APRIL 1983

MDC H0538

SPACE STATION NEEDS, ATTRIBUTES, AND ARCHITECTURAL OPTIONS

Technology Development

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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CONTRACT NO. NASW-3687

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PREFACE

The McDonnell Douglas Astronautics Company has been engaged in a study for the National Aeronautics and Space Administration to determine Space Station needs, attributes, and architecture. The study, which emphasized mission validation by potential users, and the benefits a Space Station would provide to its users, was divided into the following three tasks:

Task 1: Mission Requirements
Task 2: Mission Implementation Concepts
Task 3: Cost and Programmatics Analysis

In Task 1, missions and potential users were identified; the degree of interest on the part of potential users was ascertained, especially for commercial missions; benefits to users were quantified; and mission requirements were defined.

In Task 2, a range of system and architectural alternatives encompassing the needs of all missions identified in Task 1 were developed. Functions, resources, support, and transportation necessary to accomplish the missions were described.

Task 3 examined the programmatic options and the impact of alternative program strategies on cost, schedule and mission accommodation.

This report, which discusses technology development, was prepared for the National Aeronautics and Space Administration under contract NASw-3687 as part of the Task 1 activities.

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Section 1
INTRODUCTION AND SUMMARY

Technology development missions will develop advanced space station capabilities by providing on-orbit testing of (1) technology for space station growth applications and (2) generic mission and payload equipment for future mission applications. Space station growth applications are defined in this report as subsystem technology; future mission applications, as mission technology.

The initial technology development mission input was compiled from a NASA mission data base and the MDAC mission data base. About 75 missions, which had some overlapping objectives, some inadequately defined objectives, and a mixture of high-value and low-value objectives, were included. This original data base was refined to these 14 missions that fulfill the criteria of important future capabilities:

- Large Structure - Construction
- Large Structure - Control
- Fluid Storage and Management
- ECLS H_2O Recovery
- ECLS O_2 Recovery
- Satellite Service Technology
- OTV Service Technology
- Crew Manipulator/Robotics
- Evaluation of Man's Role
- Advanced Technology Radiator
- Materials and Coating Technology
- Zero-g Antenna Range
- Laser Communications and Tracking
- Tether Dynamics

These missions are not necessarily the only important missions, but they are representative of high-value missions and associated requirements. Figure 1-1, a portion of the mission data base, shows the pertinent data for each of the 14 missions.

FIGURE 1-1.
TECHNOLOGY DEVELOPMENT MISSION SUMMARY

VGD967

SPACE STATION DATA BASE
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Apr.14, 1983

STATUS
O=operational
P=planned
C=candidate
I=opportunity

ACCOMMODATION
R=required S=supply
D=desired L=launch
A=acceptable M=maint/repair
R=assemb/build

VIEW
A=any M=multiple
E=earth S=solar
I=inertial V=velocity
Z=anti earth

LEGACY
S=spacelab
O=other legacy

CODE	NAME	VEHICLE	STAT	DATE	DUR	INC DEG	INC MAX	INC MIN	ALT DES	ALT MAX	ALT MIN	STAT PLAT	SERV MOD	RACK	PAL	PORT	POWER	DATA	DUTY	POWER *DUTY	LMASS	EXPEND	G
TFM001	LASER COMM&TRACK DEV	MH	I	92	1	28	97	0	400	999	300	R		0	.5	1	1000	10	.05	50	200	0	0
TGN001	LSS CONTR EXP	MH	C	93	1	28	90	0	400	999	300	R		0	2.0	1	500	0	.02	10	600	0	0
TGN002	ZERO G ANT RANGE	MH	I	92	1	28	90	28	400	999	300	R		0	2.0	1	1000	1	.04	40	1000	0	0
TGN003	MATERIALS&COAT TECH	MH	I	92	5	28	97	28	400	600	300	D	M	0	1.0	1	200	0	.01	0	1400	0	0
TGN004	TETHER DYNAMICS	MH	C	94	1	28	97	0	400	600	300	R		0	.5	1	1000	0	.01	10	250	0	0
TGN005	LRG STRUCT CONSTR	MH	C	94	1	28	57	28	400	999	350	R		0	2.0	1	500	1	.03	15	600	0	0
TGN006	FLUID STORE&MANAG	MH	C	92	1	28	97	28	400	999	300	R		0	3.0	1	500	0	.02	10	9000	0	0
TGN007	LIQUID DROPLET RAD	MH	I	94	1	28	97	0	400	999	350	R		0	.5	1	200	0	.01	2	400	0	0
TGN008	ECLS WATER REC	MH	C	93	1	A	97	28	400	700	370	R		1	.0	0	150	10	.01	2	80	0	0
TGN009	ELCS OXY REC	MH	C	93	1	A	97	28	400	700	370	R		2	.0	0	500	10	.01	5	100	0	0
TOP001	SATELL SERV TECH	MH	P	92	1	28	90	28	400	999	300	R	SS	0	.0	1	1000	0	.05	50	500	0	0
TOP002	OTV SERVICE TECH	MH	P	92	1	28	90	28	400	999	300	R		0	3.0	1	1500	0	.05	75	500	0	0
TOP003	CREW/MANIP CONT	MH	C	93	1	A	97	28	400	700	370	R	L	1	1.0	1	150	10	.06	9	550	0	0
TOP004	MAN ROLE EVAL	MH	O	92	1	A	90	28	400	700	370	R		1	.0	0	50	5	.03	2	100	0	0
TOTALS ARE:																	8150	47			15280		
NUMBER OF MISSIONS:	14																						

CODE	VIEW	CREW SIZE	HRS (G)	DAYS YR	SKN		SAVE CONS	SAVE RISK	BENE SAVE CONS	BENE SAVE RISK	PRIORITY	EVA OPS	SPACE STAT IMPORTANCE
TFM001	M	2	3.00	20	14	4	28	23	56	644	4.00	12	10
TGN001	A	1	1.00	30	18	4	28	24	72	672	3.00	6	10
TGN002	[illegible]	2	8.00	10	21	5	25	25	105	625	2.00	[illegible]	10
TGN003	A	2	4.00	10	15	4	32	26	60	832	4.00	240	5
TGN004	E	2	4.00	30	16	4	31	24	72	744	3.00	0	10
TGN005	E	3	8.00	60	21	5	23	24	105	552	1.00	10	10
TGN006	A	1	4.00	30	17	4	28	24	68	672	1.00	4	10
TGN007	A	1	4.00	30	15	4	32	23	60	736	4.00	10	10
TGN008	A	1	.15	180	14	5	33	25	70	825	2.00	0	10
TGN009	A	1	.14	180	18	5	29	22	90	638	2.00	0	10
TOP001	A	2	8.00	60	19	5	26	25	95	650	1.00	20	10
TOP002	A	2	4.00	60	18	5	26	23	90	598	1.00	20	10
TOP003	A	2	4.00	60	18	4	29	23	72	667	3.00	8	10
TOP004	A	1	1.00	260	22	5	30	26	110	780	1.00	0	10

Technology Missions

Duty Cycle for Power

Number of EVA Operations

Operating Power (W)

Importance of Space Station On Scale of 1-10

No. of Attach Points

Note: All Technology Missions are attached to the Space Station Except TGN003. It Would Be on a Platform or Dedicated Satellite and is Only Candidate for Transportation Node.

Internal Volume
SS-Small Spacelab Module (Equiv)
Racks-Spacelab Equipment Rack (Equiv)

Crew Time
(Crew Size) x (Hrs/Day) x (Days/Yr)
= Man-hours/Year

Based on the space station program drivers, 9 of these 14 missions relate to subsystem technology drivers (Figure 1-2); the primary requirements those missions impose on the space station are shown. Similarly, 8 of the 14 missions relate to mission technology drivers (Figure 1-3); space station requirements imposed by these missions are shown. The space station requirements are defined later in this report.

Three missions (Evaluation of Man's Role, Large Structure - Construction, and Large Structure - Control) are duplicated on Figures 1-2 and 1-3 because they are included in both the subsystem and mission categories. For simplicity, Evaluation of Man's Role is discussed as a part of the mission technology category, and the two large space structure missions are discussed as a part of subsystem technology.

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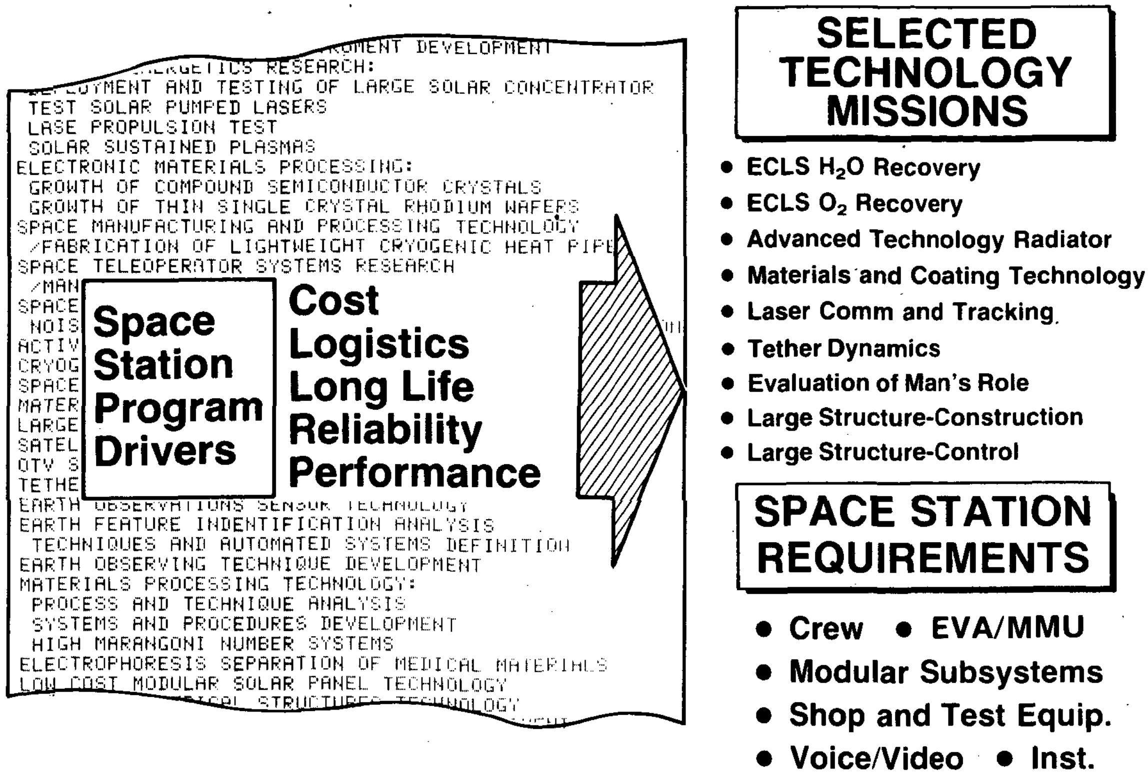
FIGURE 1-2.

TECHNOLOGY DEVELOPMENT IN ORBIT

VGB661

SUBSYSTEM TECHNOLOGY



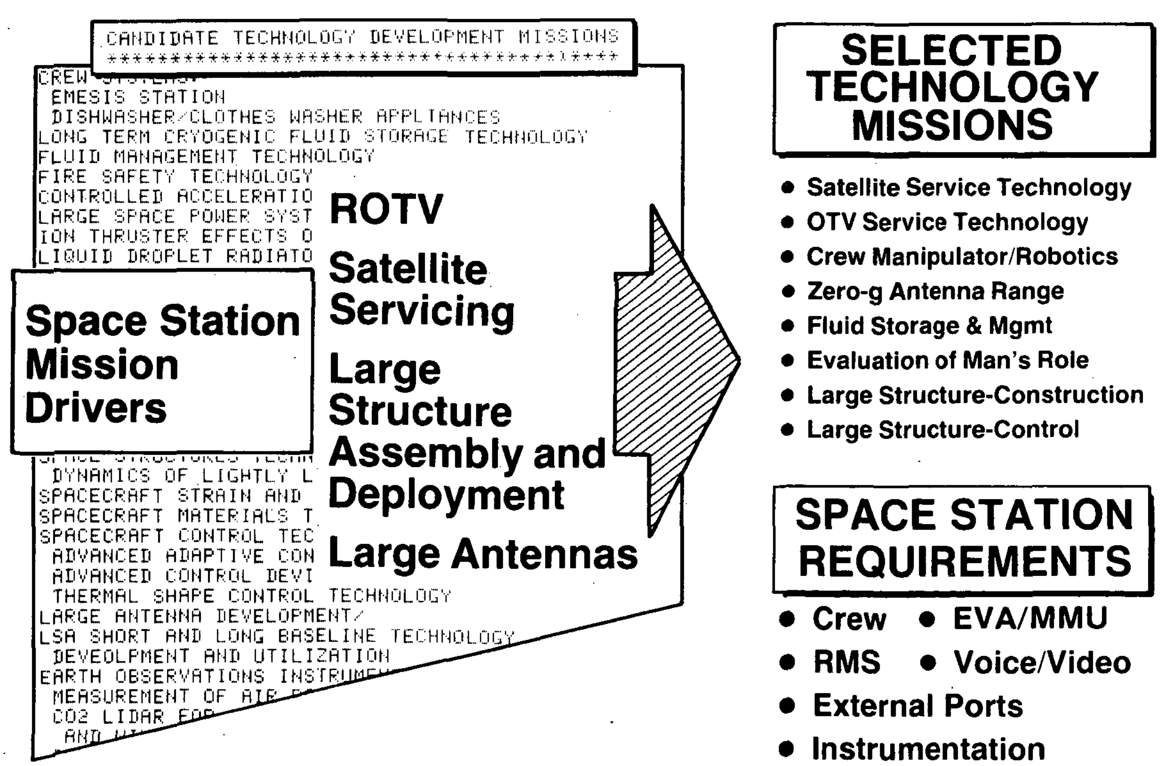
MCDONNELL DOUGLAS

FIGURE 1-3.

