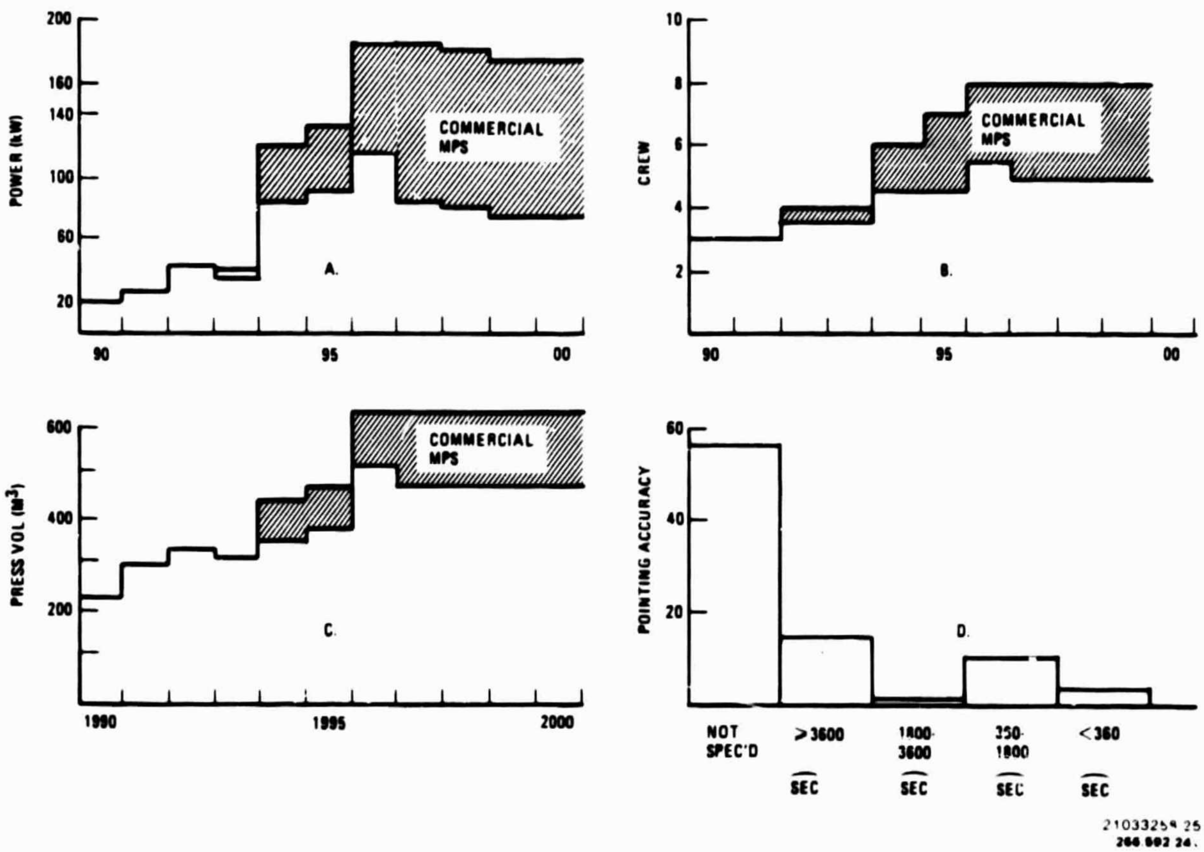

Figure 2-7. Man-Operated Mission Resource Requirements

The dominant power user is commercial materials production. These missions also require significant crew support and pressurized volume. We have shown that commercial MPS activities should become routine in the 1996-1997 timeframe, and since the station will be modular, it can accommodate the missions when they become economically viable and the demand for services materializes. A second large power user in later years is the closed ecological life support system (CELSS).

Crew requirements are nominal with commercial materials processing accounting for about 40% of the total in the out years. The crew time required for free-flyer support and station operations were derived as part of the accommodations analyses and are additive to those shown in the Figure.

The station provides a stable platform that will support 84% of the payloads. These payloads require a pointing accuracy of 1 degree or greater. Fourteen payloads require higher accuracy, and must, therefore, be equipped with additional pointing means. Three of the payload elements that are in the less than 3600 arc sec category are defined to incorporate fine pointing mounts already. Mass, size, and power for the pointing systems are included in the payload element descriptions.

Pressurized volume requirements will be satisfied by adding modules to the station throughout the decade. Commercial materials processing requirements were segregated in the same manner as power and crew size.

The data requirements vary from as low as 1 kbps to approximately 300 mbps. As there are only two missions with requirements greater than 200 mbps and the TDRSS capability is up to 300 mbps, it was determined that the station and associated systems can accommodate data transmission requirements.

Near continuous low gravity conditions are required for life sciences and materials processing missions. Although requirements are in the 10^{-3} to 10^{-5} g range, most missions can tolerate short term excursions to higher levels. Others will be shut down during operational periods when satisfactory levels cannot be maintained. Some life science missions also require a zero to 1g centrifuge.

The major sensitivities of attached missions to Space Station operations are the sensitivity of low g research activities to local disturbances from crew activities, transportation elements activities, e.g., docking, etc., and sensitivity of many viewing sensors to contamination, such as from the local atmosphere cabin leakage or other sources that could cause deposition on sensitive surfaces or interrupted viewing for optical, IR and X-ray Earth Observations and Astrophysics missions. These requirements should be satisfied by appropriate design countermeasures and operational constraints.

In summary, the Space Station must provide users with satisfactory orbits and with pressurized modules with space and mounting for research lab equipment and commercial equipment, as well as control and data handling systems. External mounting provisions with the proper orientation are required for very large sensors, antennae, and structural elements. Crew and electrical power resources are required, as well as basic platform accuracy and stability.

2.4.2 <u>SATELLITE SERVICING</u>. The free-flying mode includes both individual satellites and space platform accommodation of the payload elements. The primary involvement of the Space Station with free-flyers is through support operations including assembly/construction, emplacement, service, reconfiguration, and retrieval. Large free-flyers that are delivered to LEO in modular

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form can be assembled and checked out prior to being placed in their operational orbit. Free-flyers that have long lifetimes will be man-tended to provide servicing, repair, and updating. Due to unique orbit characteristics, free-flyers have been subdivided into three groups: LEO/HEO, GEO and Escape (planetary) missions. The LEO/HEO free-flyers are further subdivided by inclination and the servicing requirements defined for each year (Figure 2-8).

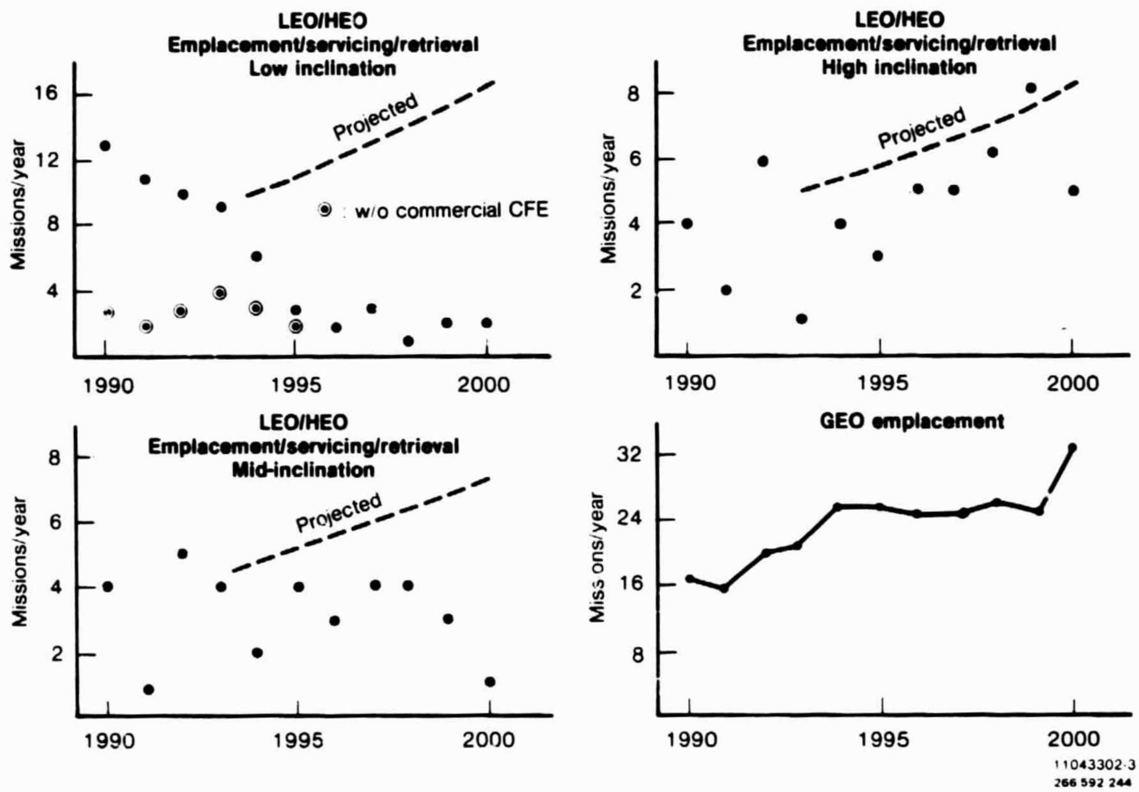

Figure 2-8. Baseline Free-Flyer Traffic Model

In reviewing the traffic level over the decade, the "planning horizon" problem is seen influencing the data. There is a higher level of activity early in the decade than there is later, an indication that users see more clearly needs within the near term than in the far term. As techniques and capabilities are proven in the early years, planning and provisions for the use of servicing will increase in the out years. The upcoming Solar Max Repair Mission should do much to improve confidence in on-orbit repair and servicing. The data reflects planned servicing actions only. Necessary unplanned maintenance actions will increase the traffic, especially in the out years, which are expected to have a larger accumulation of on-orbit free-flyers. For this reason, a projection of trends in the out years was used as a basis for the servicing analysis.

