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Final Report Volume II
Trade Study &
Technology Selection
Technical Report
D190-27487-2

Advanced Platform Systems Technology Study

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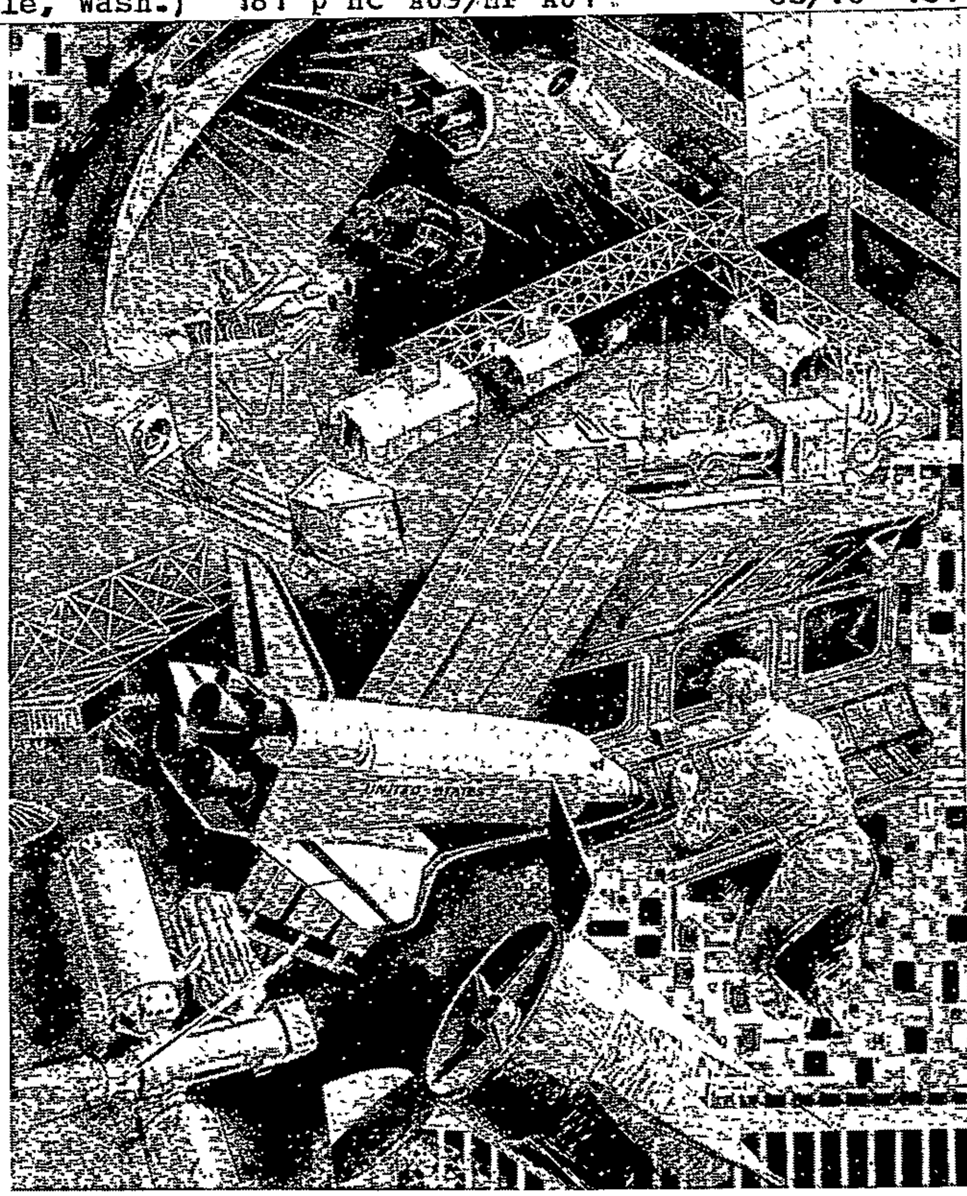

April 1983

BOEING

D180-27487-2

ADVANCED PLATFORM SYSTEMS TECHNOLOGY STUDY

Final Report

VOLUME II

TRADE STUDY AND TECHNOLOGY SELECTION, TECHNICAL REPORT

D180-27487-2

Conducted for NASA Marshall Space Flight Center

Under Contract Number NAS8-34893

April 1983

Boeing Aerospace Company

Spectra Research Systems

FOREWORD

The Advanced Platform Systems Technology Study (Contract NAS8-34893) was initiated in July 1982 and completed in April 1983. The study was conducted for the National Aeronautics and Space Administration, Marshall Space Flight Center, by the Boeing Aerospace Company with Spectra Research Systems as a subcontractor. The study final report is documented in four volumes.