TECHNOLOGY DEVELOPMENT IN ORBIT

VGB660

MISSION TECHNOLOGY



The EVA Capability Technology mission is also described in this report. Although the development of EVA capability is vital to the success of the space station, the mission is not included in the tabulations because it can be accomplished on the Shuttle; therefore, it does not require a space station mission. From a schedule standpoint, it is desirable that this development be done on the Shuttle because the results will be a major determinant in allocating tasks between EVA and various levels of automation using either manipulators or robotics.

The technology selected for the final space station configuration may obviate some of these missions. Until the systems engineering work has been done to define the station concept, these missions, particularly the subsystem technology missions, can only be considered tentative.

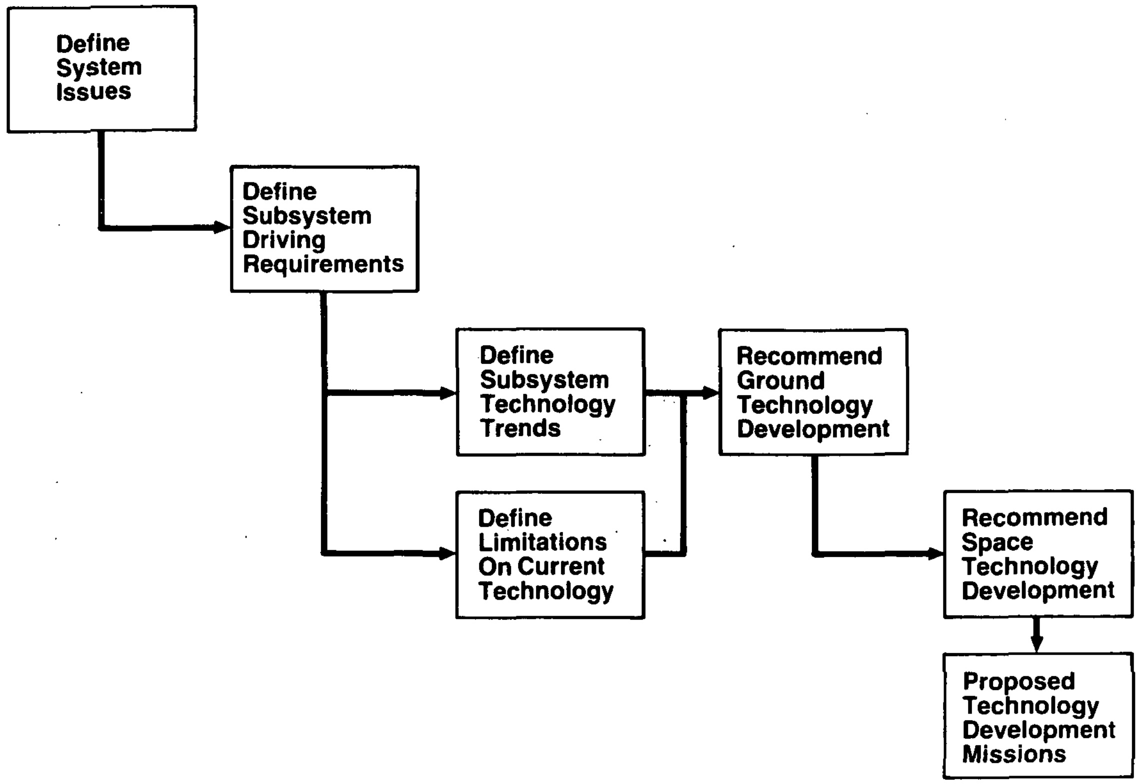
Section 2
SUBSYSTEM TECHNOLOGY TRENDS

The approach used to refine the missions from the original 75 candidates to the final 14 is shown in Figure 2-1. The analysis started with the identification of the key system issues and proceeded to the subsystem drivers related to those system issues. The subsystem trends and technology limitations were identified and related to these subsystem drivers to determine the important developments needed.

In the normal system engineering process, the space station concept definition study would be used to guide the selection of the most appropriate subsystem technology level. From the study, the critical technology

FIGURE 2-1.
TECHNOLOGY DEVELOPMENT METHODOLOGY

VGD966



developments would be highlighted, in turn indicating the critical technology development missions, particularly the subsystem technology missions. Because of the relative timing of the technology activity vis-a-vis the system engineering effort on this program, the concept definition has not yet caught up with the technology work. This shortcoming is indicated by an ECLS trade study (see Section 2.3) showing how the technology development missions might be affected by the system engineering.

The subsystem breakdown used in this analysis is the same one used in the MDAC Space Station Systems task (Task 2 of the study):

- Power
- Data management
- Environmental control and life support
- Thermal control
- Structure and material
- Attitude control system
- Communications and tracking system
- Mechanism technology
- Auxiliary propulsion

The subsystems are discussed in the order shown. For each subsystem, the technology trends for both the initial and the growth space stations are divided into three groups: existing hardware, current hardware, and advanced hardware.

Technology approaches in the existing-hardware category conform to technology maturity Level 8 as defined by Carlisle and Romero.[1] Level 8 is "operations," which is interpreted to mean operational space usage of the candidate hardware, perhaps in a different size but in a similar application.

Technologies in the current-technology category are judged to be in the range of Level 4 to Level 7, depending on the item. The strongest candidates for the initial space station are found in the current-technology list,

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[1]Carlisle, R. F. and Romero, J. M., "Space Station Technology Readiness," presented at the ASME Winter Annual Meeting, Phoenix, Arizona, November 17, 1982.

although some existing hardware items are also good candidates. Also, it is possible that some of the advanced-technology items may be ready when final selections for the initial station occur (about 1986). The bulk of the technology development effort for the next few years will focus on the current-technology items.

Technologies in the advanced-technology category (Levels 1-3) are relatively poorly understood now and are primarily candidates for the growth space station (technology readiness approximately 1992). Any hardware technology concepts in this category should be compatible with the corresponding current-technology approaches so they can economically serve as a system upgrade.

2.1 ELECTRICAL POWER SUBSYSTEM

The factors that relate to the electrical power subsystem (EPS) technology include EPS technology drivers, technology trends, and technology development issues related to high-priority candidate technologies for the growth space station.

2.1.1 Power System Technology Drivers

Table 2-1 summarizes the key requirements that drive EPS technology and relates these drivers to the key space station system issues. Many of the driving requirements impact several system issues. These requirements are listed under the most significant issue as follows:

Table 2-1. Power System Technology Drivers

System issues	Driving requirements
Life-cycle cost	• Improved efficiency - reduce area and drag • Long life, maintainable, low-weight and low-volume energy storage, solar array, and array gimbal • Packaging--maximum array per Shuttle payload
Mission capture and performance	• Power capability--average, continuous, and peak (limited solar array launch size and shape and energy storage) • Space station attitude requirements, array gimbal capability
Safety	• Refuge emergency power capability • Minimize, isolate explosive and toxic energy storage devices
Growth Potential	• High-capacity distribution system in all modules

A. Improved system and solar array efficiency reduces the required solar array area, which reduces life cycle cost via array production cost and reduced propellant logistic cost for drag makeup.

B. Long-life, low-weight, and low-volume EPS components reduce production and transportation costs for replacement; ease of maintenance reduces the operations components of life-cycle cost.

C. Array packaging is important because it requires a long cargo bay, thus limiting the power output of utility modules that can be launched in a single package and leading to high transportation cost.

The system power output capability (steady-state average and, to a lesser extent, peak power) is the principal system requirement that affects mission capture and performance. Power output capability is limited by solar array size and shape and by energy storage capacity. Space station array gimbal requirements and capabilities may have a significant effect on power output and on accommodation of pointing or viewing payloads.

The ability to provide power in emergency situations can have a significant impact on safety. In addition, batteries and regenerative fuel cells can rupture or explode and release hazardous KOH; safety is dependent on proper location, isolation, and usage.

An oversized (high-capacity) distribution system is required in all modules of the initial space station to allow for station and power growth, thus impacting distribution system type and voltage selection.

2.1.2 EPS Technology Trends

A summary of candidate technologies for the initial and the growth space station is presented in Table 2-2. Some of the functions listed in the table are further described as follows:

A. Power Generation (Primary). The largest flight-proven solar arrays were part of the Skylab program (Orbital Workshop and Apollo Telescope Mount arrays). Rigid arrays of this type would impose severe penalties on weight and packaging volume for power levels needed by the space station. Hence, the PEP and Space Platform flexible substrate planar solar arrays under development by NASA OAST/MSFC/JSC for the past 10 years is badly needed. Continuing development and flight certification of this technology is vitally important.

Table 2-2. Power System Technology Trends (Page 1 of 2)

Function	Existing Hardware (Level 8)	Current Technology (Levels 4-7)	Advanced Technology (Levels 1-3)
Power generation			
Primary	Skylab rigid panel array Orbiter fuel cell power (FCP) plant	Flexible planar array (5.9 cm, 6- to 8-mil cells, coilable mast)	Advanced, compact, flexible planar array Concentrator array - Cassegrainian - Low concentrator ratio Reactor thermoelectric Solar Brayton
Emergency	Primary system - modular, graceful degradation Distributed or small array system Orbiter FCP (gaseous or supercritical H_2/O_2)	Improved orbiter FCP (subcritical H_2/O_2)	
Power transfer gimbal	Coiled cable Small slip rings	Large, maintainable slip or roll rings	Large, maintainable rotary transformers

Table 2-2. Power System Technology Trends (Page 2 of 2)

Function	Existing Hardware (Level 8)	Current Technology (Levels 4-7)	Advanced Technology (Levels 1-3)
Energy storage	50 A·h NiCd battery	H_2/O_2 regenerative fuel cells (RFC; SPE or alkaline; approximately 55% efficiency)	H_2/O_2 RFC (approximately 65% efficiency)
			Bipolar NiH_2 battery H_2/Br RFC (approximately 75% efficiency)
		NiH_2 battery (e.g., approximately 50 A·h, IPV)	Momentum wheels (composite; magnetic bearings)
Power conditioning	Shunt-array taps	Shunt, switched mode	Resonant
	Buck, switched mode	Buck, TCC, and CUK switched-mode series regulation (advanced components and designs)	Very high frequency Series regulator with array voltage limiter
Power distribution and control	28 VDC	140 $\pm$30 VDC or 220 $\pm$ 50 VDC	High-frequency AC
	400 Hz feeders	60 Hz feeders	Solid-state switching
	Mechanical switching	New I-V sensors	Standard user power conversion modules
Power management	Central control On-off switching	Autonomous microprocessor control (emergency manual intervention)	Expert system (minor manual intervention) Data bus hierarchy
		Spacecraft data bus link	

Silicon solar cells (5.9 by 5.9 cm, 6 to 8 mils thick) are an appropriate low-cost, current-technology choice for 1986 readiness; 2- by 4-cm cells, or those of an intermediate size, are also candidates. The current coilable longeron mast, perhaps with minor improvements, is appropriate. Development of an advanced array of this type, with more compact and suitable launch packaging, should be pursued for the growth space station (see the advanced-technology column in the table). Concentrator arrays are also a growth station candidate, along with the solar Brayton cycle and the SP100 reactor thermoelectric system.

B. Power Generation (Emergency). Power source and power distribution system modularity may provide graceful degradation to an extent sufficient to preclude the need for a separate emergency system; alternatively, a small solar array system or a fuel cell system associated with one of the emergency refuge areas should suffice. There is no strong need for technology development effort to support the function.

C. Power Transfer Gimbal. The prime candidates for a DC system in the initial station are coiled cables, slip rings, and perhaps roll rings; rotary transformers are an additional candidate for an AC system.

D. Energy Storage. The 50-A•h NiCd battery, which has developed to NASA standard battery specifications, is currently flying on the Multimission Modular Spacecraft (MMS, e.g., Landsat D); this battery is a candidate for the initial space station, along with the current technology options. Other candidates for the initial space station include H_2/O_2 fuel/electrolysis cells (regenerative fuel cells) and NiH_2 batteries; fuel cell options include the General Electric solid polymer electrolyte (SPE) and the United Technologies alkaline cells. The existing hardware can be assembled into a system by about 1986; storage efficiency will be about 55%, which can likely be improved to about 65% for the growth station.

Individual pressure vessel (IPV) NiH_2 batteries (50 to 100 A•h), and perhaps common pressure vessel (CPV) batteries, are also candidates for the initial station; the bipolar NiH_2 battery is a good candidate for the growth station. The H_2/bromine fuel cell with its high efficiency, and perhaps momentum wheels (e.g., composite wheels with magnetic bearings), are also growth station candidates.

E. Power Conditioning. The buck, switched-mode series regulator with peak power tracking was used on Skylab as an array voltage regulator and battery charger. The NASA standard power regulator unit (SPRU) used on MMS is a higher power, more modern unit of this type, as is the MSFC P^3 concept. The current P^3 approach is an initial station candidate for battery charging and voltage regulation, along with the switched-mode shunt and improved (components and designs) switched-mode series units, i.e., buck, transformer-coupled (TCC), and CUK.

F. Power Distribution and Control. Current systems (e.g., the Orbiter system) use 28-VDC systems with some 400-Hz AC as required. The prime candidate for initial station power transmission involves DC distribution at battery charge/discharge voltage (140 $\pm$ 30 V or 220 $\pm$ 50 V, considering array plasma and component limitations and system architecture). Also employed will be 28-V, 400-Hz, and perhaps 60-Hz local feeders. High-frequency AC is perhaps a candidate for growth stations.

2.1.3 EPS Technology Development Issues

Table 2-3 is a summary of high-priority technology development issues for the growth space station (advanced technology column of Table 2-2). These issues include the following:

A. Advanced, Compact, Flexible, Planar Solar Array. The primary need in this area is a short, compact mast (stowed); such a mast would permit higher aspect ratio arrays and improved packaging in the Orbiter cargo bay.

B. Concentrator Solar Array. Development of an array capable of deployment and retraction and compact packaging on a utility module in the cargo bay are particularly important for these arrays. Low-earth-orbit life and end-of-life efficency are also significant issues.