The station will support free-flyers in the lower inclinations using an OTV and TMS, as appropriate. This comprises 50-75% of the total traffic. However servicing of free-flyers in polar orbit will most likely be provided directly from the orbiter. A summary of the requirements (Table 2-8), discloses minimum impact on station resources.

Table 2-8. LEO/HEO Free-Flyer Servicing Summary

REQUIREMENT	28½ DEG	57 DEG	90 DEG
No. in operation Typical mass (kg)	1-8 1000 to 55,000	1-4 1350 to 12,500	1-7 1600 to 19,000
Service/Reconfig. Interval Access means	1-3 years Visit – TMS – Option-Shuttle, or Self Propulsion	1-3 years Visit – shuttle or OTV/TMS	1-3 years Visit – shuttle or TMS/self propulsion when station avail.
Crew – per service Crew Time EVA	1 to 2 men 1-4 days required	1 to 2 men 1-2 days required	1 to 2 men 1-2 days required
Power-service (avg kW)	<1	<1	<1

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2.4.3 HIGH ENERGY STAGING. The predominant emplacement traffic throughout the decade is the geosynchronous orbit communication satellites. Planetary missions include 12 deliveries to high-energy escape trajectories as well as a sample return mission. There are four science missions to GEO during the decade. DOD upper stage traffic to HEO/GEO that will require station support, varies from four per year in 1990 to nine per year in 2000.

The commercial satellite traffic model (Figure 2-8) was derived by SPACECOM who analyzed seven different traffic projections for the 1981 through 2002 period. Two separate approaches were used and near identical results obtained. These were further validated by a separate GDC analysis for the years 1983 to 1995.

In early years, GEO spacecraft would be delivered by the planned upper-stage, i.e. PAM, IUS, or Centaur, operating from the shuttle orbiter. The station involvement will probably be limited to being an observer, if at all.

During later years after transition to Station/OTV basing operations, the orbiter can deliver the spacecraft to a Space Station/OTV operations base in LEO, where the spacecraft would be mated to an OTV or required stage, and transferred to its operating orbit.

Where satellite weights permit, the satellites could be grouped for launch by the orbiter, and subsequently by the OTV. A further growth is possible by grouping the spacecraft on a platform similar to the LEO platform for sharing of platform services, thus reducing spacecraft construction, launch, and servicing costs.

A growth is foreseen where certain high value satellites could be retrieved from their operating orbits by the OTV, and returned to the Station/OTV base for servicing or repair, or possibly repaired in-situ by an OTV-TMS vehicle.

2.5 BENEFITS

A space station would enable the scientific and commercial communities to expand and improve upon their exploitation of space. As a part of the Space Transportation System (STS), it would extend the ability to test and verify operational capabilities of space system elements beyond that available with the shuttle orbiter and automated satellites. The advancements in technology to be gained during such a program will also reflect back into nonspace areas in the same manner experienced in the Apollo and STS programs. Of specific interest are performance and social benefits. Economic benefits are discussed in Section 4.

Performance benefits for a continuously manned Space Station over alternative methods of accomplishing the same or similar objectives stem from two principal sources. The first relates to improved ability to perform tasks and to an increase in quantity of output. The second relates to improved output quality. The increase in quantity also leads to cost benefits. The capability for long term manned presence will permit scientific research for periods exceeding that available in Spacelab, which are limited to a week or two and a maximum of one month. The Space Station will enhance man's ability to assemble large structures. The continuous time on orbit will permit larger construction projects. The availability of a permanent stable platform will also make the process more efficient over one supported only by shorter term orbiter missions. With respect to providing support to free-flyer satellites and platforms, the Space Station provides a base for maintenance and repair on an as-needed basis as well as for scheduled activities. Thus the useful life of observation type spacecraft can be extended by replenishment of consumables and changeout of sensors on a planned basis as well as by repair, as necessary.

Scientific and social benefits are closely interlocked. As man gains greater scientific knowledge, he is able to enhance the quality of life available to all. Strides made in basic research provide the needed background and information to push forward in applied research where the social benefits are more visible. For example, earth resources, weather/climate, ocean, and atmosphere research missions are important for improving man's capability to manage renewable resources, locate new sources for nonrenewable resources, and control his environment. New pharmaceuticals made possible by access to the space environment for materials processing can have far reaching effects. In addition to pharmaceuticals, there are anticipated advancements in metallurgy, semi-conductors and ceramics. There may even be new material combinations just over the horizon that we cannot presently imagine.

SECTION 3
MISSION IMPLEMENTATION CONCEPTS

Space Station architectural options and plans for station evolution were developed to meet the time-phased requirements of the selected mission set. We have defined a recommended Space Station system architecture and a plan for evolution of the system from initial IOC in 1990 to full capability before the end of the decade.

Space Station operations and subsystems were studied to define the level of capability required, and to identify the key technology advancements needed.

We used the approach shown in Figure 3-1, beginning with analysis of the requirements to accommodate and operate the selected missions, to develop a set of architectural options consisting of manned station elements, platforms, and transportation system elements. Trade studies of the capability vs costs of the concepts led to selection of a recommended architecture for the Space Station system.

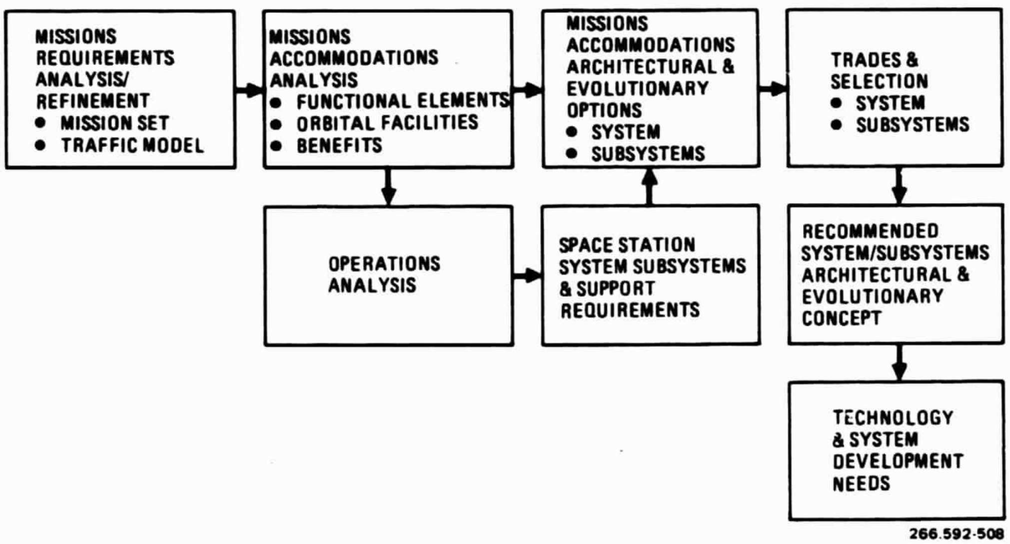

Figure 3-1. Approach to Analyses of Space Station Implementation Concepts

The functional elements of this architecture were defined, and a program plan developed for evolution of the total system to best meet the needs for mission accomplishment, considering cost, STS operations, and programmatic factors.

3.1 MISSION REQUIREMENTS ANALYSIS

The requirements of the selected mission set were analysed to define the Space Station system architecture required to accommodate, operate, and service the mission elements/equipment. These integrated mission/station requirements were defined for each of the functional areas.

a. Manned research, development, and production (RD&P) operations at 28.5 degrees, 57 degrees, and polar orbital inclinations
b. Free-flyer servicing at required operating orbits (28.5 degrees, 57 degrees, and polar)
c. High Energy missions staging and payload preparation at 28.5 degrees
d. Assembly, construction and test operations at 28.5 degrees

The major integrated requirements are summarized below for each functional area.

3.1.1 MANNED RD&P OPERATIONS. RD&P requirements were defined for the 28.5-degree orbit facility; these requirements include pressurized volume and mounting areas for mission equipment and crew accommodations, electrical power and heat rejection for mission and station equipment, communications, data, tracking systems, and station orientation and pointing capabilities.

As an example of the level of requirements that exist for this station, the electrical power and crew accommodation requirements are shown in Figure 3-2 and 3-3.

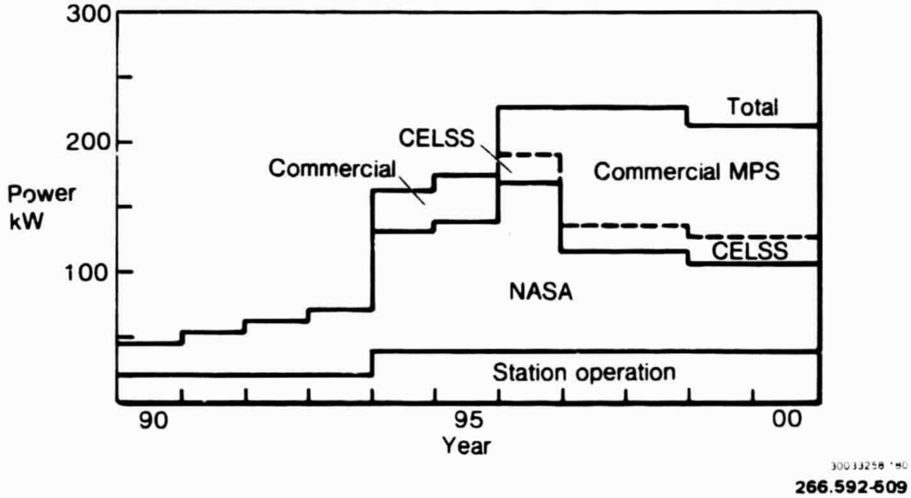

Figure 3-2. Electrical Power Requirements

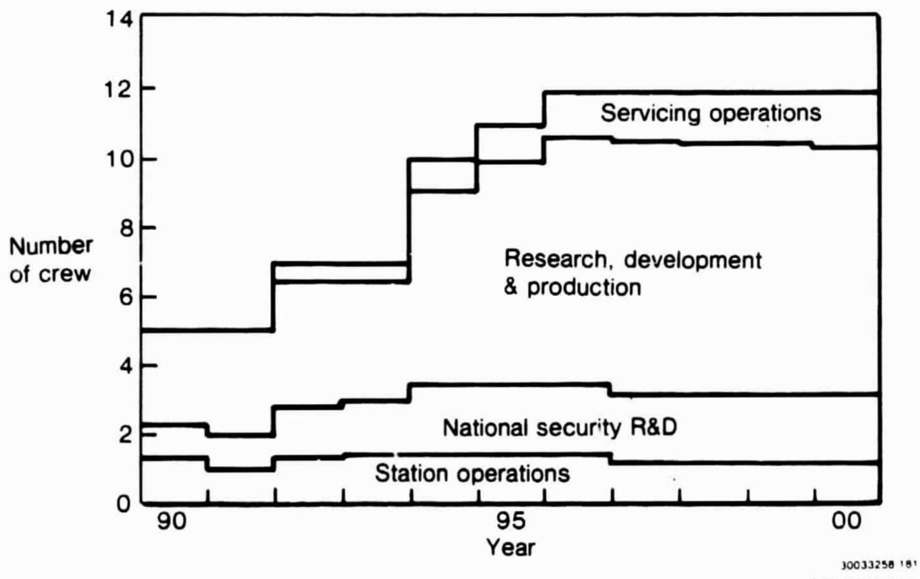

Figure 3-3. Crew Size Requirements

3.1.2 FREE-FLYER SERVICING. Requirements were defined for the servicing of free-flyers for life extension, sensor update, refueling, and repair. This servicing can be accomplished in-situ by an unmanned Teleoperator Maneuvering System (TMS), or by return to the station by the TMS (Table 3-1). The station resources to accomplish these operations were added to those required for the manned RD&P operations at 28.5 degrees. TMS propellant requirements are shown in Figure 3-4.

Table 3-1. Station-Based TMS Missions - 28.5-Degree Orbit

Mission Type	90	91	92	93	94	95	96	97	98	99	2000
Placement	(3)	(2)	3	3	3	3	3	3	4	4	5
Retrieval	(2)	(2)	2	2	2	2	2	2	2	2	2
Service in-situ	(8)	(7)	5	4	5	6	7	8	9	9	10
ET disposal	-	-	-	-	2	3	3	3	3	3	3
Unscheduled	-	(1)	2	3	3	3	3	3	2	2	2

(#) Shuttle/TMS operations in early years

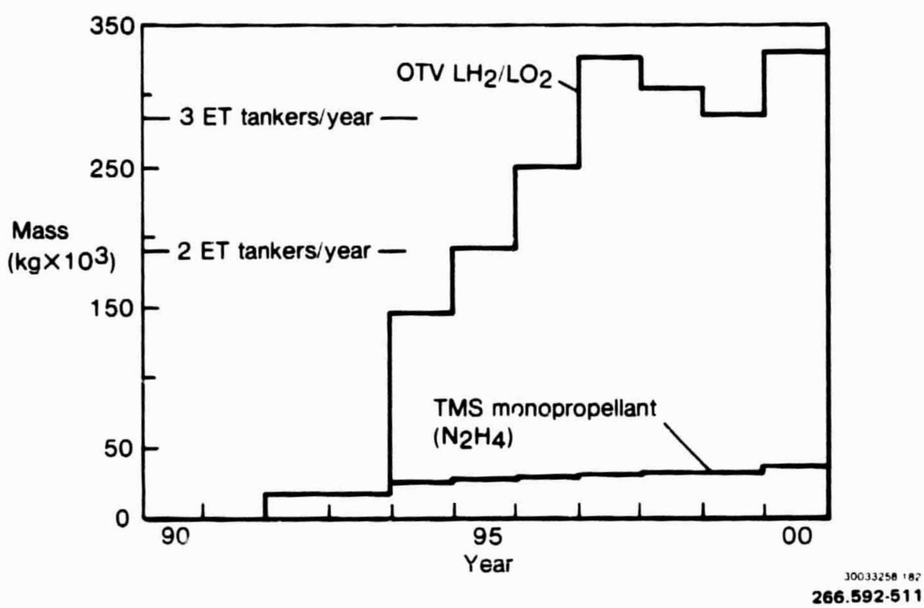

Figure 3-4. OTV and TMS Propellant Requirements

3.1.3 HIGH ENERGY STAGING AND SATELLITE PREPARATION. Table 3-2 identifies the number of OTV missions required to emplace, service, etc, the total number of satellites (including DOD) identified in our mission model. These requirements are modest in early years during development and evolution from expendable upper stages to full OTV capability about 1994. The major capabilities required for the 28.5-degree station to accommodate the OTV operations include OTV servicing and fueling, propellant storage and handling, payload storage and processing, and added crew accommodations, controls, power, tracking, and communications.

Early studies demonstrated that very significant economic benefits can be derived by incorporating the space-based OTV capability into early station operations. Consequently this capability should be developed as rapidly as technology allows.

Table 3-2. Station-Based OTV Missions

Mission Type	90	91	92	93	94	95	96	97	98	99	2000
Placement	(10)	(13)	(10)	(14)	13(5)	15(5)	19	19	25	23	26
Retrieval	-	-	-	-	-	1	2	-	1	1	-
Service in-situ	-	-	(1)	-	-	1	1	2	1	1	3
Escape	-	-	(4)	(2)	(1)	(1)	-	4	-	-	-
Manned sortie	-	-	-	-	-	-	-	-	-	1	1

(#) expendable upper stage missions in early years.

OTV propellant requirements are shown in Figure 3-4. Delivery of these propellants, and transfer to station storage/usage facilities is a major consideration discussed in detail in Volume II Book 2, and considers the following:

a. Use of an ET-tanker
b. Scavaging of propellants directly from the ET.

3.1.4 ASSEMBLY CONSTRUCTION AND TEST. Appropriate operational requirements were defined for carrying out identified assembly and construction activities. In early years, these operations are minor/modest, later in the decade they are combined with the OTV payload assembly requirements.

3.1.5 TOTAL STATION. The requirements for RD&P operations are the major drivers for pressurised volume, area, crew accommodations, power, and data resources. The incorporation of the free-flyer servicing, OTV, and assembly operations require only a moderate increase in the RD&P capabilities to satisfy their requirements, particularly in the early years.

3.2 ARCHITECTURAL OPTIONS AND TRADES

A system architecture was derived by developing candidate families of system elements for each of the functional areas.

a. Manned RD&P operations at each operating orbit - 28.5 degrees, 57 degrees, and polar.
b. Free-flyer servicing at 28.5 degrees, 57 degrees, and polar orbits
c. High-energy staging/OTV operations at 28.5 degrees
d. Assembly operations at 28.5 degrees

3.2.1 ARCHITECTURAL OPTIONS. The architectural options evaluated are summarized in Figure 3-5 and consist of manned station elements at each operating orbit, operations and servicing facilities, unmanned facilities, free-flyers and platforms.

Primary transport options are the TMS for co-orbital satellite servicing from the stations, and OTV for transfer of satellites to GEO and HEO locations.

FACILITY OPTIONS	MAN-OPERATED RESEARCH, DEVELOPMENT & PRODUCTION (RD&P)	MANNED OPERATIONS & SERVICING (O&S)	MAN SUPPORTED (TEMPORARILY MANNED)	MAN-SERVICED FREE-FLYERS AND/OR PLATFORMS	NON-SERVICED (CONVENTIONAL SATELLITE)
MISSION TYPE	MAN'S PRESENCE REQUIRED OR BENEFICIAL	• OTV/TMS BASE • SATELLITE SERVICING • LSS CONSTRUCTION • TECHNOLOGY DEVELOPMENT	NEEDS OCCASIONAL EXTENDED MAN'S PRESENCE (>SHUTTLE TIME)	SEPARATELY-OPERATED FOR SPECIAL ORBITS OR COMPATIBILITY CONFLICTS	• SHORT TERM • GEO SATELLITE • NOT SERVICEABLE
ORBITS	LEO 28.5, 57, POLAR	LEO 28.5, POLAR	LEO 28.5, POLAR	LEO 28.5, 57, POLAR, GEO	LEO 28.5, 57, POLAR, GEO

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Figure 3-5. Space System Architectural Options Considered

3.2.2 ARCHITECTURAL OPTION TRADES. Trade studies of the options available for a total Space Station system focused on the capabilities required at each potentially manned element of the system, and on alternate means to accomplish mission objectives without permanent man's presence. The alternates included separation of missions that could be accommodated as free-flyers, onto platforms where possible, for automated/ground control, and servicing by shuttle visits.

From these studies it was concluded that a manned facility at 28.5 degrees was required with an initial capability for RD&P operations in 1990. Capability for free-flyer servicing and OTV/assembly/payload operations would be added in 1992 and 1994, respectively.

Manned facilities at 57 degrees were not considered justified at this time since identified missions could be satisfied by either 28.5-degree or polar facilities. Delay of a polar orbit station until after the year 2000 was considered appropriate based on the limited requirements defined.

For the manned station at 28.5 degrees, a major consideration is whether the facilities for OTV and payload servicing/assembly operations should be separated from the RD&P operations because of the obvious conflicts and incompatabilities between these two types of operations.