C. H_2/O_2 Regenerative Fuel/Electrolysis Cells (RFC). Demonstration of life, reliability, and performance under realistic LEO duty cycles; storage efficiency; and system-upgrade compatibility with the current-technology RFC system are the key issues. Verification of zero-g operation may be needed, depending on the specific fuel cell and electrolysis cell approaches selected. Gaseous O_2 and gaseous H_2 storage volume is a concern, and efficient operation at higher pressures should be pursued.

D. Bipolar NiH_2 Battery. Development issues are similar to those for the RFC.

E. H_2/Bromine RFC. Issues are also similar to those for the RFC.

Table 2-3. High-Priority Power Technology Development Issues

(Growth Space Station)

Candidate approach	Development issues
Advanced, compact, flexible, planar solar array	• High aspect ratio (short mast canister);** efficient, low-cost, thin, large-area cells and covers/superstrates;* improved blanket* and mast** life
Concentrator solar array	• Low-volume packaging, deployment, retraction;** efficiency, optical degradation (space/mission environment);* thermal cycles, life;* alignment and thermal distortion;* array, mast dynamics;** low cost
H_2/O_2 regenerative fuel/ electrolysis cell (RFC)	• RFC system efficiency, volume, and transient response to large load change. LEO orbit life and reliability at increased temperatures and pressures with realistic duty cycles; verify zero-g electrolysis*
Bipolar NiH_2 battery	• Battery system life, efficiency, reliability, DOD, and temperature relationships; zero-g verification;** safety
H_2/bromine RFC	• System efficiency and transient response; life and reliability with realistic duty cycles; zero-g verification**
Solid-state switching	• Device development; system architecture implications
Expert system for power management	• Software/hardware architecture for artificial intelligence

*Small-scale space test candidate
**Full-scale space test candidate

In summary, although several EPS technology candidates were identified, none were believed to have sufficient impact on the space station to warrant their being a technology development mission.

2.2 DATA MANAGEMENT

The data management subsystem includes all the data functions up to communications. The technology drivers are listed in Table 2-4. Of the technology drivers listed, two categories are dominant--those associated with data storage and handling and those associated with automation and the role of the crew.

Table 2-4. Data Management Technology Drivers

System issues	Driving requirements
Life-cycle costs	Automation ground or space (autonomy) Software cost and schedule Standard user interface
Performance	Mass data storage and high-data-rate input/output Low error rates
Long life and reliability	Fault tolerance Space radiation tolerance
System growth and flexibility	Modular design Onboard data base size, access Onboard integration

Data storage problems arise from the large quantities of data and the associated high data rates generated by some of the missions, primarily in the science and applications category. These data, which must in many cases be stored prior to transmission, demand higher storage capability than that currently available. Coupled with this is the requirement (in some cases) to read data out at the 300-Mbps rate of the tracking data relay satellite, using that satellite efficiently. Mass data storage and the associated high-date-rate input/output, which are considered limiting technologies for efficient conduct of the space station science missions, will be discussed later in the report.

The other technology drivers, those associated with the role of the crew, are important because automation (particularly the software) and support for the crew, life systems, power, etc., are costly. Therefore, it is important that the crew be used effectively, by carefully selecting the tasks to be performed and the degree of associated automation.

Table 2-5 lists the technology trends, based on the technology drivers, for the key functions associated with data management. The table also reflects the advanced-technology needs in data storage and system autonomy/automation. These needs for the entire end-to-end data system are summarized below.

- On-board mass data storage
  - Communications buffer
  - Data archive
- Ground-based mass data storage
- Reconfigurable controls and displays
- Automation/autonomy techniques
  - Expert systems
  - Automated subsystems management
  - Automated mission planning and scheduling
- Software languages and development tools
- Advanced space-to-ground communications

With the exception of the advanced communications capability discussed in Section 2.7, all technology needs can be developed on the ground. None require technology development missions per se. However, the decisions about what functions to automate and how to do it are related to the technology development missions, particularly Man's Role in Space, EVA Capability Technology, Crew/Manipulator Controls, Fluid Storage and Management, OTV Service Technology, and Satellite Servicing Technology missions.

2.3 ENVIRONMENTAL CONTROL AND LIFE SUPPORT (ECLS)

The ECLS system comprises all the components necessary to support the vital functions of the crew. The technology drivers for this system are shown in Table 2-6. The drivers that impinge on the technology development missions are the improved EVA and robotics capabilities related to mission technology and the recycling fluids related to subsystem technology.

Table 2-5. Data Management System Technology Trends

Technology item or function	Existing (Level 8)	Current Technology (Levels 4-7)	Advanced Technology (Levels 1-3)
System autonomy	Sequence storage	Fault tolerance	Learning systems
	Safe-hold	Autonomous Navigation	Internal reprogramming
Radiation tolerance	10^5 rads for MSI		10^6 rads - VLSI
Data bus	Twisted pair 1 Mbps rate	Twisted pair 8 Mbps rate	Fiber optic
Higher order language	HAL-S Jovial	HAL-S Jovial	ADA
Mass data storage	Tape recorder Capacity: 10^9 - 10^{10} Rate: 32 Mpbs	Improved tape recorders	Bubble memories Optical disc memories Modular computer memory
Displays	CRT	CRT with user reconfigurable software	Plasma displays LCD displays
Voice synthesis and recognition		Limited voice synthesis	Extended synthesis and recognition
Generic microprocessors		MIL-STD-1750A	Advanced 16- and 32-bit generic microprocessors

Table 2-6. ECLS Technology Drivers

System issues	Driving requirements
Reduced life-cycle costs	Automated subsystem controls
Increased ECLS performance	Recycle fluids
Improved crew performance	Improved EVA capability Improved robotics capability
Safety	Reduced toxicity and flammability of materials

Table 2-7 summarizes the technology trends for the major ECLS functions.

Since the MDAC baseline configuration is the current technology level, there are a number of potentially desirable upgrades to the system identified as advanced-level technology. In essence, these upgrades consist of closing the oxygen loop and completing the closure of the water loop to include urine, and developing an improved-mobility 8-psia suit for EVA.

The lack of crew activity during the prebreathe period is a cost penalty. The 8-psia suit is one solution to the problem, since it requires a shorter prebreathe period than that for the 5-psia suit currently available. Further studies, which should be included in the space station systems studies, may yet find other solutions. Pending results of such studies, however, MDAC recommends the 8-psia suit.

A trade study of the development of an advanced ECLS system should also be included in the space station systems studies. Figure 2-2 shows some results of a preliminary study. Shown is the relative cost of both the current and advanced ECLS systems. The initial cost of the current system is about 75% of the advanced system, but it has higher resupply costs because of the need for more gas and water supply. The cost of the current system surpasses that of the advanced system in 7 to 11 years, depending on the cost of the advanced system relative to the current and assuming that the advanced system is selected instead of the current for the initial space station. Selection of the advanced system entails more technical, cost, and schedule risk. Since it may take as long as 11 years to break even, such risk may not be considered worthwhile.

Table 2-7. ECLS Technology Trends (Page 1 of 2)

Function	Existing (Level 8)	Current technology (Levels 4-7)	Advanced technology (Levels 1-3)
Atmosphere supply			
O_2 supply	High-pressure storage Supercritical storage	High-pressure storage Supercritical storage Solid polymer water electrolysis with Sabatier CO_2 reduction	Static feed water electrolysis with Sabatier CO_2 reduction (1987) or with Bosch CO_2 reduction
N_2 supply	High-pressure storage Supercritical storage	High-pressure storage Supercritical storage	Hydrazine dissociation
Atmosphere Revitalization			
Temperature and control	Condensing HX with slurper	Condensing HX with slurper Wall temperature control added	
CO_2 control	Replaceable LiOH Regenerative molecular sieve (dump)	Regenerative molecular sieve Solid amine system	Electro-chemical depolarized concentrator
Contaminant control	Bacteria filters Sorbent beds Catalytic oxidizers	Bacteria filters Sorbent beds Catalytic oxidizers	
Contaminant monitoring	CO_2 sensor Mass spectrometer	CO_2 sensor Mass spectrometer Gas chromatograph and mass spectrometer total gas analyzer (TGA)	Advanced TGA computerized interpretation

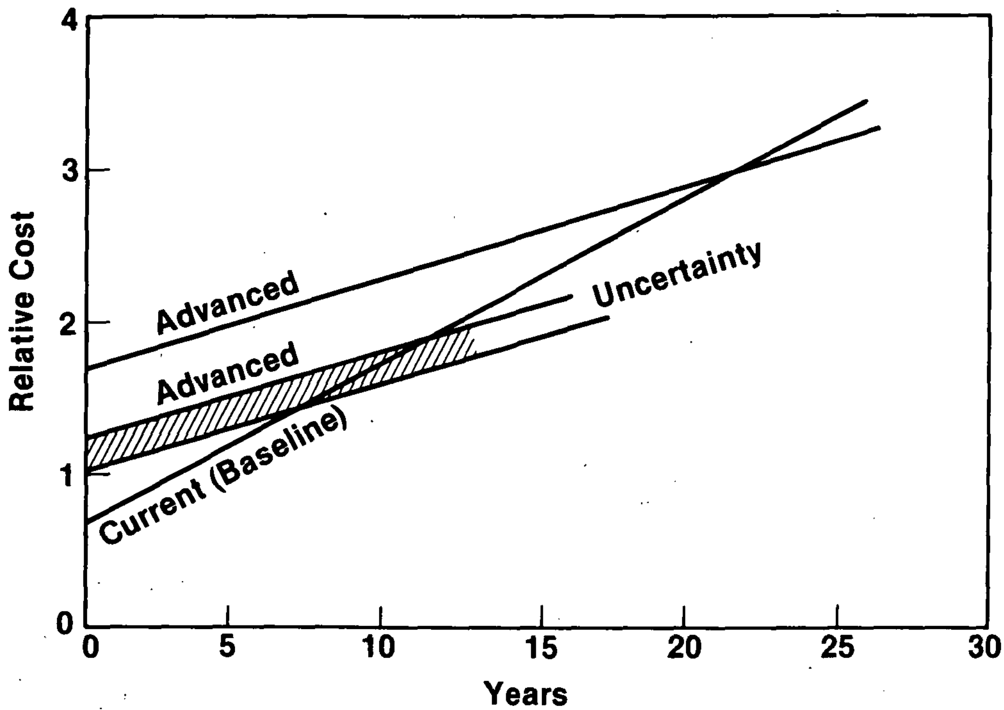
Table 2-7. ECLS Technology Trends (Page 2 of 2)

Function	Existing (Level 8)	Current (Levels 4-7)	Advanced (Levels 1-3)
Water Supply	Metal bellows storage tanks plus multifiltration recovery of condensate	Storage tanks plus recovery from condensate and wash water (VCD or TIME)	Vapor compression distillation (VCD) of urine
		Multifiltration for wash water	Thermoelectric integrated membrane evaporation (TIME) recovery system of urine
EVA/robotics support			
Suit	5-psia Orbiter	8-psia Orbiter	8-psia semihard
Mobility aids	Orbiter MMU	Orbiter MMU	Advanced MMU
Robotics			Manipulator control development
Waste Management			
Fecal handling	Orbiter slinger commode	Slinger commode with on-orbit liner replacement	Slinger commode with automatic fecal removal
Urine handling	Orbiter centrifugal separator with urine	Centrifugal separator with urine storage	Centrifugal separator with urine storage
Trash handling	Stowage with chemical deactivation	Stowage with vacuum drying and compaction	Pyrolytic incinerator

An alternative to choosing either the current or the advanced ECLS systems is to initially use the current system and to replace it later with the advanced system. If this advanced system had no carry-over from the current system, the breakeven point would move to 21 years after the installation of the advanced system. Such a long payback period would make this approach even more questionable. It is included to indicate the importance of performing system studies before selecting the subsystem technology level.

FIGURE 2-2.
ECLS COST TRADES CURRENT VERSUS ADVANCED

VGB396



If the results of an ECLS trade study indicate that the advanced technology should be pursued for a growth space station, then the development issues outlined in Table 2-8 need to be addressed.

2.4 THERMAL CONTROL

The thermal control system collects, transports, and rejects space station heat. The primary technology drivers for the thermal system are improved radiators and improved transport concepts (Table 2-9). Technology trends in the thermal functions are shown in Table 2-10. The critical advanced technologies are the advanced radiator, either heat pipe or liquid droplet, and the thermal bus, particularly the bus interface between modules. Of these two, the advanced radiator, since it is subject to the full space environment including solar and space radiation, contamination effects, etc., is the only one requiring a technology development mission on space station. The thermal bus operation can be developed in ground tests with possible Shuttle flights for verification.

Table 2-8. ECLS Development Issues for the Growth Space Station*

Candidate approach	Development issues
O_2 recovery from CO_2 - static feed water electrolysis and Sabatier CO_2 reduction, and electrochemical, depolarized CO_2 concentrator	Further prototype testing on the ECLS manned simulator to verify life, efficiency, safety, and maintainability Flight test of small integrated atmosphere revitalization system prototype to verify zero-g effects
Vapor compression distillation (VCD) for water recovery from urine	Further prototype testing of the ECLS manned simulator level to verify potability, efficiency, crew acceptability, and maintainability
Thermoelectric integrated membrane evaporation (TIME) water recovery from urine	Flight test of small prototype desirable to verify zero-g effects Select the most appropriate (VCD or TIME).
8-psia space suit	Further prototype testing to verify mobility, tactility, and work rate Flight test required to verify mobility and work rate in zero g
Waste management fecal collector with automatic removal and storage	A slinger commode with automatic removal and storage must be tested in a manned simulator to verify performance, safety, acceptability, and maintainability A flight unit with manned usage is required to verify zero-g effects

*Technology ready by 1992 for 1996 IOC.