To define the degree of incompatibility and extent of conflicts that may exist between the RD&P and OTV/payload operations, we estimated the interuption in mission operations that would occur with each OTV docking and launch operation. Other concerns, as identified in Table 3-3, were also investigated.

The cost of the lost mission time due to these disturbances was estimated. This cost was compared to the delta cost of separate facilities. It was concluded, as shown in Figure 3-6, that the cost of separate facilities is not warranted. Therefore, for the selected architecture we have concluded that the OTV/TMS operations should be carried out on the same orbital facility as the RD&P operations for maximum cost effectiveness of the Space Station system. However, this decision is subject to future review in the event of any major programmatic changes.

Table 3-3. Combined Facility Concerns

• Environmental conflicts -- Dynamic disturbances -- Contamination	• Infrequent shutdown of sensitive missions required
• Scheduling conflicts	• Minimized by infrequent O&S missions
• Growth limitations	• Growth through 2000 manageable
• Greater complexity & risk	• Not a decisive factor

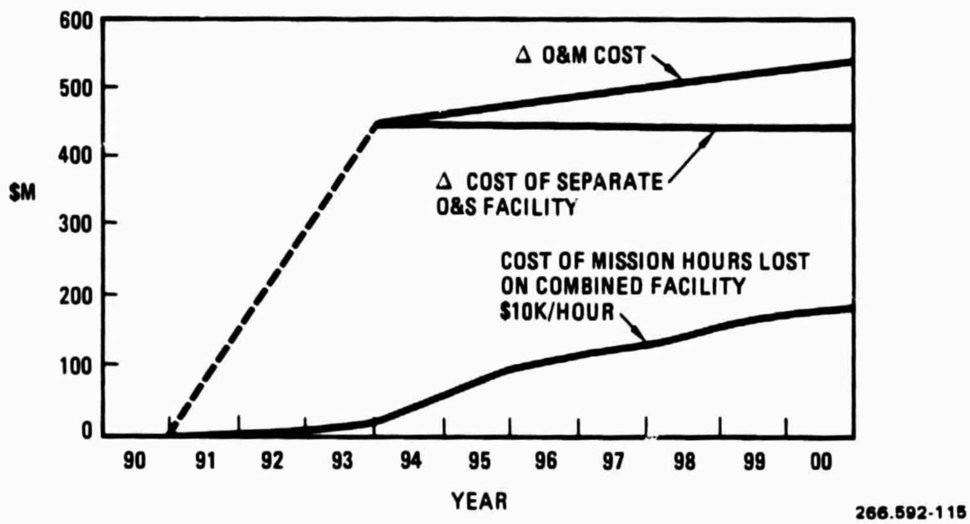

Figure 3-6. Cost - Lost Mission Hours vs Separate Facilities

This choice of combined facilities imposes certain important considerations on the configuration and design phases of the station development:

a. Definition of OTV/payload operations that minimize the acceleration disturbances and atmospheric contamination in the station vicinity.
b. Design of RD&P facilities that minimize acceleration disturbance by attenuation or isolation.
c. Design of the facility to maximize operational/scheduling flexibility.

3.2.3 SELECTED SPACE STATION SYSTEM ARCHITECTURE. The station system architecture selected based on the completion of trade studies discussed in Section 3.2.2, is shown in Figure 3-7, and is composed of the following elements:

a. Manned station in a 28.5-degrees by 400 km orbit for the conduct of:
   1. Man-operated research, development and production
   2. Servicing of co-orbital free-flyers using TMS for recovery and placement

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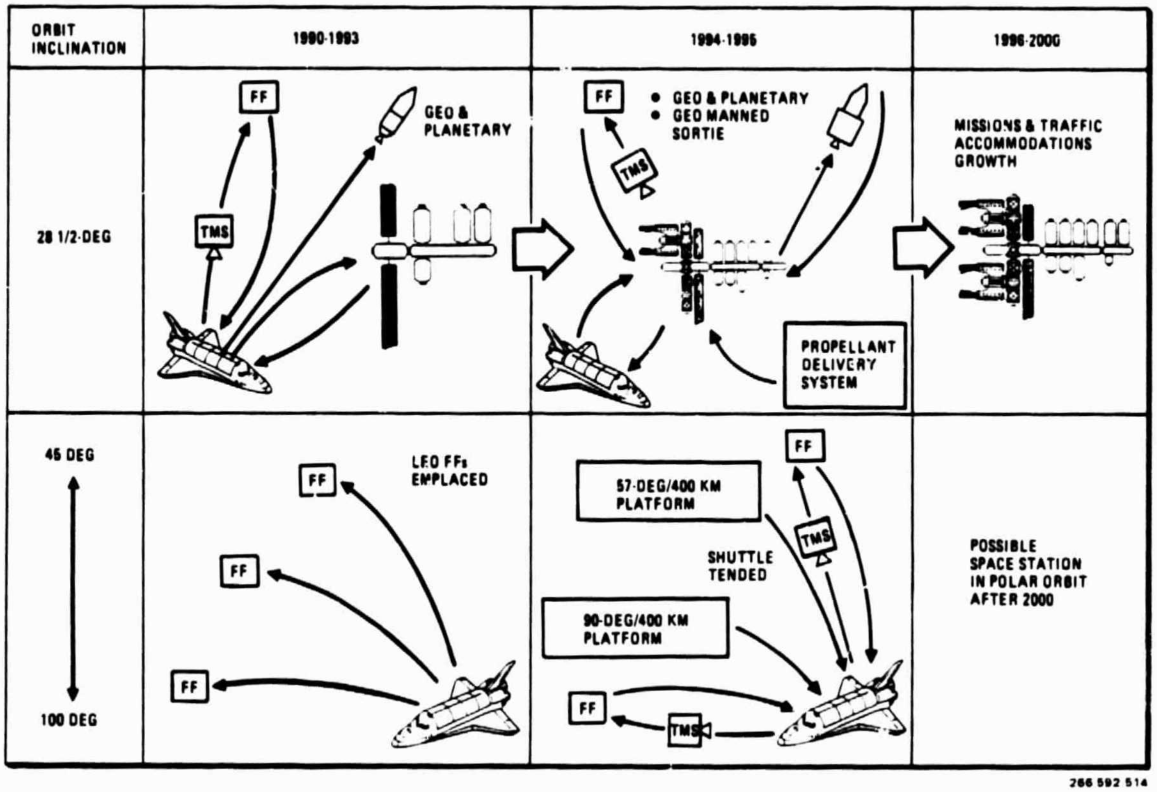

Figure 3-7. Selected Architecture for the Space Station System

   3. OTV and GEO/HEO payload operations
   4. Assembly, construction, and test of very large structures/payloads

b. Platforms at 57-degree and polar orbits for grouping of payloads.

Other elements of the over-all Space Station system include the following:

a. Transport systems including a reusable OTV for delivery/retrieval of satellites to/from GEO/HEO, and provisions for delivery of OTV propellants to the station, i.e., a shuttle-derived ET tanker or equivalent.
b. Shuttle for delivery of mission elements, station elements, and consumables, and for servicing free-flyer satellites and platforms in orbits unaccessible from the station.
c. Communication and data links to TDRSS orbital and ground facilities, and to ground control facilities.
d. Ground launch facilities at KSC and Vandenberg AFB to support all orbits.
e. Mission control and support facilities.

This architecture accommodates all requirements of the selected mission set except for the desire for manned operations in polar orbits late in the decade:

a. It provides for the very significant economic benefit that can be derived from inclusion/operation of the space-based reusable OTV.
b. It allows for evolutionary growth by increase in the manned facilities at 28.5 degrees and eventual addition of manned facilities at polar orbit.
c. It falls within the STS operational constraints/flights per year, and within the expected budget constraints both for mission equipment and station elements.

3.3 SPACE STATION SUBSYSTEM AND OPERATIONS STUDIES

For purposes of ensuring concept feasibility, identifying needed technology advancements, and to permit realistic cost and schedule estimates, the station subsystems and operations were subjected to analysis.

The results of the subsystem studies are briefly summarized in Table 3-4 showing the approach to implementing the subsystems, and basic features considered important. The technologies required are discussed in section 3.5.

A major concern is the high electrical power requirements that mainly center on the very large demands of material processing in space (MPS). This capability can be added incrementally as this projected need materializes; however, the apparent large increase in demand over the decade will require particular attention during initial design to assure incorporation of adequate modular growth capability.

Table 3-4. Summary of Station Subsystem Implementation Concepts

Subsystem	Capacity/Rate	Implementation Concept
Electrical Power	1990: 50 kW 1997: 200 kW	Concentrator solar arrays, high frequency AC distribution, Add arrays as required
Thermal Control	Consistent with electrical power generated	Centralized radiator system, two-phase pumped fluid thermal bus
Flight and Structure Control		Annular momentum control devices (AMCDs) and propulsive methods. Distributed, low frequency structural control
Communications and Tracking	250 mbs capability	TDRSS links, TDAS after 1995
Data Management	250 mbs aquisition 10^{11} bit storage	Distributed system, storage and on-board processing
Crew and Life Support	1990: 5 men 1997: 12 men	Initially open-loop 1990 technology, update to partially closed loop, ECLSS later in the decade
Operations Management		Autonomous on-board systems and operations control. Automated maintenance and logistics systems
Automation and Control	GN&C RMS Self Test	Station controls/housekeeping fully automated Robotics/remote systems reduce need for extensive EVA

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Data rates for on station collection/processing, and for subsequent transmission are compatible with TDRSS capabilities.

Station flight control, orientation, and pointing of the externally mounted mission viewing instruments for both earth and celestial viewing, while maintaining an earth oriented station, imposes a design/configuration problem.

Crew and life support accommodations are moderate at start using primarily expendable consumables, evolving towards closed-loop self-sufficiency by the end of the decade.

Automation has been investigated, particularly for long-term or frequent repetitive operations, and candidate areas identified, so man can concentrate his efforts on those mission activities where his direct intervention and control can be most beneficial to results.