Table 2-9. Thermal Control System Drivers

System issues	Driving requirements
Maximize life and growth potential	In-place refurbishment
	Modular design
Reduce life-cycle costs	Automatic thermal control
	Long-life, refurbishable radiator coatings
Improve thermal system performance	Improved heat collection and transport
	Combination cold-plate and structural mounting for cooled component
	Improved radiators (heat pipe, liquid droplet)

Table 2-10. Thermal Control Technology Trends

Function	Existing (Level 8)	Current (Levels 6-7)	Advanced (Levels 1-5)
Heat transport	Circulating water/ Freon 21	Single fluid (Freon E-1)	Heat pipes
Heat rejection	Fin-tube, silver-teflon	Extruded aluminum hybrid (heat pipe, fluid)	Heat pipe radiators
			Liquid droplet radiators
		Replaceable panels	Refurbishable coatings with reduced degradability
Heat collection	Brazed nonsupportive cold-plates	Extruded aluminum cold-plates	Thermal bus

2.5 STRUCTURES AND MATERIALS

The structures and materials technology drivers are shown in Table 2-11. The drivers associated with construction and control of large structures and long-term effects of the space environment relate most closely to the subsystem technology missions.

Table 2-11. Structures and Materials Technology Drivers

System issues	Driving requirements
Performance	High specific strength, stiffness, and damping
	Low or no outgassing
	Low space duration effects
	Resistance to thermal aging
Attitude control system performance	Optimum structural response stiffness and damping
Long, safe life	Conservative pressurized module design
	Large deployable structures
Low logistics cost	Automatic manufacture of outsized structures

To minimize weight and transportation costs, materials should have high structural efficiency. They should also possess a low coefficient of thermal expansion in order to minimize structural distortion in the Space Station cyclic thermal environment. The use of high-stiffness materials will minimize structural distortion, and materials with inherent damping are recommended in order to further minimize structural control problems.

All materials used on space station must be environmentally stable for at least 10 years, with a goal of 30 years. In order to reduce maintenance costs and overall life-cycle costs, materials will have to be resistant to space radiation and thermal aging/cycling environments. Outgassing will have to be limited to current satellite requirement levels and eliminated in the area of cold optics surfaces in order to prevent experiment degradation.

Table 2-12, which shows the structures and materials trends, indicates the need for metal matrix structures, deployable structures and antennas, and on-orbit fabrication.

Table 2-12. Space Station Structures and Materials Technology Trends

Technology	Existing level	Current level	Advanced level
Materials	Metals - Al, Ti, steel, invar	Metals - Al, Ti, steel, invar	Increased performance, survivable materials - metal matrix composites, carbon-carbon, ceramics
	Resin, matrix composites - graphite-epoxy	Resin-matrix composites - graphite-epoxy - graphite-polyimide	Long-life optimized thermal control coatings
	Low-maintenance thermal control coatings	Low-maintenance thermal control coatings	Long-life lubricants and seals
	Low-maintenance lubricants and seals	Low-maintenance lubricants and seals	
Structures	Primary modules - spacelab and Shuttle external tank	Technology for new space-station-unique primary module design	Space-station-unique primary modules
	Docking and berthing structures - Apollo-Skylab and ASTP	Design, development of "hard-docking" structures for all space station applications	Universal docking, berthing structures (advanced designs)
			Large deployable beams, trusses, and antennas
	Small deployable booms, masts, and antennas	Technology for module-mounted honeycomb or extruded radiator structures with meteoroid, space-debris bumper	Large erectable structures
	Rigid aluminum and advanced composite truss structures		Deployable radiator concepts (heat pipe or hybrid)
		Design and response analysis of a multi-body, modular initial space station	Liquid droplet radiators
			Design, analyze, and control large flexible structures (passive and active controls technology)
		Small erectable trusses	
		Small deployable beams and trusses	Automated on-orbit fab/assy of large structures
			Very large trusses and antennas

A critical aspect of large space structure design is control of these large structures. Large flexible space structures have dynamics and control requirements that must be met through advances in structural design and analytical methods. These requirements are summarized in Table 2-13.

To be reduced to a practical size for transport in the Orbiter's cargo bay, large space payloads must be efficiently folded, but they must maintain adequate stiffness to withstand launch loads and must be deployable once on orbit. These deployable payload components will by nature have a large number of joints. To provide accurate control and response of these structures, the joints must have well-defined structural characteristics (i.e., linear response).

Whether passive damping is incorporated at the joints or distributed throughout the structure, it is beneficial for reducing structural dynamic response to a variety of disturbances. It also reduces the amount of work that the active control system must supply.

Optical systems must be more rigid than other types of large space structures, because they have very stringent optical performance requirements. Structural deformation can cause line-of-sight error, image quality error, and jitter. Low damping results in high settling times. This type of structure, as well as others, may require a balanced approach of passive damping, active control, and isolation of onboard excitation sources.

To actively control the dynamic response of large flexible structures in space, viable control laws, capable of reducing the system's response to environmental and onboard disturbances, must be developed. The effectiveness of such control laws will depend to a large degree on placing sensors and actuators properly throughout the structure and on having accurate information about the dynamics of the structure interaction with the control system.

From these structure and material considerations, including dynamics and control, the development growth issues have been summarized (Table 2-14).

Table 2-13. Dynamics and Control Technology Drivers

Driving requirements	Impact
Deployment	Required to place efficiently compacted payload components into their operational positions
Efficient joint designs	Required for reliable deployment Improve structural response predictions
Passive damping	Improve effectiveness of isolation system Reduce structural control requirements
High optical performance	Minimize LOS error, IQ error, jitter, and settling time
Viable control laws	Reduce dynamic response to disturbances
Sensor, actuator placement	Maximize robustness of control system
Controls and dynamics integration	Dynamics of a large flexible space structure interact with its control system

Table 2-14. Structural Subsystem Structures Development Issues Growth Space Station

Candidate approach	Development issues
Metal matrix composite structural materials or other increased-survivability, high-performance materials	Design, analysis, fabrication and structural test and verification data base
Nonstructural materials Thermal control coatings Lubricants Seals	Very-long-life, highly reliable, optimized materials
Very large, flexible, low-frequency response structures	Capability to design, analyze and optimally control large structures - passive and active controls technology
	Capability to assemble large structures
	On-orbit fabrication and assembly
Very large, deployable, erectable trusses and antennas	Deployment complexity and risk, assembly cost, and achievement of structural performance requirements

2.6 ATTITUDE CONTROL SYSTEM

The initial space station configuration can be made compact and stiff enough to be controlled by conventional systems and components. However, when the space station is developed to its more advanced capability, its numerous experiments will require large flexible components that must be mounted on long, probably flexible booms.

The ability of control theory to encompass the use of arbitrarily distributed sensors and actuators is limited and requires further work. Precise knowledge of structural dynamics interaction with the control system, for large flexible space structures with many low-frequency modes within the bandwidth of the control system, is still essentially unknown. A space station with such large structures will introduce the technology drivers identified in Table 2-15.

Without this advanced control capability, it will not possible to build a lightweight growth space station. Therefore, the control system is a limiting technology for the space station. Limiting technologies are discussed in Section 2.10.

Table 2-16 identifies technology trends at the component level. Development of the advanced-technology components does not present any unusual problems; however, the control subsystem as a whole is critical.

Table 2-15. Attitude Control System

System issues	Driving requirements
Reduced life-cycle cost	Increased autonomy
Maximize performance	Optimize structural response stiffness and damping
	Control flexible vehicle with large, on-orbit configuration changes

Table 2-16. Attitude Control System Technology Trends (Guidance, Navigation, and Control) (Page 1 of 2)

Function	Existing (Level 8)	Current (Levels 4-7)	Advanced (Levels 1-3)
Subsystem architecture	Control system bandwidth separated from structural frequencies	---	Distributed sensors, actuators, and processing. Fl modes controlled, passive and active structural damping
Attitude determination	Analog drive circuit star trackers, digital sun sensors, 3-axis magnetometer	Solid state star trackers	Multistar tracking sensor (3-axis), sun sensors, earth sensors, 3-axis magnetometer autonomous system
Inertial sensors (angular rate, attitude)	Spun-mass gyros (gimbaled, floated, tuned flex)	Ring laser	Fiber-optic laser
Position and velocity knowledge (ephemeris)	Software onboard propagation of ground predictions	Autonomous with global positioning system	Autonomous position, velocity, and attitude determination
Actuators	Ball bearing control movement gyros, DC torquers, stepper motors, electromagnets	2-gimbal control moment gyros with unlimited gimbal freedom	Large-momentum storage device coupled with energy storage, large electromagnets, magnetically suspended wheels
Relative motion	Brushless tachometers, optical and magnetic encoders	Laser orientation and position, optical mirror	
Pointing systems	Instrument pointing system (IPS), smaller dedicated systems	Advanced gimbal system (AGS)	Annular suspension pointing system (ASPS), magnetically levitated mounts and joints

Table 2-16. Attitude Control System Technology Trends (Guidance, Navigation, and Control) (Page 2 of 2)

Function	Existing (Level 8)	Current (Levels 4-7)	Advanced (Levels 1-3)
Rendezvous and docking	Manual telescope tracking radar with target transponder, and eyeball and manual docking	Ground tracking of both objects, radar without transponder, eyeball and manual close in	Autonomous rendezvous and docking
Propulsion	Hydrazine (N_2H_4)	N_2O_4/MMH (bipropellant)	Electrothermal augmented mono-propellant, advanced bipropellants, resistojets

2.7 COMMUNICATIONS AND TRACKING SYSTEM

The communications and tracking system will be faced with growth in data rates, traffic rates, and complexity of communication needs as space station activity increases. The technology driving requirements are summarized in Table 2-17. The most critical of these are the omnidirectional, wideband, and secure communications and the multitarget, omnidirectional traffic control.

The associated technology trends for the communication and tracking functions are shown in Table 2-18. The advanced-technology requirements include laser communications and tracking.

Table 2-17. Communications and Tracking System Technology Drivers

System issues	Driving requirements
Life-cycle costs	Autonomy Standard user interface
Performance	Omnidirectional, wideband communications Secure communications - commercial missions Multitarget, omnidirectional traffic control
System growth and flexibility	Easy-to-use internal communications
Maximize mission capture	Proximity operations - communications, tracking, and control

Table 2-18. Communications and Tracking System Technology Trends

Technology item or function	Existing (Level 8)	Current (Levels 1-4)	Advanced (Levels 1-3)
Wideband communications	Radio frequecy (Ku band)	Millimeter wave or laser communications	Millimeter wave or laser communications
Omnidirectional communications	Multiple antennas Mechanically steered	Phased arrays	Phased arrays
Multiple access techniques	Frequency division multiplex, time division multiplex		Adaptive time division multiplex
Traffic control, surveillance, docking, and rendezvous support	Ku-band radar, mechanically steered antenna	Laser tracking	Multifunction, phased-array radar
Video data communications	Wideband analog video	---	Compressed digital TV
Internal voice communications	Analog wire	Integrated digital voice and data	Infrared wireless voice communications

Based on analysis of the critical needs and technologies, the communications and tracking development issues were determined. Table 2-19 lists the top-level objectives of a development program to achieve laser communication and tracking capabilities.

Table 2-19. Communications and Tracking Development Issues

Candidate approach	Ground development test
Laser communication - space-to-space	Prototype performance demonstration
Laser communication - space-to-ground	Flight unit environmental and performance tests
Laser tracking	Instrumentation development Atmospheric effect characteristics
Improved COMSAT antennas	Prototype performance demonstration
Improved RF sensor antennas	Flight unit environmental and performance tests Instrumentation development

2.8 MECHANISM TECHNOLOGY

The mechanical components of a space station require a wide variety of mechanical functions varying from berthing and docking to remote manipulator and robotics operations. The technology drivers associated with these mechanical functions are listed in Table 2-20. Of these, the most likely to need research and technology development missions are those associated with remote manipulation and joints for deployable structures. Remote manipulation will require considerable flexibility in tasks and in force. Large deployable structures will, as noted earlier, probably involve many joints on a very flexible structure. If the control system is to properly control such a structure, the joints must be very linear (i.e., very low dead-band). Such joints, whether rotating or sliding, must be very carefully designed and built. Both of these technologies require development and are included in the proposed mission.

Table 2-20. Mechanism Technology Drivers

System issues	Driving requirements
Maximum mission capture	Service spacecraft and platform - teleoperator maneuvering system and remote manipulation
	Propellant transfer mechanisms
Growth and flexibility	Berthing and docking mechanisms, pressurized and unpressurized modules
	Gimbals and rotating joints
	Deployable joints (hinging, sliding, rotating) with linear joint response
	Deployment mechanisms

Table 2-21 describes the technology trends for all the major mechanical functions. These mechanisms must be verified in space; except for those noted previously, the normal development process should suffice. No subsystem technology development missions are required in advance of space station IOC.

2.9 AUXILIARY PROPULSION

The space station will require propulsion for orbit maintenance and attitude control and adjustment. The propulsion systems must be highly reliable and trouble-free but should also have high efficiency so that the amount of propellant to be carried and the frequency of resupply is minimal. Storable monopropellant and bipropellant auxiliary propulsion systems that have been extensively developed for spacecraft are viable candidates for space station applications; however, the higher specific-impulse potential of H_2/O_2 bipropellants (450 sec compared to 300 sec) and other advanced concepts is most desirable and worthy of in-depth study.

Table 2-21. Mechanism Technology Trends

Function	Existing Level	Current Level	Advanced Level
Berthing and docking electromechanical	Apollo, Skylab and ASTP mechanisms	Design studies of light-weight, less complex designs complete	Mechanisms with load path outside pressure seal and attenuators with position lock Docking mechanisms with stiffness matched to control system characteristics
Gimbals and rotating structural joints	None in size and function required for space station	Design studies and development models of large gimbals complete	Roll rings for electrical power transfer and long-life or replaceable seals for fluid transfer
Solar array and radiator deployment	None in size and function required for space station	Development models of solar array deployment mechanisms have been demonstrated (solar electric power solar array)	Stronger, stiffer, lighter deployment masts
Handling and positioning aids for spacecraft servicing	None existing	Phase B design study accomplished	---
Remote manipulation in space	Orbiter remote manipulator system and end effector	Concept studies for large remote manipulator system for space station, designs and models for grasping end effectors are complete	---
Remote umbilical operation	ASTP (electrical only) Aircraft in-flight refueling technology	Design and concepts studies complete for cryogenic umbilicals with self-sealing, quick disconnects	---
Appendage deployment actuation	Redundant electric motor gear actuators in production (PAM)	Roller drive actuators in development	---

Large platforms in low earth orbit will have station-keeping energy requirements far exceeding those for current satellites using inert gas, monopropellant, or storable bipropellant chemical systems. Thus, H_2/O_2 propulsion, with 50% higher I_{sp}, is a logical choice to reduce weight and resupply frequency for this application. This system would also permit integration with life-support and power systems using H_2 and O_2. Advanced resistojet propulsion systems using hydrogen propellants would have similar potential benefits.

H_2/O_2 propellants using unconventional tankage (LO_2) will permit maximum propulsive energy to be packaged within the Shuttle cargo bay for delivering large and heavy payloads to final orbit.

The use of propellants such as hydrogen and oxygen would also make it possible to consider integrating the propulsion feed system with the supply and feed systems of similar fluids required for life support and power generation. This integration could result in simplified logistics, increased flexibility, weight savings, and overall reliability improvement. However, the more advanced approaches will require the expansion of the technology base relative to these system concepts.

Table 2-22 lists the propulsion system options. Storable propellants, in addition to having potentially lower performance, are toxic and corrosive, leading to potential safety and reliability problems. The exhaust from these systems also tends to contaminate spacecraft surfaces, which may create problems for the thermal control and optical systems.

With the storable systems, however, the problems of low-g resupply should be much simpler than with cryogenics systems. There are no problems related to system thermal conditioning or chill-down, and the design of systems or devices for bringing about liquid transfer in a low-g environment are much more staightforward. Surface tension devices, positive expulsion bladders, or diaphragms could be used for this application with a high confidence of success and with minimum supporting technology R&D.

Table 2-22. Space Station Propulsion Options

System	Features: Desirable	Features: Undesirable	Development Status
Inert gas	Simple Clean exhaust Good control Simple resupply	Poor performance Hazards of high pressure	Excellent
Monopropellant chemical	Simple Single fluid simplifies Control and resupply	Low performance Toxic/corrosive fluids	Good
Storable bipropellants	Extensively used Fair performance	Toxic/corrosive fluids	Good
Cryogenic bipropellants	Excellent performance potential Benefits of a single working fluid Possibilities of integration with ECLS/EP subsystems	Power input Pulse mode operation	Low

Hydrogen-oxygen propellants are not hypergolic, as are commonly used storable combinations. Thus, pulse-mode operation with H_2/O_2 must be carefully evaluated under the environments anticipated for the space station.

In addition to the engine problems relative to ignition and pulse-mode operation, one other major area of concern with a cryogenic system is fluid storage of the cryogens. The following storage system technologies applicable to the space station and the orbital transfer vehicle should be investigated and developed:

- Predictable low-heat-leak, long-life insulation system (integrated multilayer insulation and foam substrate system with GN_2 purge)
- Techniques for heat input and tank pressure control
  - Design criteria for LH_2 tank thermodynamic vent systems
  - Design criteria for LO_2 tank thermodynamic vent systems and/or mixers
- High reliability, low-weight refrigeration system for long mission

The heat into the stored cryogen must be minimized by an appropriate insulation system. Although there is still some question about predictability, considerable work has been done in designing multiradiation barrier insulations (multilayer insulations), and the basic materials are available.

The heat that does enter the cryogen must be appropriately handled. If the incoming heat is absorbed as propellant temperature rise in the total fluid mass, rather than direct vaporization, the overall weight penalty is usually less and venting is less frequent. However, internal tank mixers must be used to ensure uniform propellant heating. These mixers may also be combined with a heat exchanger to provide efficient gas phase venting in zero or low gravity. Considerable research, however, has not yet demonstrated these concepts in a long-term low-g environment.

For very long-term storage (years), active refrigeration would probably be more efficient. Although the fundamental engineering probably exists, relatively little detailed work has been done.

The last area of concern with a cryogenic system is the transfer of cryogens, either from the tank to the engine or in a resupply mode. These liquid transfer technologies should be developed:

- Surface-tension acquisition systems for reliable on-demand flow of liquid in low-g
  - For multiburn and pulse-mode propulsion
  - For in-orbit resupply
- Low-g mass gaging requirements and design system to satify these needs
- Thermodynamic and fluid dynamic model for a cryogenic receiver and supply system, to be used to evaluate transfer sequences and options considering
  - Transfer time
  - Vent loss
  - Pressures
  - Transfer efficiency
  - Control requirements

Surface-tension devices have been studied and evaluated, and can certainly be applied, but have not yet been demonstrated in low-g. Problems such as potential screen drying due to heat tranfer in cryogenic system have not been totally resolved. Handling of the vapor generated when filling an initial warm system, and how this interacts with the tankage, the process control system, and any surface tension acquisition system must be further investigated and demonstrated in low-g experiments.

In many cases, the problems discussed can be solved without low-g data by "overdesigning" or designing around the issue, but this requires compromise and tangible design penalties that should preferably be avoided.

The propulsion technology trend is summarized in Table 2-23. The storage and transfer of cryogenic propellants is the subject of a mission technology mission.

Table 2-23. Propulsion Technology Trend

Technology	Existing Level	Current Level	Advanced Level
Propulsion	Storable bipropellants	H_2/O_2 bipropellant (Integrated with other fluid systems)	Resistojets Plasma/ion Biowaste

2.10 LIMITING TECHNOLOGIES

The following limiting technologies have been identified throughout this section:

- Data rates and mass data storage
  - Compatible with experiment output and tracking and data relay satellite system capacity
- EVA function limits
  - Dexterity
  - Duration
  - Prebreathe
  - Mobility
  - Torque reaction
- Control of large space structures
  - Stiff versus flexible structure
  - Configuration growth
  - Deployable structure joints and actuators
- Automation software cost and schedule
  - Hardware versus software trades
  - Modular memory

In the strict sense of the term, there are no "limiting" technologies applied to the space station since a useful space station can be built without any new technology development. There are no enabling technologies, only enhancing technologies.

Within the category of enhancing technologies, however, some technologies are more enhancing than others. That is the sense in which MDAC selected these so-called limiting technologies. They are not essential, but they are critical to developing the space station to its full potential.

For example, data rates and mass data storage are essential for high data payloads to function efficiently and for the tracking and data relay satellite to be used efficiently. Therefore, data rates and mass data storage are limiting technologies.

Similarly, EVA limits are critical for some operations and for the optimal allocation of tasks to the crew or to automation. Since the optimal use of the crew is one of the keys to a cost-effective space station, EVA is a limiting technology. The critical EVA development issues are summarized in Table 2-24. These issues are derived from the previously discussed requirements for extending EVA mobility and reducing prebreathe time.

Table 2-24. EVA Development Issues

Candidate approach	Development issues
	Ground functional and neutral buoyancy tests for the following:
8-psia space suit, revised operational techniques	Elimination of prebreathe time; development of new suit technology, joints, materials
Nonexpendable thermal control system for portable life-support system	Closed-loop thermal control system using phase-change cooling rather than vaporizing water
Increased capability of suit hardware	Work-enabling suit accessories, advanced tools to eliminate EVA accommodations on system hardware. Portable, universal test equipment, increased command capability (two-way, to supply data and troubleshooting procedures to EVA crewman)

To fully exploit the opportunities offered by a space station, the growth space station is essential; therefore, control of large flexible structures is also a limiting technology. A growth station, with large flexible components supported by long flexible beams, cannot be built without a system capable of controlling such flexible structures. The critical technology development tests associated with large space structure construction are as follows:

- Ground testing of structure assembly techniques for truss and beam/column structures
- On-orbit assembly of small deployment truss structural subsystems using EVA crewmen, remote manipulator system, and ground-tested assembly procedures

- On-orbit dynamic response testing of small deployable and erectable structural subsystems to generate the data base needed to validate design and response analysis tools for very large structures
- On-orbit dynamic response testing to verify capability to control large-structure dynamic response

These tests include both ground and STS tests necessary to support the space structure construction mission.

In summary, these primary limiting technologies are necessary to fully exploit space station potential. Although there are other technical advances important to space station exploitation, they are not reported because they are not considered critical.

Section 3
TECHNOLOGY DEVELOPMENT MISSION DESCRIPTION

As discussed in Section 1, the technology development missions are separated into subsystem technology missions and mission technology missions.

The approach for defining the subsystem technology missions was outlined in Figure 2-1. The initial step in this procedure was to define the subsystem trends (see Section 2). The remaining step was to define the missions and the steps leading to them (see Section 3.1).

The identification and definition of mission technology missions (see Section 3.2) varied somewhat from this procedure, although the following missions were derived from subsystem trends:

- Large Space Structure Construction (duplicated under subsystem technology missions)
- Large Space Structure Control (duplicated under subsystem technology missions)
- Man's Role in Space (duplicated under subsystem technology missions)
- EVA Capability (identified in part from the ECLS technology trends and the limiting technologies)

Other sources of mission technology missions were the technology drivers, man's long-duration capabilities, and servicing of replaceable orbital transfer vehicles and satellites. These missions are vital to the space station because they will determine the optimum allocation of tasks and the degree of autonomy given to the crew and because they maximize the mission capture of the space station.

A chart for each mission describes the mission and defines its objective, benefits, critical environments, space facilities, and hardware.

Information about each mission can be found in the Mission Summary (see Figure 1-1). The following data, however, are of particular interest:

- Power
- Crew time
- Number of servicings (EVA time)
- Number of times space station is used as a transportation node
- Internal volume
- Number of attach points to space staton
- Priorities (1 to 10, 10 being the highest)

Except for priorities and number of times space station is used as a transportation node, these data are furnished in the text covering each mission.

The basis for priority judgment was to assign zero if the mission could be done on the ground, 5 or less if it could be done on the Shuttle, and 5 to 10 if it could be done on the space station. We didn't know how to interpolate between 5 and 10, so we set all equal to 10. The priority is 10 for all missions except EVA Capability, which is 5.

The space station is used as a transportation node (to collect and send payloads or equipment to another orbit) by only the Materials and Coatings Technology mission, TGN003. For that mission, the number is 120, one per month for 10 years. For all other missions, the number is zero.

3.1 SUBSYSTEM TECHNOLOGY MISSIONS

The subsystem technology missions are:

- ECLS Waste Water Recovery
- ECLS O_2 Recovery
- Liquid Droplet Radiator
- Materials and Coatings Technology
- Laser Communication and Tracking Development
- Tether Dynamics
- Evaluation of Man's Role (discussed in Section 3.2, Mission Technology Missions)
- Large Space Structure Construction
- Large Space Structure Control

3.1.1 ECLS Waste Water Recovery Mission - TGN008

There are two competing approaches for achieving waste water recovery--vapor compression distillation (VCD) and thermoelectric integrated membrane system (TIMES). Early ground testing will have determined which of these approaches should be utilized on the initial Space Station for condensate and wash-water recovery. A short-term Orbiter or Spacelab flight will have demonstrated the zero-g operation. It is assumed that urine and fecal water recovery will not yet have been verified to a level acceptable for the initial Space Station; however, it is expected that the urine recovery mode will be ready for a zero-g test demonstration very early in the initial Space Station operation (approximately 1990).

The test unit (Figure 3-1) will probably be a small VCD prototype rated for up to six crewmen. It will be separate from the baseline water recovery unit to avoid contamination in case the urine recovery is not completely successful. The test will not only allow the demonstration of the liquid-gas separation in zero-g but will also be run long enough (30 to 90 days) to determine potential degradation due to zero-g contamination buildup.

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FIGURE 3-1.

ECLS WASTE WATER RECOVERY MISSION (TGN008 PRIORITY 2) VGB405

OBJECTIVE — Demonstrate Water Recovery Operation In Space

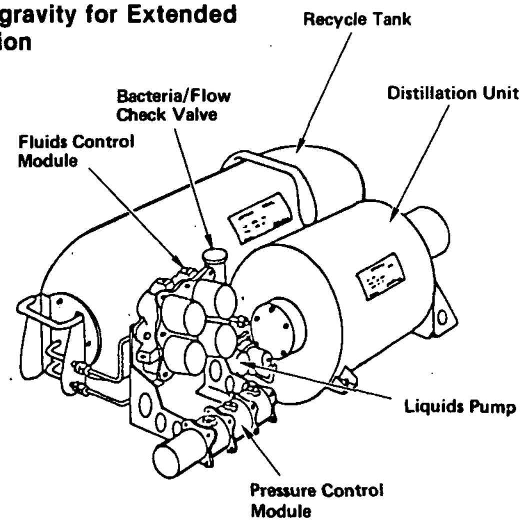
BENEFIT: Long-Duration Mission Life Cycle Cost Reduction Due to Reduced Resupply Weight and Volume

CRITICAL ENVIRONMENTS — Microgravity for Extended Duration

SPACE FACILITY REQUIREMENTS
- 30- to 90-Day Duration
- 10^{-5} to 10^{-6} g
- Pressurized Cabin
- Crew Metabolism

MISSION/HARDWARE
- IOC 1990
- Weight 70 kg
- Power 100 W

DESCRIPTION — A Small-Scale Prototype Vapor Compression Water Recovery Unit to Handle 6 Crewmen. The Unit Would Provide Station Drinking Water as Long as Monitoring Instrumentation Indicates Potability



The prototype will weight approximately 70 kg and consume 100 W of electrical power. The envelope will be 30 by 60 by 70 cm, and the volume will be the equivalent of one rack. The output water will be monitored for potability and acceptability to the crew evaluated. The crew time is estimated to be 15 hours per day for 180 days per year. Because the unit is inside the space station, it does not require any EVA servicings or attach points.