3.4 SPACE STATION EVOLUTION

Plans for evolving the Space Station from the initial IOC capability in 1990, to the final all-up capability of the system in the year 2000, were studied to formulate a plan that meets the constraints of overall funding limits, STS operational capabilities, and best meets the requirements of the selected mission set. This was accomplished by first defining the functional elements required to accomplish each of the mission/operational functions within the selected station architecture.

The functional elements of the station consist of the following (Figure 3-8):

a. Station core functional elements for crew habitability, power distribution and control, station control, and communication/data, logistic off-load, consumables storage, and shuttle docking provisions.
b. Mission equipment areas comprising pressurized laboratories and mounting/pointing facilities.
c. OTV servicing and payload assembly areas, including propellant storage and handling facilities.
d. Solar arrays and heat rejection radiator assemblies.
e. Accessways and interconnections between station elements.

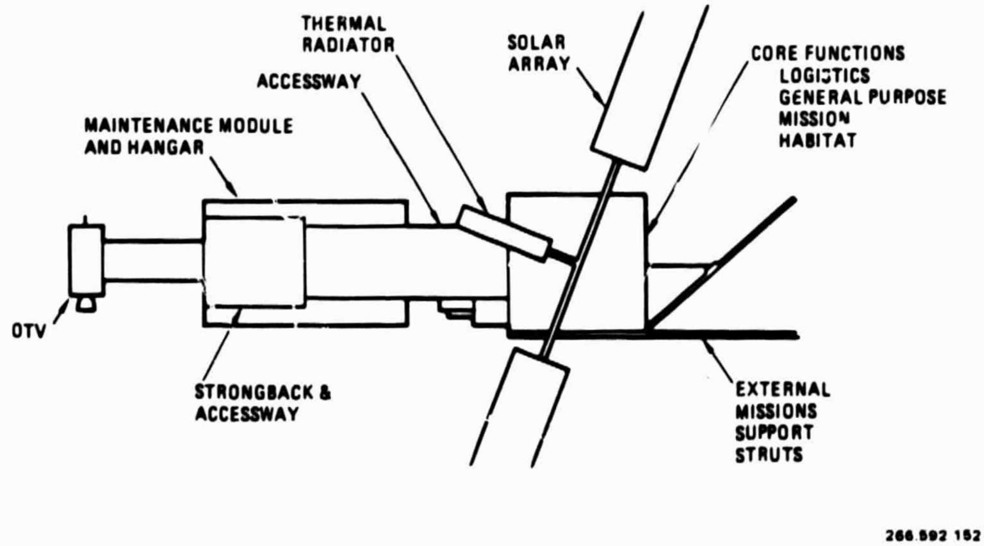

Figure 3-8. Functional Elements of the Space Station Architecture

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In addition to these Space Station functional elements, evolution plans must include:

a. A reusable space-based OTV.

b. An OTV propellant delivery system.

c. A TMS system, station-based, supported by ground logistics for parts, consumables, and propellants.

Items not included in our studies of station evolution, but recognized as a necessary part of the space station system are the ground-based facilities for launch, control, and support.

The plan proposed for evolving the Space Station system is shown in Figure 3-9 and outlined below.

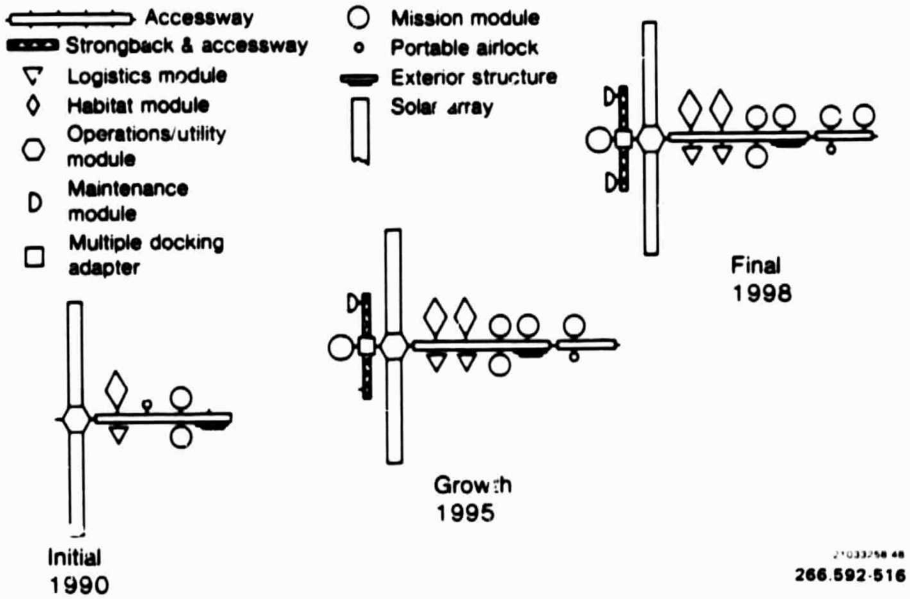

Figure 3-9. Concept for Evolution of the Space Station Element

The manned Space Station functional elements for power, habitability, communication/data, station controls, and the first sets of mission equipment are delivered and emplaced in orbit by the shuttle over a series of five flights during 1990. The station is progressively assembled, operated and checked out so it can be manned and operated by the end of the year.

The OTV capability is initiated early in the decade with progressive build-up of the technology and facilities needed to begin OTV operatons by 1994, at which time propellant handling and storage facilities are completed along with the necessary payload processing capabilities. A second OTV servicing facility is added in 1996 to accommodate the increased traffic in OTV payloads and operations (Figure 3-10).

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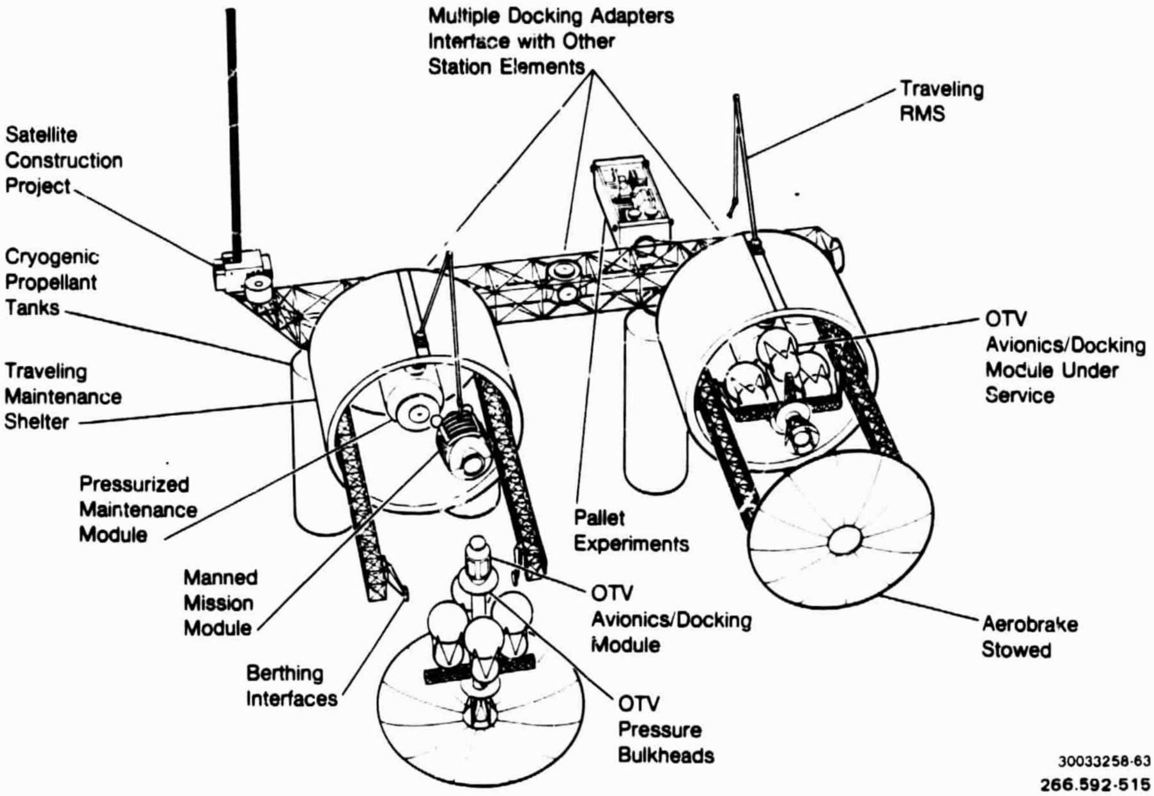

Figure 3-10. Space-Based OTV Servicing Facility Concept

Platforms are emplaced at 57-degree and polar orbits in 1992 and 1995, respectively.

TMS capabilities for servicing free-flyers are incorporated into the station in 1992.

3.5 SPACE STATION TECHNOLOGY NEEDS

Technology needs for the Space Station system have been identified and are discussed in Volume II Book 2 and are summarized below.

System level needs include those associated with development of the space-based OTV and focus on propellant scavenging on-orbit, transfer and storage and loading for both the OTV and the TMS systems. Assembly of very large payloads and structures introduces the need for automated/remote techniques to avoid extensive manned EVA operations, as well as improvements in EVA capabilities. Shuttle, TMS, and OTV docking and berthing capabilities all remain to be developed, and are crucial to station operations.

Space Station subsystem level technologies needing upgrading for greater capability and efficiency of operation have been identified in all of the subsystems areas. Some of the more critical technology areas are listed in Table 3-5.