3.1.2 ECLS O_2 Recovery Mission - TGN009

The most promising O_2 recovery unit is actually combined with CO_2 collection and control, CO_2 reduction, and a humidity controller (Figure 3-2). This package is called an atmosphere revitalization system (ARS). Each of the basic functional units involves liquid and gas separation, making it highly desirable to conduct a flight experiment in zero-g to demonstrate the validity of these techniques. Since these units are sensitive to contamination buildup, which may be different in zero-g environment, it is

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FIGURE 3-2.
ECLS O_2 RECOVERY MISSION
(TGN009, PRIORITY 2)

VGB403

OBJECTIVE — Demonstrate Oxygen Recovery Operation in Space

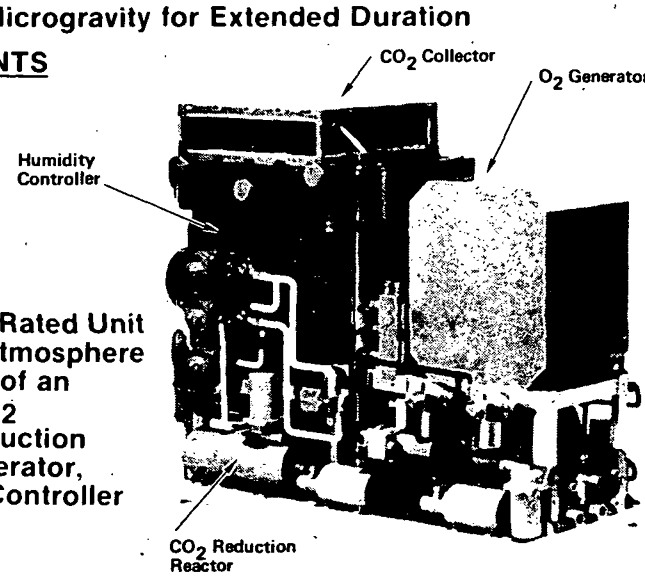
BENEFIT — Long-Duration Manned Mission Life-Cycle Cost Reduction Due to Reduced Resupply Weight and Volume

CRITICAL ENVIRONMENTS — Microgravity for Extended Duration

SPACE FACILITY REQUIREMENTS
- 30- to 90-Day Duration
- 10^{-6} to 10^{-5} g
- Crew Metabolism
- Pressurized Cabin

MISSION/HARDWARE
- IOC 1993
- Small-Scale Prototype

DESCRIPTION — A 1-Crewman Rated Unit Run in Parallel With the Station Atmosphere Revitalization System. Consists of an Electrochemical Depolarized CO_2 Concentrator, Sabatier CO_2 Reduction Subsystem, Electrolysis O_2 Generator, and Dedicated Microprocessor Controller



important to run the ARS for reasonably long durations (30 to 90 days) to establish contamination buildup rates. A long-duration test would also verify zero-g maintainability via contrived failures.

The recommended test unit is a small-scale prototype rated for one crewman. The unit would consist of an electrochemical depolarized CO_2 concentrator, a Sabatier CO_2 reduction system, an electrolysis O_2 generator, and a dedicated microprocessor controller. The unit is run in parallel with the normal Space Station atmosphere revitalization system, and the input and output O_2, CO_2, and humidity levels are measured to monitor performance. For safety, the output air is also monitored for potential toxins.

The flight package will weigh approximately 100 kg and consume an average power of 425 W. The envelope of the unit will be 0.7 by 1.0 by 0.35 m, and the volume will be the equivalent of two racks. The experiment IOC is expected in 1993, and the production IOC, approximately 1996. The crew time is 14 hours per day, and the number of servicings is one per day. Since the unit is inside the Space Station, it requires no EVA time and it uses no attach ports.

3.1.3 Liquid Droplet Radiator Mission - TGN007

Though not necessarily a preferred choice, the liquid droplet radiator (LDR) is used here because it is representative of advanced technology radiators. It offers two significant improvements for the growth Space Station. First, preliminary studies indicate that an LDR will weigh one fifth to one third as much as the most efficient conventional radiators currently available; thus, launch weights will be reduced for growth steps in the mid-1990s. Second, the LDR is not as vulnerable to meteoroid punctures or to the radiation and contamination degradation associated with thermal coatings. The level of maturity of the concept, however, is quite low, although the basic principles are recognized and reported and conceptual designs have been formulated. It is expected that a combined Air Force and NASA development effort over the next three years will bring this concept to the point where the critical functions and characteristics will have been demonstrated by analysis and test. After several more years of brassboard and prototype engineering model testing, a model should be ready for testing in space, where the low vacuum, microgravity, and space plasma are all considered critical for complete demonstration.

The test unit (Figure 3-3) will probably be a small-scale model that is deployable from a small pallet. It will not be connected to the Space Station thermal loop but will contain its own heat source (electric heaters). The radiator loop will be tested at several ejection temperatures and flows. Temperatures, flows, pressures, fluid loss, and contamination of adjacent test surfaces will be measured. The unit will weigh approximately 400 kg and consume an average of 1000 W of electrical power. Its launch volume will be the equivalent of one half of a Spacelab pallet, with no additional internal volume required, and it will require one attach port. Ten EVA operations are necessary to support the tests.

FIGURE 3-3.

LIQUID DROPLET RADIATOR MISSION VGB409A

(TGN007, PRIORITY 4)

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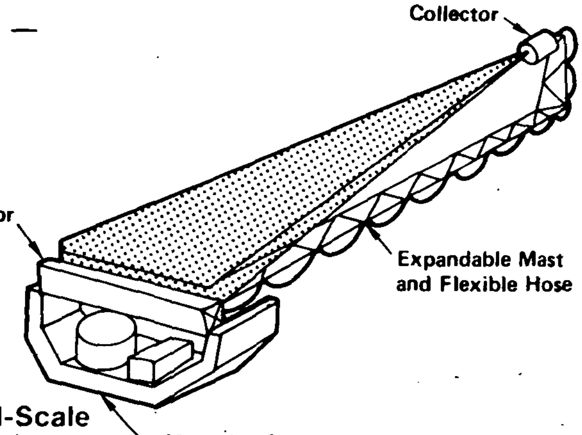
OBJECTIVE — Demonstrate Liquid Droplet Radiator (LDR) Operation in Space

BENEFIT — Enables Significant Heat Rejection Capability for Spacecraft. Reduces Weight by Factor of 3 to 5

CRITICAL ENVIRONMENTS — LEO Atmosphere and Microgravity

SPACE FACILITY REQUIREMENTS —
- 30 to 90-Day Duration
- 10^{-6} to 10^{-3} g
- 10^{-6} to 10^{-7} torr, Vacuum
- 20 x 3 x 3m Deployed Volume
- LEO Plasma

MISSION/HARDWARE
- IOC 1994
- Small-Scale Prototype
- 200-W Average Power
- 400 kg
- 1/2 Pallet Launch Volume



MISSION DESCRIPTION — A Small-Scale Electrically Heated LDR (~ 2 kW) is Deployed and Tested at Several Ejection Temperatures and Flows. Temperatures, Flows, Pressures, Fluid Loss, and Contamination of Adjacent Test Surfaces are Measured

3.1.4 Materials and Coatings Technology Mission - TGN003

Certain characteristics of the space environment, including Space Station effluents, may affect critical physical properties of materials and coatings used in future space projects. The extent of contamination and its major effects on these materials and coatings is unknown, and extremely difficult to simulate in laboratory testing. The inability to exactly simulate space environment conditions accounts for the major difference between laboratory test data and in-flight experimental data.

The relatively short-duration Shuttle tests will provide initial data, but to obtain long-term orbital data, a facility that exposes the experimental samples to the particle and radiation fluxes produced by the space station is needed. This facility, containing several material and coating experiments, would be attached to a gimbaling platform on the Space Station. The orientation of the experiment could be repositioned to determine its effect on sample contamination. Periodic measurements of the samples would be required to establish the time-integrated cumulative effects of environmental exposure on the samples. Sample experiments could be exchanged for terrestrial laboratory evaluation.

This facility (Figure 3-4) will provide material and coating degradation data that will ensure long-term operation of future spacecraft designs. One pallet will occupy a single port, and no space station interior volume is required. The electrical power required is 100 W. The Materials and Coatings Technology mission has very large servicing needs--240 EVA operations. Two crewmen, four hours per day for a total of 10 days, are needed to support the mission over a 10-year period.

3.1.5 Laser Communication and Tracking Development - TFM001

Laser technology has great potential for space communication links (space-to-space and space-to-ground) and for space-based tracking systems. An example of the latter is a Space Station rendezvous and docking support system that could provide high-accuracy tracking at short and medium ranges. In communications applications, laser links have much wider bandwidths than conventional radio frequency links and offer improved data security due to the very narrow, well-controlled beamwidths. Because of atmospheric attenuation, space-to-space links have another measure of security from ground intercept.

FIGURE 3-4.
MATERIALS AND COATINGS TECHNOLOGY MISSION
(TGN003, PRIORITY 4)

VGB404

OBJECTIVE – Determine the Space Environment Effects on Critical Physical Properties of Various Materials and Coatings

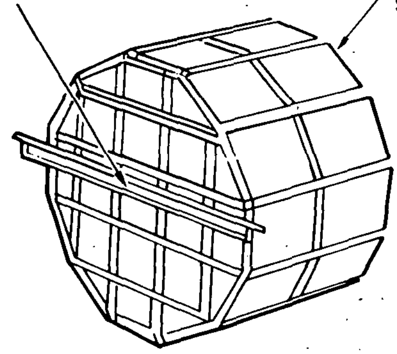
BENEFIT – Provide Realistic and Low-Cost Data on Long-Term Exposure to Combined Space Environments (Vacuum, Radiation, Temp, and Effluents); Lead to More Cost-Effective Spacecraft/Advanced Space Stations

CRITICAL ENVIRONMENTS – Long-Term Exposure to the Combined Natural and Induced Space Environments

SPACE FACILITY REQUIREMENTS
- 10-Yr Duration
- Manned Interaction/Support
- Controlled Proximity to Environmental Contamination Sources

MISSION HARDWARE
- IOC 1992
- LDEF-Type Carrier
- Various Material/Coating Experiments
- Instrumentation
- 1400 kg

MISSION DESCRIPTION – Expose the Material/Coating Experiments to the Space Environment in Varying Orientations for an Extended Period of Time. Periodic Measurement Will be Recorded to Establish Time-Integrated Cumulative Effects on the Measured Physical Parameters



A Space Station can provide the capability to perform in-orbit demonstration of these laser systems (Figure 3-5). For space-to-space communication links and space tracking applications, a teleoperator is required to provide the link separation and to act as a target for tracking demonstrations. For the space-to-ground link, a laser communications terminal on the Space Station would communicate with one or more ground terminals; in this case, a specific objective of the mission would be to improve the characterization of atmospheric effects on the laser link. One thousand watts of electrical power is required for this mission. EVA (two men, six times per year) is required to install and service the laser link in the teleoperator maneuvering system (TMS). One port is required, and the experiment hardware will occupy the equivalent of one-half pallet.

3.1.6 Tether Dynamics Mission - TGN004

This mission will conduct deployment, operation, and retrieval tests on a tether on orbit. Conducting tethers will be used, and electrodynamic forces will be generated. These forces can be used to control the tethers or to

FIGURE 3-5.

LASER COMMUNICATION AND TRACKING DEVELOPMENT

(TFM001, PRIORITY 5)

VGB464

OBJECTIVE

- Demonstrate Space-to-Space Laser Communication and Tracking System. Investigate Propagation Effects for Space-to-Ground Laser Link

BENEFITS

- Improved Bandwidth and Security for Space-to-Space and Space-to-Ground Communication Links; Improved Rendezvous/Docking Support

CRITICAL ENVIRONMENTS

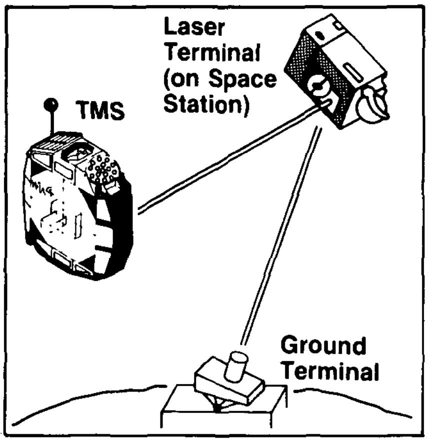
- Low-g, Vacuum and Free Space

SPACE FACILITY REQUIREMENTS

- TMS
- Crew Interaction/Support
- Attitude Stability/Knowledge

MISSION/HARDWARE

- Laser Communication Terminals
- Laser Tracker
- Laser Reflector System
- Ground Laser Communicaion Terminals



MISSION DESCRIPTION

- User Space-Station-Mounted Laser Communication Unit to Communicate with Second Terminal on TMS. Perform Tracking Experiments Using TMS and Targets of Opportunity. Measure Space-to-Ground Link Performance (e.g., Pulse Dispersion and Attenuation

provide thrust or drag for the tip (the far end of the tether) and the host satellites. A tether length of about 100 meters will be adequate for these tests. Tether dynamic responses to mechanical and electrodynamic forces will be measured and compared to theory. If positive results come from this experiment, a benefit could be the use of a long tether to supplement Space Station drag make-up propellant. Figure 3-6 summarizes this mission.

The Space Station must supply a stable earth-referenced platform for tether deployment and retrieval. Also, the tether must be visible from the Space Station for safety and test-monitoring reasons.

Although no EVA operations are planned, two crewmen are required for four hours per day, 40 days per year. One port is used with the half-pallet equivalent external volume; no internal volume is needed. One thousand watts of electrical power is required.

FIGURE 3-6.

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TETHER DYNAMICS MISSION

(TGN004, PRIORITY 3)

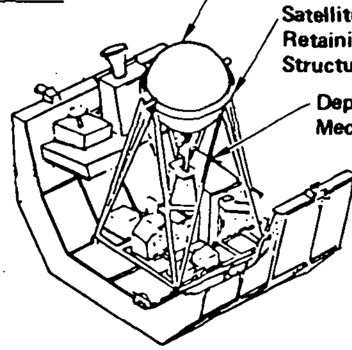
VGB409

<u>OBJECTIVE</u> — Test Electrodynamic Force Characteristics of Conducting Tethers

<u>BENEFIT</u> — Data Base and Theory Validation for Conducting Tethers With Potential for Application to Space Station Station-Keeping

<u>CRITICAL ENVIRONMENTS</u> — Needs Realistic Low-g, Gravity Gradient, Thermal, Electromagnetic, Large Test Volume, and Atmospheric LC Drag of Space

<u>SPACE FACILITY REQUIREMENTS</u>
- Stable Earth-Referenced Orientation for Several Orbits
- Tether and Spacecraft Visible from Space Station
- 30-Day Duration for Two Separate Missions



<u>MISSION/HARDWARE</u>
- IOC 1992
- 250 kg
- 1 Pallet

<u>MISSION DESCRIPTION</u> — Deployment and Retrieval Tests of Electrodynamic Forces for Tether Control, and Thrust and Drag Generation

3.1.7 <u>Large Space Structure Construction Mission - TGN005</u>

Future space missions will depend on the successful assembly and testing of very large, lightweight space structures, e.g., structural subsystems for large deployable reflectors and antennas. This experiment, as envisioned by MDAC, will provide the technology data base for design, analysis, construction, and testing of large space structures.

The long-duration, low-gravity, and stability characteristics of the Space Station will be an ideal base for the assembly and testing of very large space structures. In addition, the Space Station remote manipulator system (RMS) and multiple-astronaut EVA capability will be needed for the planned experimental construction and assembly activities.

For this mission experiment, the Shuttle would launch high-density packaged structural elements and modules that would subsequently be assembled by the Space Station RMS and the EVA crewmen to produce a portion of a large space structure. Structural response testing of the assembled structure would determine mode shapes, damping-influence coefficients, and other design data. Thus this experiment not only provides valuable approaches and procedures for the assembly and construction of large space structures, but also generates the data base needed to develop the design and the validated analysis tools for future space systems.

A brief summary of this mission experiment is presented in Figure 3-7. The mission equipment, consisting of two pallets, occupies one port. EVA operations will number 10 per year. Three crewmen at eight hours per day will be utilized 60 days per year. The mission equipment will draw 500 W of electrical power.

3.1.8 Large Space Structures Control Experiments Mission - TGN001

The Space Station must support construction, assembly, or deployment capability for large test structures. On-orbit sensor and actuator

FIGURE 3-7.
LARGE SPACE STRUCTURE CONSTRUCTION
(TGN005, PRIORITY 1)

VGB401

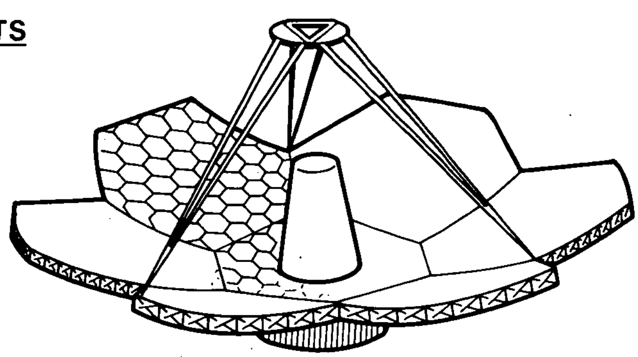
OBJECTIVE — Provide a Technology Base for Design/Analysis of Very Large Space Structures

BENEFIT — Future Space Missions Depend on Assembly and Testing of Very Large, Lightweight Space Structures (e.g., Stellar Astronomy Using the NASA Large Deployable Reflector Optics Concept)

CRITICAL ENVIRONMENTS — 10^{-6} to 10^{-3} g, Vacuum and Space Radiation

SPACE FACILITY REQUIREMENTS
- Unlimited Space
- Stable Platform
- Remote Manipulator/EVA
- Crew, 60 Man Hours/Mission

MISSION/HARDWARE
- IOC 1992
- 600 kg
- Deployable and Erectable Structural Elements
- Instrumentation



MISSION DESCRIPTION — Launch Packaged Structural Elements and Modules for Assembly of a Portion of a Large Space Structure Using the Manipulator and EVA Crewmen. Accomplish Structural Response Testing to Determine Mode Shapes, Damping/Influence Coefficients, and Other Design Parameters reconfiguration may be required. A free-flyer mode may be required to isolate the test structure from Space Station disturbances, so deployment and retrieval capabilities may be required. The capability to control and monitor the testing must be provided.

This set of experiments will evaluate dynamic modeling and control techniques for large space structures. The space environment provides the very low-gravity setting needed to realistically evaluate nonlinear structural joint vibration characteristics. Most structural looseness is masked on earth by the 1-g structural loading. The structures will be instrumented for characteristics identification and control-system feedbacks. Actuators on the structure will be used to excite it and to determine the adequacy of the control systems and damping. Various control-system algorithms and control approaches will be evaluated with respect to performance criteria such as vibration damping, shape control, pointing stability and accuracy, disturbance isolation, and maneuver response. Adaptive control techniques will be investigated along with real-time parameter estimation techniques. This mission is summarized in Figure 3-8.

FIGURE 3-8.

LARGE SPACE STRUCTURES CONTROL EXPERIMENTS MISSION (TGN001, PRIORITY 3)

VGB408

MCDONNELL DOUGLAS

OBJECTIVE — To Validate Large Space Structures Modeling and Controlling Techniques

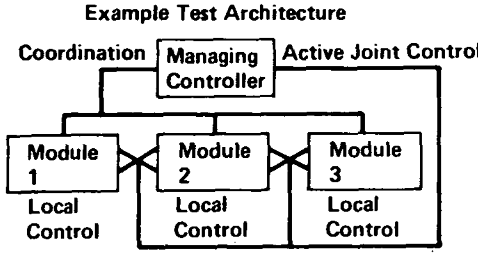
BENEFIT — Provides Test Data Leading to Better Control Performance for Growth Space Stations and Attached Payloads

CRITICAL ENVIRONMENTS — Low-g, Low Aero Damping, Large Test Volume, Low Vibration, Space Thermal Environment

SPACE FACILITY REQUIREMENTS
- Mounting Mechanisms
- Construction and Deployment
- Data Monitor and Test Control

MISSION/HARDWARE
- IOC 1992
- Large Deployed Volume
- More Than One Mission

Example Test Architecture



MISSION DESCRIPTION — Experiment With Large Structures With Distributed Actuators and Sensors. Sensor Outputs Used for System Identification and Control Feedbacks. Thermal and Mechanical Disturbances to be Evaluated. Low-g Environment Allows Nonlinear Structural Characteristics to be Evident

With a launch mass of 600 kg and a two-pallet, single-port attachment to the Space Station, the deployed structure may be very large, possibly necessitating a free-flyer mode. One crewman for one hour per day is needed 30 times per year. Six EVA operations are planned.

3.2 MISSION TECHNOLOGY MISSIONS

The Mission Technology Missions are:

- Man's Role in Space
- EVA Capability Technology
- Crew/Manipulator Controls
- Fluid Storage and Management
- OTV Service Technology
- Satellite Servicing Technology
- Zero-g Antenna Range
- Large Space Structure Construction
- Large Space Structure Control

The last two missions are discussed in Section 3.1, Subsystem Technology Missions.

The approach used for the mission technology missions differs from that used for subsystem technology missions. Key system issues were identified and matched up to corresponding technology drivers as indicated below.

System Issue	Technology Driver
Cost	Satellite and OTV service
	ROTV
Performance	Man's role and robotics
	Structural dynamics and control
Long, safe life	Satellite service
Growth potential, flexibility	Erectable, deployable structure
Maximum mission capture	Satellite and OTV service

The drivers fall into three broad categories: service-related technology, deploying and controlling large structures, and trades of man's role versus automation and robotics. The mission technology missions were determined by these drivers.

A comparison of man's role in terms of EVA versus an automated technique illustrates an important point. The function used in the comparison is that of unlatching the array, radiators, antennas, etc., for a deployable solar array packaged in the Shuttle bay. Fifteen latches, hence 15 mechanisms (duplicated for redundancy), are necessary. The cost estimate for the automated mechanisms is $2.4 million. Two EVA crewmen can manually perform the same functions in approximately 2.5 hours. Using a rather conservative cost for EVA for $41,000 per man-hour, the total cost for the two crewmen is $210,000. Thus, for this example, the automated solution is about 10 times the cost of EVA manual operations.

One of the main reasons the example favors EVA is that the tasks are nonrepetitive. The EVA times are well within limits and involve no excessive hazard. From the example, we can draw the following criteria to assist in the determination of man's role: repetition frequency, complexity, and hazard.

Other operations could involve the use of TV and a telemanipulator, a solution that represents a kind of middle ground between EVA and robotics or automation.

The example suggests the outlines of a mission technology development program. The following missions have been identified as necessary to support OTV and satellite servicing technology:

- Man's Role in Space - To identify man's long-term capabilities
- EVA Capability - To identify man's capability to do manual operations
- Crew Manipulator/Controls - To determine man's capability in teleoperations
- Fluid Storage and Management - To input propellant transfer requirements

An additional mission, the capability of which requires mission technological development, is the Zero-g Antenna Range. Clearly the capability to construct large space structures and to control the dynamics of these structures (described in Sections 3.1.7 and 3.1.8) is also required to support zero-g antenna tests in this antenna range.

3.2.1 Man's Role in Space

This mission (Figure 3-9) will provide basic data on man's capability during extended-duration space flight. These data will be used to determine the tasks that will be assigned to the crew and the degree of automation (i.e., maniuplator, robotics) needed to support them for each task.

Much of this kind of analysis and testing has been done, and more will be done before the space station is deployed; all the resulting data will be used. However, the long-duration effects on man and the specific characteristics of the space station that will impact his capabilities remain to be identified in the proposed mission.

This mission will require 50 W of power, one crew member full time, and an internal volume of about 1000 ft^3.

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FIGURE 3-9.
MAN'S ROLE IN SPACE
(TOP004, PRIORITY 1)

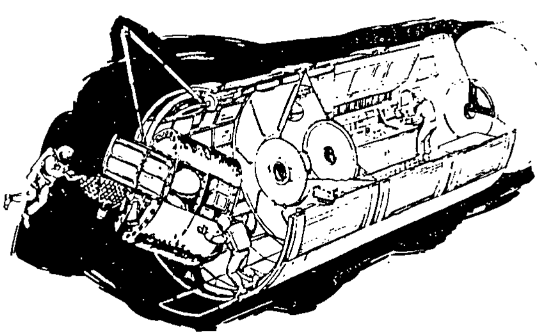
VGB399

OBJECTIVE — Establish Effects of Extended Space Flight on Men's Sensory, Cognitive, and Psychomotor Behavior

BENEFIT — Specifications for Optimal Design of Future Systems

CRITICAL ENVIRONMENTS — Extended Duration in Weightlessness of Space

SPACE FACILITY REQUIREMENTS — Dedicated Volume (1000 ft^3) Isolated From Visual and Auditory Distractions Habitability Module and Life Support Facilities Missions to 180-Day Duration



MISSION/HARDWARE (IOC 1992) —
Psychophysical Measurement Equipment
TV Cameras
Video Tape Recorders
Control/Display Consoles
Task Boards and Various Performance Aids

MISSION DESCRIPTION — Investigate Human Capabilities to Perform Complex Tasks in Space, Acquisition and Retention of Critical Skills, Problems of Locomotion and Restraint, Work-Rest-Sleep Cycles, and Design of Performance Aids

3.2.2 EVA Capability Technology Mission

Orbital operations associated with maintenance and servicing activities for various space systems (Figure 3-10) will require crewmen in an extravehicular activity (EVA) mode to perform the necessary tasks. However, task performance is somewhat hindered by the lack of familiarity with working in the space environment and the limitations imposed by the confines of the pressurized spacesuit. Although these parameters cause some restrictions to the crewman's ability, Skylab experience and more recent neutral-buoyancy simulations have shown that a significant work capability exists in EVA operations.

Development of orbital techniques and support equipment for EVA operations is required to extend the capabilities of an EVA crewman to perform work in space. The purpose of this mission is to evaluate various techniques developed in neutral-buoyancy simulations and determine their feasibility in the natural space environment. Due to the timeliness of establishing EVA capabilities, the initial missions will be demonstrated in conjunction with Shuttle operations.

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FIGURE 3-10.

VGB462

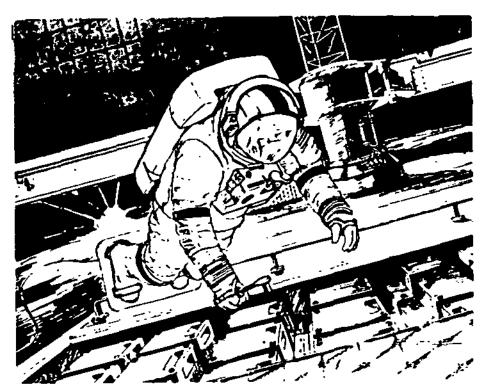
EVA CAPABILITY TECHNOLOGY MISSION

OBJECTIVE
- Establish Capabilities/Limits for EVA Crewman to Perform Work in Space

BENEFIT
- More Cost Effective Spacecraft Via Optimum Application of EVA to Facilitate Various Spacecraft Operations (i.e., Deployment, Construction, Servicing, and Maintenance)

CRITICAL ENVIRONMENTS
- Zero g, Thermal/Vacuum, and Lighting

SPACE FACILITY REQUIREMENTS
- Multiple 2-Crewman, 6-Hour EVA Missions
- Space Shuttle Support
  - 8 psia Suit
  - RMS Assist
  - Video Coverage
  - Manned Support (Personnel and Equipment)



MISSION/HARDWARE
- IOC 1985
- EVA Support Equipment
- Various Task Hardware
- Shuttle Mission Planning

MISSION DESCRIPTION
- Perform Various EVA Tasks Which Have Been Previously Developed in a Simulated 0-g Environment to Expand/Define EVA Capabilities/Limits

The benefits derived from these missions will lead to more cost-effective space systems by implementing EVA to perform various spacecraft operations such as appendage deployment, system construction, satellite servicing, and space system maintenance operations and by providing data for the allocation of tasks between EVA, manipulators, and robotics.