Table 3-5. Station Subsystem Major Technology Issues

Discipline	Major Technology Issue/Requirement
Power Management	• Photovoltaic vs nuclear • Solar concentrator arrays • AC distribution • NiH batteries vs regenerative fuel cell storage
Thermal Management	• Heat pipe radiator • Dual heat rejection temperature buses • Nontoxic distributed system • Fluid selection
Flight and Structural Control	• Annular Momentum Control Devices (AMCD) • Active structural damping components & techniques
Communications and Tracking	• High speed multiplexers • Bit storage (10^{11} bits) • Video data compression • Efficient S- and K-band phased array antennas • High speed (150-300 mbs) crypto hardware
Data Management	• Data storage devices • Fault tolerance • Data security • Radiation hardness
Crew and Life Support	• Water reclamation • Atmosphere revitalization • Waste management • Operational medicine • Food • Systems integration • Hygiene equipment • EVA equipment
Systems and Operations	• Management information systems • Inventory control systems • Robotics • Space construction • Shuttle berthing/docking • Fault monitoring/identification systems • Design for growth • Space maintainability

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SECTION 4
ECONOMIC BENEFITS, COST AND PROGRAMMATICS

As an integral part of our analysis of Space Station costs and programmatics, we analyzed the economic benefits of a manned station, and explored a broad range of options for partnership between Government and private industry in Space Station development and operation.

The major study conclusions regarding Space Station economics can be summarized by the following three points:

a. The Space Station has significant potential economic benefits projected at $1.7 billion annually by the mid 1990s.
b. The Space Station function with the greatest quantifiable economic benefit is the space-based OTV.
c. Private investment in Space Station development and operations is potentially feasible, and can be encouraged through Government actions.

To illustrate the concept of private investment, we have developed a Space Station Prospectus, which presents the critical economic and programmatic data in a format more familiar to the investment community.

4.1 ECONOMIC BENEFITS

The study of economic benefits of the Space Station included the three main functional areas: man-operated Research Development and Production (RD&P), satellite servicing, and OTV operations. Of the three areas, as shown in Figure 4-1, the space-based OTV clearly distinguishes itself as the most economically attractive function.

The man-conducted research and production, and satellite servicing functions were found to have lesser, but still significant economic benefits.

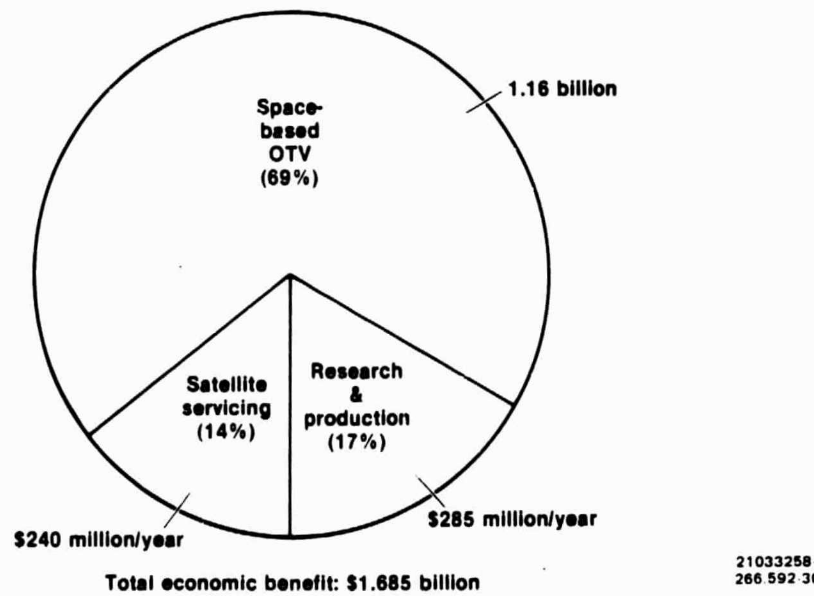

Figure 4-1. Space Station Economic Benefits - Projected for Mid-1990s

4.1.1 BENEFITS OF A SPACE-BASED OTV. The benefit of the OTV is based primarily on the advantages of space-basing and reusability. The reusable OTV allows the cost of buying an upper stage and delivering it to LEO to be spread over many flights; the amortized OTV unit and delivery cost contributes about $1 million to the cost of an OTV mission, while expendable upper stages can cost over $100 million per mission for purchase and launch to LEO.

By delivering a 10,000-lb payload to GEO for a projected cost of $17.5 million, plus the cost of delivering the payload to the Space Station, the OTV provides an economic benefit per mission, in net cost advantage over competitive launch systems of over $62 million.

The annual benefit of the OTV, based on an average of 17.3 OTV missions per year (calculated as a 75% market share of 23 potential OTV missions annually) is estimated at approximately $1.08 billion, as shown in Figure 4-2.

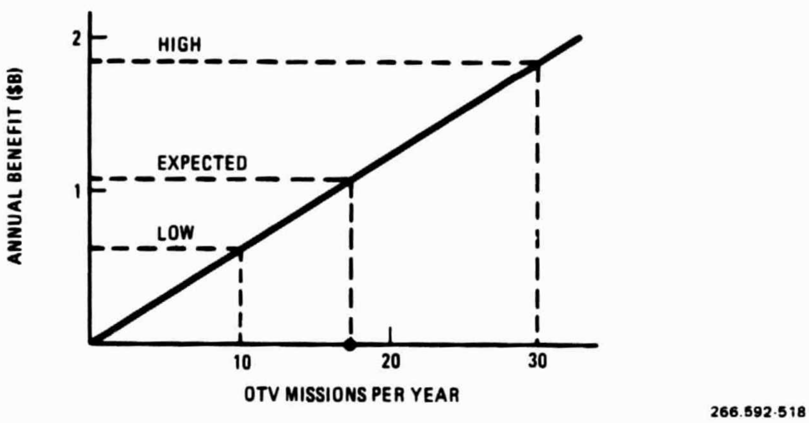

Figure 4-2. Benefits for Space-Based OTV

The estimate of OTV benefits is based on the assumption that propellant can be delivered to LEO for $500 per pound -- utilizing a shuttle-derived ET tanker or propellant scavenging from the external tank. However, 75% of these benefits are still achievable if propellants need to be provided in a more conventional (and expensive) manner; e.g., by propellant tanks carried in the shuttle cargo bay. Delivery of propellant via the ET tanker (or by recovery from the shuttle ET) could provide an additional economic benefit in profit on sale of OTV propellant, which could benefit all STS users, estimated at $40 million per ET tanker flight, or $80 million annually.

OTV cost-effectiveness is most sensitive to the cost of delivering the OTV payloads to the Space Station via the shuttle. The nominal OTV benefit is based on an average shuttle load factor of 0.41 for a typical 10,000-lb payload, a loading efficiency that will require modest modifications in satellite design to reduce their length-to-weight ratio. These changes seem practical, in fact, much greater efficiencies are possible, and could produce further OTV benefits.

4.1.2 BENEFITS OF SATELLITE SERVICING. Satellite servicing from the Space Station is another potentially lucrative function, with annual benefits estimated at about $240 million. This benefit projection is based on a net benefit of $12 million per servicing mission, and an average of 20 servicing missions per year, as shown in Figure 4-3.

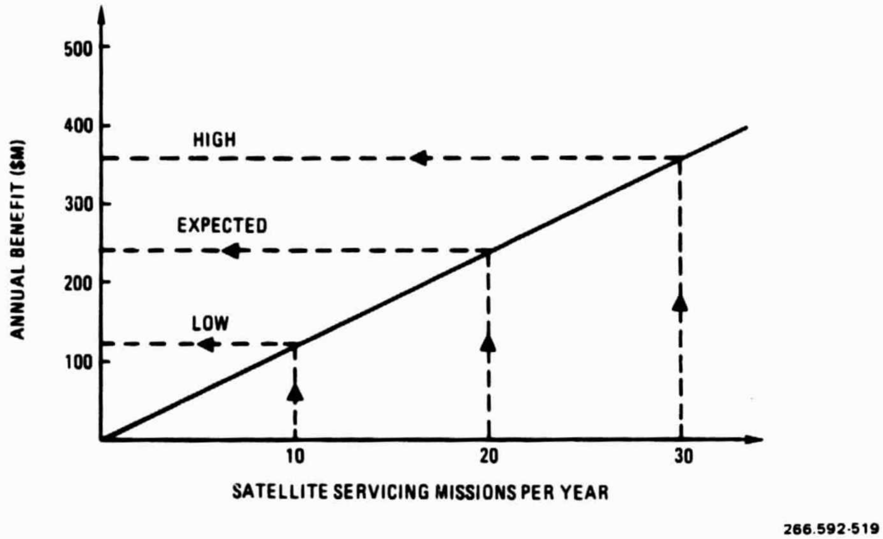

Figure 4-3. Benefit of Satellite Servicing

These estimates were derived from a satellite servicing benefits model that accounts for such factors as mission criticality (the percent of the satellites capabilities restored by the servicing mission), life extension (the number of years of operating time added to the satellite's life by servicing), and the cost of the servicing mission. It was determined that most servicing missions would be performed on LEO satellites and platforms by the Teleoperator Maneuvering System (TMS), since servicing missions requiring use of the OTV would be more expensive, and most high-orbit assets (e.g., commercial communication satellites) are relatively reliable.

The satellite servicing benefits model was developed with support from NASA centers (most notably GSFC and JPL), and is based on analyses of over 50 science and application satellites launched over the past 20 years. Consideration was given to changes in satellite design and performance that could be expected to take place between the present and the initiation of the Space Station operations, but further definition of the Space Station missions will be required for validation of the results of the benefits analysis. Satellite servicing benefits were found to be highly sensitive to most variables used in the model, particularly the mission criticality and life extension factors. One important result, however, is not sensitive to these factors - that satellite servicing from the Space Station can be expected to be more cost-effective, for a wider variety of missions, than servicing from the Space Shuttle.