3.2.3 Crew/Manipulator Controls - TOP003

Teleoperation systems can perform many activities outside the pressurized environment over long time periods and long distances with precision and without human risk. Teleoperators can be used to enhance crew EVA activities by capturing, transporting, orienting, and stabilizing materials and payloads. Teleoperated manipulators can be used with a teleoperator maneuvering system (TMS) to capture or transport large objects over even longer distances. Teleoperations will enhance or replace many classes of crew EVA. In many cases, crew EVA time can be eliminated or shortened, which may lead to reduced life-cycle costs. Each class of tasks requires trade studies to evaluate the optimum combination of crew EVA and teleoperations. This experiment will provide data for such evaluations.

Teleoperated manipulators are designed for minimum mass and zero-g operations; they are generally flexible, coupled, nonlinear systems. They can be developed and partially verified with air-bearing tables and neutrally buoyant test rigs, but they require a microgravity environment for final validation. Test durations of 30 to 60 days are desirable in order to fully explore all the classes of teleoperations with varying degrees of crew involvement.

The objectives of the mission are to determine the characteristics and limitations of interactive and adaptive control technology applied to space teleoperator systems and to develop a quantitative data base with which to compare and predict task performance with teleoperation versus that accomplished in a spacesuit.

A lightweight low-inertia dual-arm manipulator system (Figure 3-11) will be attached to the space station or associated structure. The manipulator

FIGURE 3-11.

CREW/MANIPULATOR CONTROLS

VGB402

MCDONNELL DOUGLAS

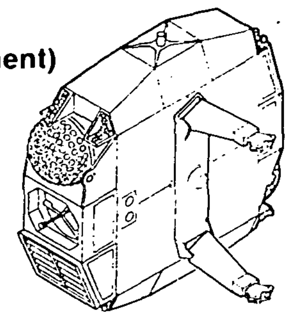
(TOP003, PRIORITY 3)

<u>OBJECTIVE</u> — To Obtain Space Performance Data for: (1) Dual Arm Teleoperator Manipulators and (2) Integrated Manipulator/TMS

<u>BENEFITS</u> — Space Program Cost/Performance Improvements (e.g., Dedicated Satellites and Space Platforms) Via Understanding of Teleoperator Utility/Performance Capability (vs EVA)

<u>CRITICAL ENVIRONMENTS</u> — Microgravity; TMS/Manipulator/Satellite Control Interactions in 6-Degree-of-Freedom Environment

<u>SPACE FACILITY REQUIREMENTS</u>
- Zero-G Space Station Laboratory (Shirt-Sleeve Environment)
- Crew/Control Interactions
- TMS



<u>MISSION/HARDWARE</u>
- Remote Manipulator Test System
- Laboratory Control and Display System
- Manipulator End-Effectors for TMS
- Task Boards/Satellite Substitutes
- TMS/Manipulator Control Station

<u>MISSION DESCRIPTION</u> — Initial Testing of Operator/Manipulator Capabilities in Space Station Zero-G Laboratory; Subsequent Testing of Manipulator System on TMS in Conjunction With Satellite Substitute

system will controlled from a teleoperator control station in the space station, through a computer interface, using both supervisory and direct control modes.

Initially, the manipulator system will be in a space station laboratory. Tests within the laboratory will include evaluation of system response to validate ground-based models, to identify system parameters, and to develop adaptive control algorithms for zero-g operations. Experiments will provide data on operator restraints, workload, mobility, and response to bilateral forces. Baseline tests will be conducted to compare task performance using the teleoperator with performance in a space suit.

The teleoperator system will be attached to a carrier vehicle such as TMS to develop the technology and integrated procedures required for remote operations such as construction, inspection, materials transfer, and repair.

These tests are expected to use 150 W of electrical power. The launch mass of the equipment is 550 kg. Two crewmen at four hours per day will be utilized 60 days per year for tasks, including eight EVA operations. One port is required, supported by one internal rack of equipment.

3.2.4 Fluid Storage and Management Mission - TDN006

The Fluid Storage and Management mission (Figure 3-12) will demonstrate the technology necessary to perform the propellant resupply function for space-based OTVs. The mission will extend the experiments currently being planned for the Shuttle payload bay. It is anticipated that significant data will be generated by the Shuttle-based experiment. However, the limited time available for storage, and inherent Orbiter thermal and disturbance environments, will limit the direct applicability of the data to a space station.

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FIGURE 3-12.

FLUID STORAGE AND MANAGEMENT MISSION

(TGN006, PRIORITY 1)

VGB537

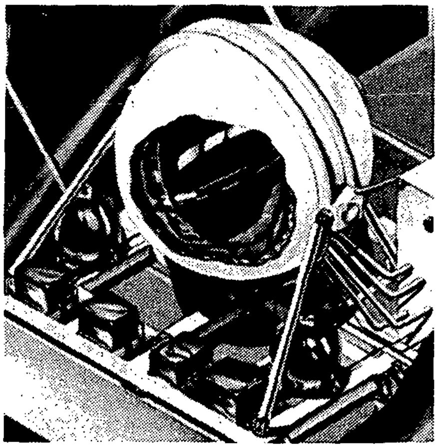
OBJECTIVE — Demonstrate Cryogenic Fluid Storage, Acquisition, and Transfer

BENEFIT — Cryogenic ROTV Depot - Cost, Weight, and Reliability (Eliminate Artificial g's)

CRITICAL ENVIRONMENTS — 10^{-6} to 10^{-5} g; 10^{-4} to 10^{-3} Transients; Heat Flux and Vacuum

SPACE FACILITY REQUIREMENTS

- 10^{-6} to 10^{-3} g (Quasi-Controllable)
- Crew Interaction/Support
- 6-Month Duration



MISSION/HARDWARE

- IOC 1992
- Subcritical LH_2 Tanks (2)
- 2000 kg
- 1 pallet

MISSION DESCRIPTION

Stabilize LH_2 in Tank With Various Steady State and Transient g-Levels and Solar Heating; Measure Fluid Transfer and Long-Term Storage Performance

The Orbiter experiment hardware, or possibly two sets of hardware, will probably be employed for the space station fluid storage and management mission. This approach minimizes test system development and hardware cost as well as the costs associated with the development of test procedures and data reduction.

The launch mass could be as large as 9000 kg for this mission. The power required is 500 W. One port is used to support three pallets. One crewman will be used four hours per day, 30 days per year. Four EVA operations are expected.

3.2.5 OTV Service Technology - TOP002

On-orbit servicing by the space station of reusable orbital transfer vehicles offers the potential for high economic payoff, especially in light of an expanding requirement for transporting payloads to geosynchronous locations. In order to support these requirements, the technologies associated with payload integration and staging need to be developed and optimized. The functional allocation between man and machine is crucial to the overall optimization and economics of space station activities. The key points pertinent to the OTV Service Technology Mission are shown in Figure 3-13. The key technology inputs come from the previous mission technology missions.

OTV Service Technology occupies one port with three pallets drawing 1500 W of electrical power. Two crewmen operate for four hours per day, 60 days per year. It is expected that 20 EVA operations will be needed.

3.2.6 Satellite Servicing Technology - TOP001

Space-based satellite servicing (Figure 3-14) offers excellent potential to reduce the cost and extend the useful life of earth-observation spacecraft. In order to support these service-class missions, space technology based on a program of both ground testing (e.g., neutral buoyancy investigations) and verification and optimization testing in space needs to be developed. Trades between manned operations and automated approaches, where clear-cut allocation decisions cannot be predetermined due to lack of actual experience and data, need to be evaluated. The foregoing mission technology missions will provide such technology.

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FIGURE 3-13.

OTV SERVICE TECHNOLOGY

(TOP002 PRIORITY 1)

VGB466

MISSION OBJECTIVE

- Develop Technology Required to Maintain Orbit Transfer Vehicles (OTV) On-Orbit Between Flights

BENEFIT

- Space Program Cost Improvements by Developing Technology for Servicing and Maintaining the OTV at the Space Station

CRITICAL ENVIRONMENT

- Operational Orbit Characteristics

SPACE FACILITY REQUIREMENTS

- OTV Service Depot/Platform; TMS and/or EVA Equipment Mission/Hardware
- IOC 1992
- Tools and Handling Equipment

MISSION DESCRIPTION

- Technology Development Associated with Manned OTV Service Operations Including Refueling, Gaging and Preservation of Propellants, Maintenance. Replacement and Checkout of Components, Installation, Integration, and Checkout of OTV and Other Stages and Payloads

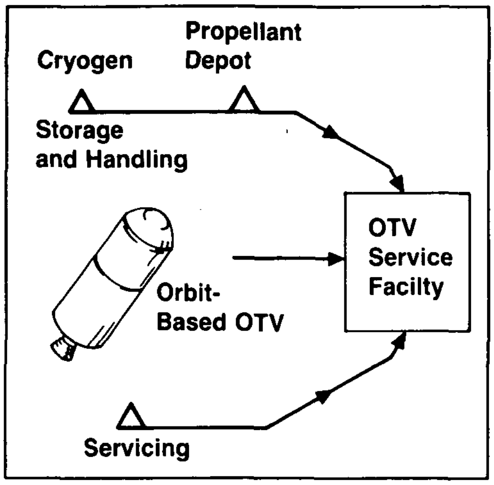

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FIGURE 3-14.

SATELLITE SERVICING TECHNOLOGY

(TOP001 PRIORITY 1)

VGB465

MISSION OBJECTIVES

- Develop On-Orbit Satellite Servicing Technology for Free Flying and Space Platform Payloads

BENEFIT

- Space Program Cost Improvements by Developing Technology for Satellite Servicing

CRITICAL ENVIRONMENT

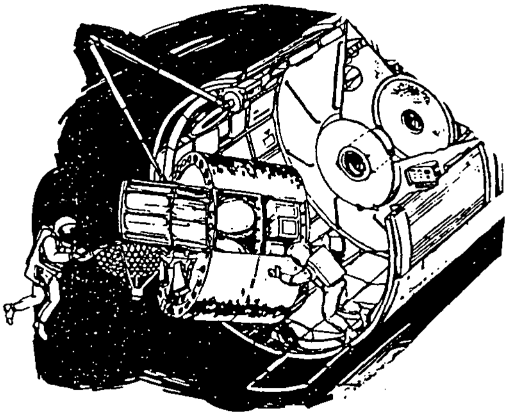
- Operation Orbit Characteristics

SPACE FACILITY REQUIREMENTS

- Satellite Service Module/Platform
- 60-Day Mission Duration
- TMS and/or EVA Equipment

MISSION/HARDWARE

- IOC 1992
- Servicing Tools/Fixtures; Instruments
- Satellite Mockups



MISSION DESCRIPTION

- Conduct Tests Using Manned and/or Automated Facilities for Subsystem Module Replacement, Checkout, Grapple/Attachment Techniques, Fluid Transfer, Servicing, and Repair of Satellites

An equivalent to a small spacelab module will require the use of one port. Through the port, 1000 W of electrical power will be made available as needed. As expected, this mission requires a large number of EVA operations (20). For 60 days a year, two crewmen at eight hours per day are required.

3.2.7 Zero-g Antenna Range - TGN002

Communications satellites and certain electromagnetic sensors used in space (e.g., synthetic aperture radar) require antennas that are so large that deployment of the antenna in space is required and pattern measurement in a one-g environment is difficult because of gravity-induced dimensional changes. A related problem is that ground antenna ranges typically have reflection characteristics that affect the pattern measurement accuracy. These problems can be alleviated by measuring antenna patterns in space with a zero-g antenna range. This capability could be implemented by mounting the antenna under test on the outside of the space station and connecting receiving and recording equipment to its feed ports. As shown in Figure 3-15, an RF transmitter is mounted on a TMS, which would be stationed away from the space station at a distance that provides far-field characteristics. The RF source transmits toward the antenna being tested, and the antenna response is measured and recorded as a function of the varying angle between the RF line of sight and the antenna boresight. Independent means of accurately measuring this angle are required. This capability could lead to improvements in achievable performance for space antennas and, consequently, to improved capability in the communication satellite systems and sensor systems where the antennas are used.

Electrical power required is 1 kW. Two crewmen will be involved for eight hours per day, 10 days throughout the year. During this time, six EVA operations will be performed. Although one port will be required, no internal volume is needed.

FIGURE 3-15.
ZERO-G ANTENNA RANGE
(TGN002, PRIORITY 2)

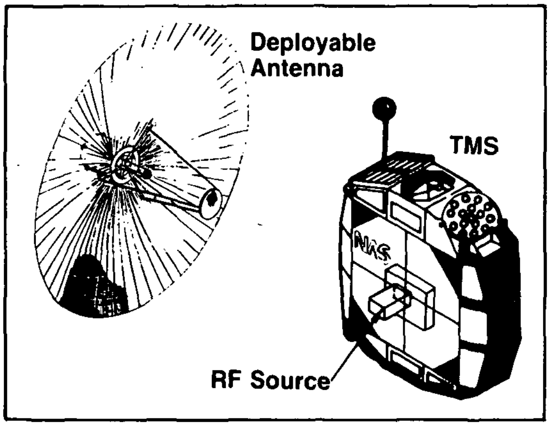
OBJECTIVE
- Evaluate Performance and Measure Antenna Pattern of Spacecraft Antennas

BENEFIT
- Improved Performance/Life Cycle Cost of COMSATS and Imaging Radar Satellites (e.g., SEE001, Ocean Payload) by Elimination of Ground Test Constraints

CRITICAL ENVIRONMENTS
- Zero-g, Reflection-Free Environment

SPACE FACILITY REQUIREMENTS
- TMS
- Attitude Stability/Knowledge
- Crew Interaction
- 10-Day Mission/Year

MISSION HARDWARE
- TMS-Mounted RF Source
- Deployable Antenna
- Optical Alignment Tools



MISSION DESCRIPTION
- Deploy Antenna on Station; Use TMS at Far-Field Range to Measure Antenna Radiation Patterns. Use Optical Tools to Measure Reflector Dimensional Accuracy

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