4.1.3 BENEFITS OF MAN-CONDUCTED RESEARCH AND PRODUCTION. Space Station research and production has the potential to yield great long-term economic benefits, particularly in the area of materials processing in space (MPS), but were found to be very difficult to quantify in a credible manner. Production of high-value pharmaceuticals and electronic materials in the zero-gravity environment of space could evolve into a multi-billion dollar industry by the end of the 1990s, and commercial development of MPS would certainly be facilitated by the availability of a permanent manned facility for experimentation and production.

The Space Station research and production function encompasses other activities whose benefits cannot be predicted or quantified, such as life sciences rsearch, which could result in improving health care on earth and thereby yield economic benefits.

Owing to the difficulty in quantifying these benefits, the economic cost advantage of the Space Station over other means of achieving similar research and production mission objectives was used as the basis for estimating the economic benefits in this area.

A cost per kilogram hour function was developed to compare the cost-effectiveness of space systems in providing payload capability and mission time duration for these activities. The Space Station was shown to have an order-of-magnitude advantage over the Shuttle/Spacelab in cost/kg-hr for such missions as MPS and Upper Atmosphere research. When the total payload and mission duration capabilities of the Space Station were considered, the theoretical Space Station economic advantage over the Shuttle/Spacelab was shown to be as high as $1 billion per year.

However, a much more conservative approach was used to arrive at a baseline estimate of Space Station benefits in research and production. A direct comparison of Space Station cost estimates with the cost of using the Shuttle/Spacelab configuration, based on an annual mission model of five one-week Spacelab equivalent missions per year, yielded a nominal estimate of $285 million per year in Space Station research and production economic benefits (Figure 4-4).

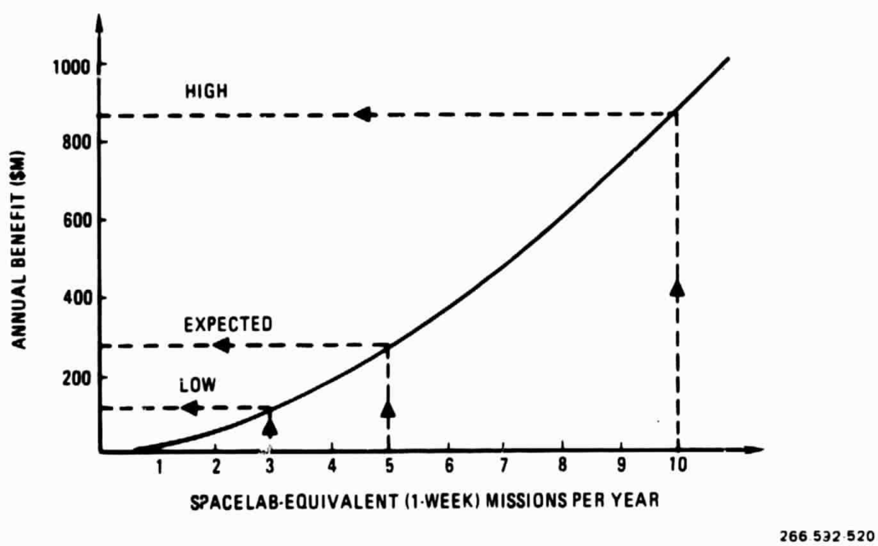

Figure 4-4. Benefits of Research and Production

4.1.4 SUMMARY OF ECONOMIC BENEFITS AND INVESTMENT RETURN. Combining the net economic benefits of these three Space Station functions, the total annual economic return was estimated at about $1.7 billion, as was shown in Figure 4-1. Space Station benefits could be substantially greater if social, performance and the non-quantifiable benefits were included.

The economic benefit of the Space Station was concluded to be a major program consideration in support of establishing a manned station capability.

Although the OTV provides the major economic benefit, the Space Station architecture with the most rapid economic payback was found to be a combined research and production and OTV station (Figure 4-5). This assumes an OTV to be operational in 1994. Since the Space Station investment horizon could be reduced by several years if an OTV capability were established first, such an 'early OTV' scenario aimed at maximizing economic return should be given further serious consideration.

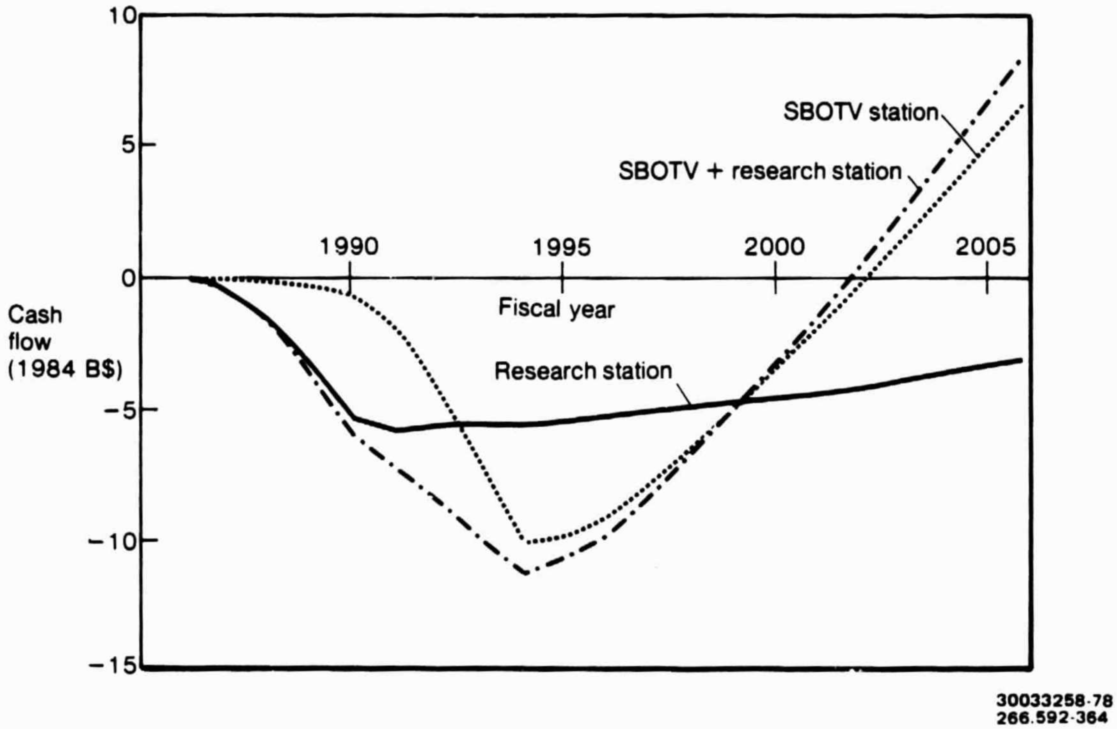

Figure 4-5. Economic Benefits Payback Period

4.2 PROGRAM COSTS

ROM total life cycle costs (LCC) have been estimated for several architectural and evolutionary options. These estimates have been generated with a parametric cost model and broad generic level definition data.

The costs for the baseline combined research and operations station is shown in Figure 4-6, together with the station associated mission payload set, the space-based OTV, and a shuttle-derived ET tanker. This option represents a research capability in 1990, and a space-based OTV capability in 1994.

The IOC cost of the initial research station is $5.5 billion (in 1984 $). The 'all-up' cost of the growth research station is $6.3 billion.

The incremental cost for the OTV capability is estimated at $3.2 billion, to which must be added the cost of the OTV ($1.5 billion), and the cost of the tanker ($1.2 billion).

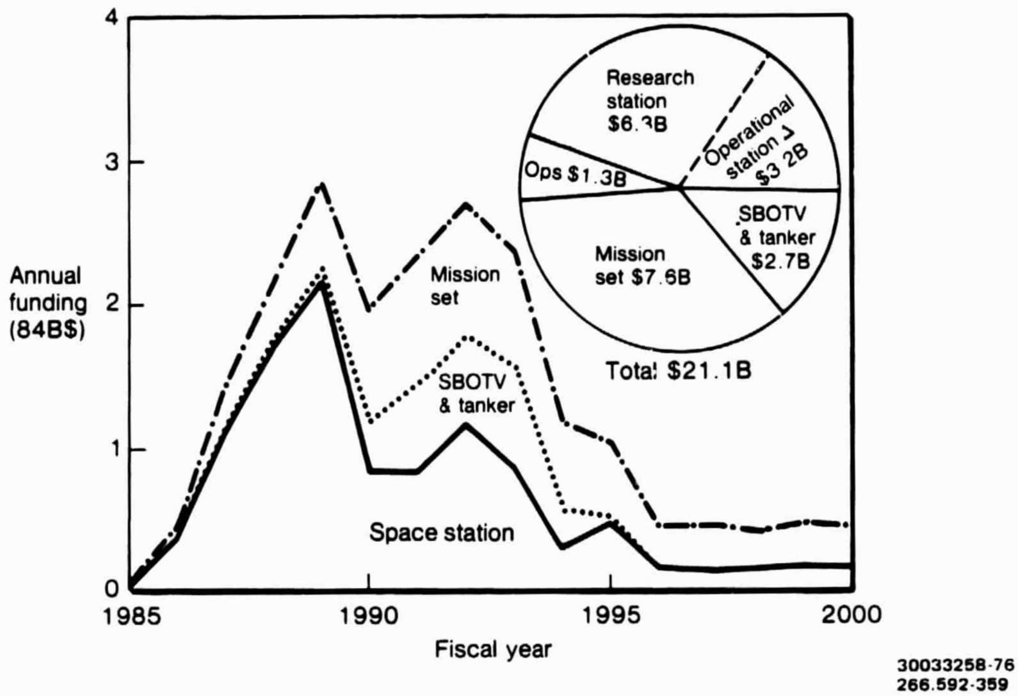

Figure 4-6. Baseline Station Funding Profile

The recommended Space Station system program is shown in Figure 4-7 in the context of the total NASA budget, including the full mission set, STS flight operations, and other components of the NASA budget. The funding peak for this program is approximately $8.5 billion, occurring in the early 1990s.

The schedule accompanying this funding program is shown in Figure 4-8, for space and ground facilities, and STS vehicles.

As illustrated in the summary of economic benefits, Section 4.1 and Figure 4-5, the economic payback period for this baseline program is approximately 12 years from the initiation of Space Station operations.

4.3 PROGRAMMATIC ANALYSIS

Our study of Space Station programmatics focused on the potential for partnership between the Government and private industry in implementing a Space Station program. We considered both Government program requirements and industry investment criteria, and developed several options for joint Government-industry programs.

The criteria used by the private sector to evaluate program opportunities are focused on economic return considerations such as investment level, investment recovery, and investment horizon. Also, industry investment criteria are sensitive to the degree of market, financial, technical, and institutional risk in a venture, which pose significant barriers to private investment in a Space Station project.

A number of alternative options for cooperation between the Government and private industry were considered, with the goal of identifying program strategies which could meet both public and private sector investment requirements.

Establishment of an industrial Space Development Corporation (SDC), which would operate a Space Station utility core for profit was determined to be a possible program option. The SDC would lease utility services to other industrial firms, who in turn would establish separate Space Station elements, possibly through Joint Endeavor Agreements with NASA, and sell their services to Space Station users.

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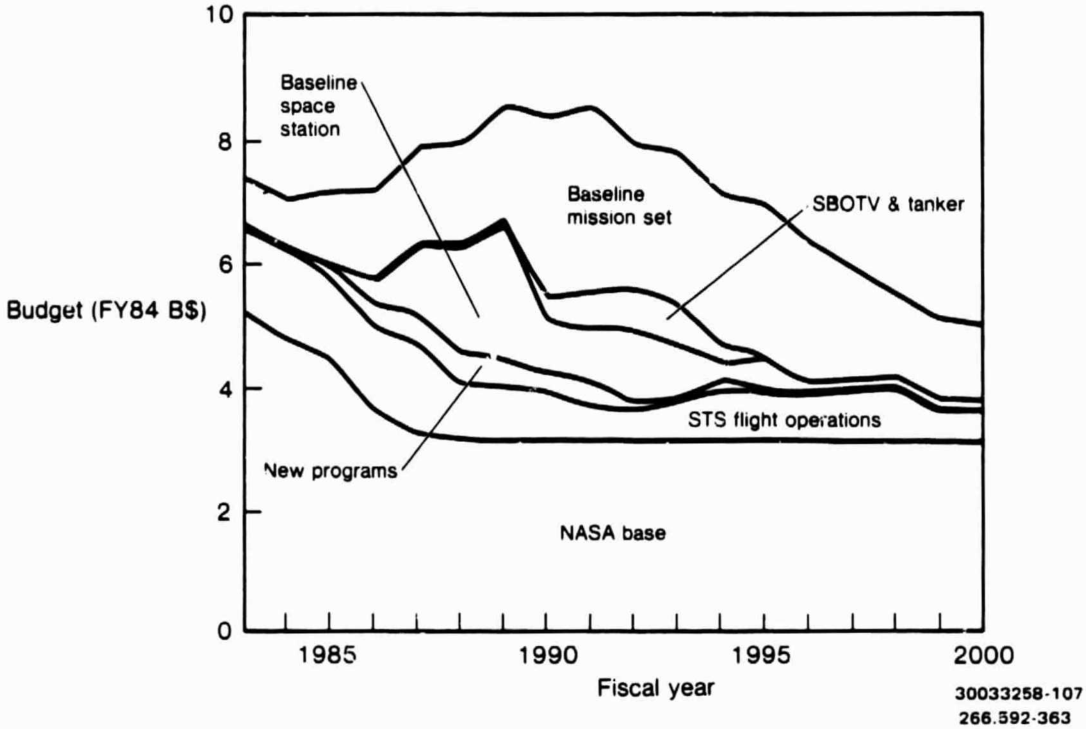

Figure 4-7. NASA Budget Profile and Station Program

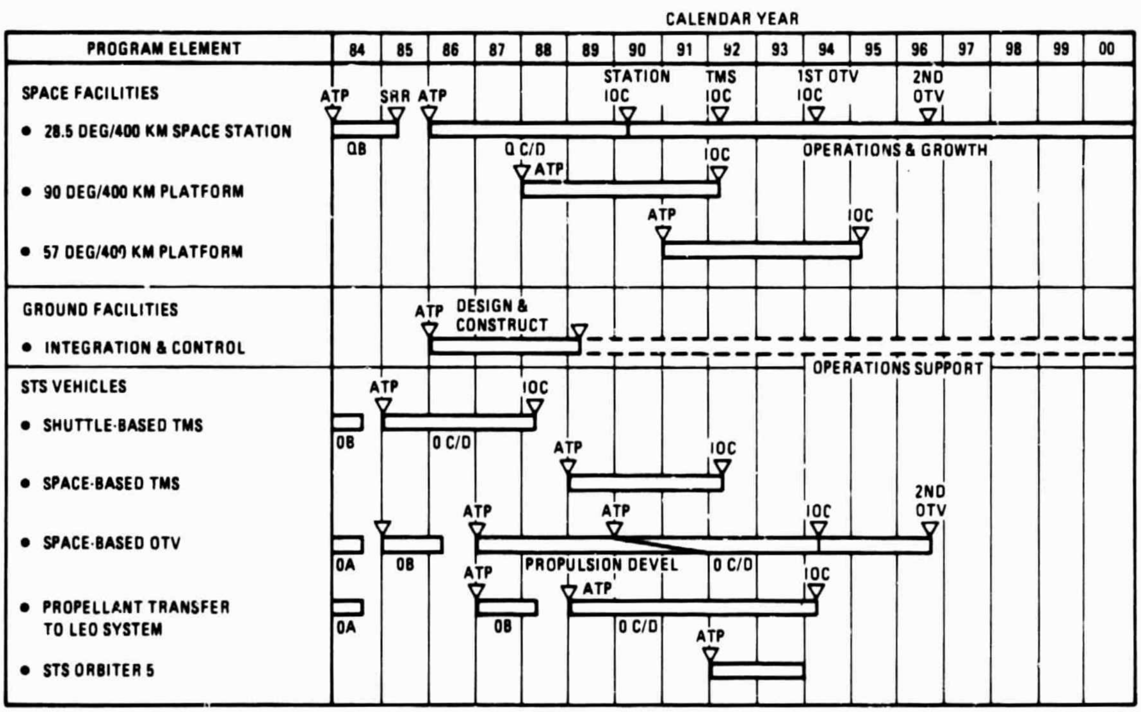

Figure 4-8. Baseline Station Program Schedule

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An alternative approach to Space Station development and operation, with an even greater degree of private sector involvement, was developed and is presented in our "Space Staton Prospectus", (Appendix I to Volume II Book 3). This fictitious prospectus was produced to illustrate how a Space Station enterprise could be initiated by a hypothetical company, Consolidated Space Enterprises (CSE), which would form a series of subsidiary companies (Figure 4-9) each one responsible for development and operation of a separate Space Station capability, as the market for it's particular service matured. CSE would retain general partnership in each subsidiary and sell shares of each to other interested companies and investors.

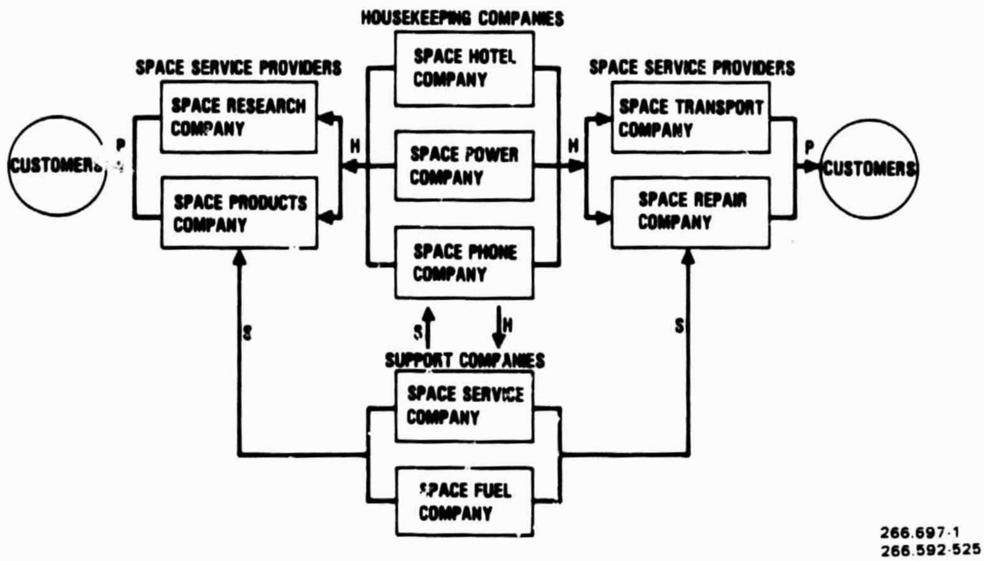

Figure 4-9. Interaction of Subsidiary Companies of CSE - (From Space Station Prospectus)

For example, a CSE subsidiary referred to in the prospectus as Space Hotel Company would develop Space Station habitat modules and life support systems, and would charge rent to all Space Station residents.

The conclusion of the programmatic analysis was that private sector investment in Space Station development and operations is indeed feasible, given proper sensitivity on the part of the Government to industry investment requirements and expectations. Based on the economic benefits analysis, the profit potential of the Space Station was shown to be substantial, but Government involvement in such a program to help reduce investment barriers was determined to be a practical necessity if near-term industry commitment to such a program is a desired objective.