D180-27487-1	Vol. I	Executive Summary
D180-27487-2	Vol. II	Trade Study and Technology Selection Technical Report
D180-27487-3	Vol. III	Support Data
D180-27487-4	Vol. IV	Technology Advancement Program Plan

Mr. Robert F. Nixon was the Contracting Officer's Representative and Study Technical Manager for the Marshall Space Flight Center. Dr. Richard L. Olson was the Boeing study manager and Mr. Rodney Bradford managed the Spectra Research Systems effort. A listing of the key study team members follows.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACS	Attitude Control System
AGC	Automatic Gain Control
APD	Avalanche Photo Diode
ASE	Airborne Support Equipment
BIT	Built-in Test
BTU	British Thermal Units
BW	Bandwidth
CCTV	Closed Circuit TV
CELSS	Controlled Ecological Life Supply System
CG	Center of Gravity
CMG	Control Moment Gyro
CMOS	Complimentary Metal Oxide Semiconductor
	Centimeters Per Second
CMOS/SOS	CMOS/Silicone on Sapphire
CRC	Cyclical Redundancy Check
dB	Decibels
DISCO	Distributed Star Coupled
DOD	Department of Defense
EC/LSS	Environmental Control-Life Support System
EMI	Electro-Magnetic Interference
EMU	Extra-Vehicular Mobility Unit
ETVP	Engineering Test Verification Platform
EVA	Extra Vehicular Activity
FDS	Frequency Division Multiplexing
ft	Feet
GBPS	Giga Bits Per Second
HM	Habitat Module
H/O	Hydrogen-Oxygen
hr	Hour
Hz	Hertz
IAC	Integrated Analysis Capability
IAF	International Aeronautical Federation
IBM	International Business Machines
IC	Integrated Circuits
IEEE	Institute of Electrical, Electronics Engineers
ILD	Injection Laser Diode
IR	Infrared
ISO/OSI	International Standards Organization/Open System Interconnect
IVA	Intervehicular Activity
JSC	Johnson Space Center

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

K	Thousand
KBPS	Kilo Bits Per Second
KG	Kilo Group
km	Kilo Meter
kW	Kilowatts
kWhr	Kilowatt Hours
LAN	Local Area Network
lb	Pound
LED	Light Emitting Diode
LISP	List Processor
LM	Logistics Module
LOX	Liquid Oxygen
LRU	Line Replaceable Units
LSI	Large Scale Integration
LSS	Life Support System
LV/LH	Local Vertical/Local Horizontal
M	Million
MBPS	Millions of Bits Per Second
MHz	Mega Hertz
MIPS	Millions of Iterations Per Second
MMS	Multimission Modular Spacecraft
MPS	Meters Per Second
MSFC	Marshall Space Flight Center
MSI	Medium Scale Integration
MTBF	Mean Time Before Failure
NASA	National Aeronautics and Space Administration
NIM	Network Interface Module
nm	Nautical Miles
NMS	Newton-Meter-Seconds
NOS	Network Operating System
OPERA	Orbital Payload Environmental Radiation Analyzer
OTV	Orbital Transfer Vehicle
PCS	Plastic Clad Silica
PIN	Positive Intrinsic Negative
psia	Pounds Per Square Inch Absolute
RCA	Radio Corporation of America
RCS	Reaction Control System
RFI	Radio Frequency Interference
RPM	Revolutions Per Second
SAR	Synthetic Aperature Radar
SADMP	Science and Applications Manual Space Platform
SASP	Science and Applications Space Platform
sec	Seconds
SOC	Space Operations Center
SIF	Systems Integration Facility

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

SRS	Spectra Research Systems
SSI	Small Scale Integration
TCS	Thermal Control System
TDRSS	Tracking Data Relay Satellite System
TOC	Total Organic Carbon
TV	Television
ULSI	Ultra-Large Scale Integration
VAX	Virtual Address Extension
VHSIC	Very High Speed Integration Circuit
VLSI	Very Large Scale Integration
WDM	Wavelength Division Multiplexing

KEY TEAM MEMBERS

Subject	MSFC-Management Team	Contractor Team
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1.0 INTRODUCTION

This is volume II of the final report on the Advanced Platform Systems Technology Study conducted for the Marshall Space Flight Center by the Boeing Aerospace Company and Spectra Research Systems. The overall study objective was to identify, prioritize, and justify the advancement of high leverage technologies for application on the early space station. The objective was fulfilled through a systematic approach to trade study identification and selection, trade study analysis, and selection of technology advancement items. This volume presents the results of the technical effort.

The study effort proceeded from the identification of 106 technology topics to the selection of 5 for detail trade studies. The technical issues and options were evaluated through the trade process. Finally, individual consideration was given to costs and benefits for the technologies identified for advancement. Eight priority technology items were identified for advancement and are reported in this volume together with the rationale and justification for their selection. A plan for advancing each of the eight technology items is presented in volume IV of this report. Volume III contains selected supporting data generated during the trade selection and trade study process used in the study. Volume I summarizes the overall study approach and results.

The study was divided into three primary tasks which include task 1—trade studies, task 2—trade study comparison and technology selection, and task 3—technology definition. Task 1 general objectives were to identify candidate technology trade areas, determine which areas have the highest potential payoff, define specific trades within the high payoff areas, and perform the trade studies. In order to satisfy these objectives, a structured, organized approach was employed. Candidate technology areas and specific trades were screened using consistent selection criteria and considering possible interrelationships. Figure 1.0-1 displays the overall screening process.

As shown in figure 1.0-1, a data base comprising both manned and unmanned space platform documentation was used as a source of system and subsystem requirements. When requirements were not stated in the data base documentation, assumptions were made and recorded where necessary to characterize a particular spacecraft system. The requirements and assumptions were used together with the selection criteria to establish technology advancement goals and select trade studies. While both manned and unmanned platform data were used, the study was focused on the concept of an early manned space station.

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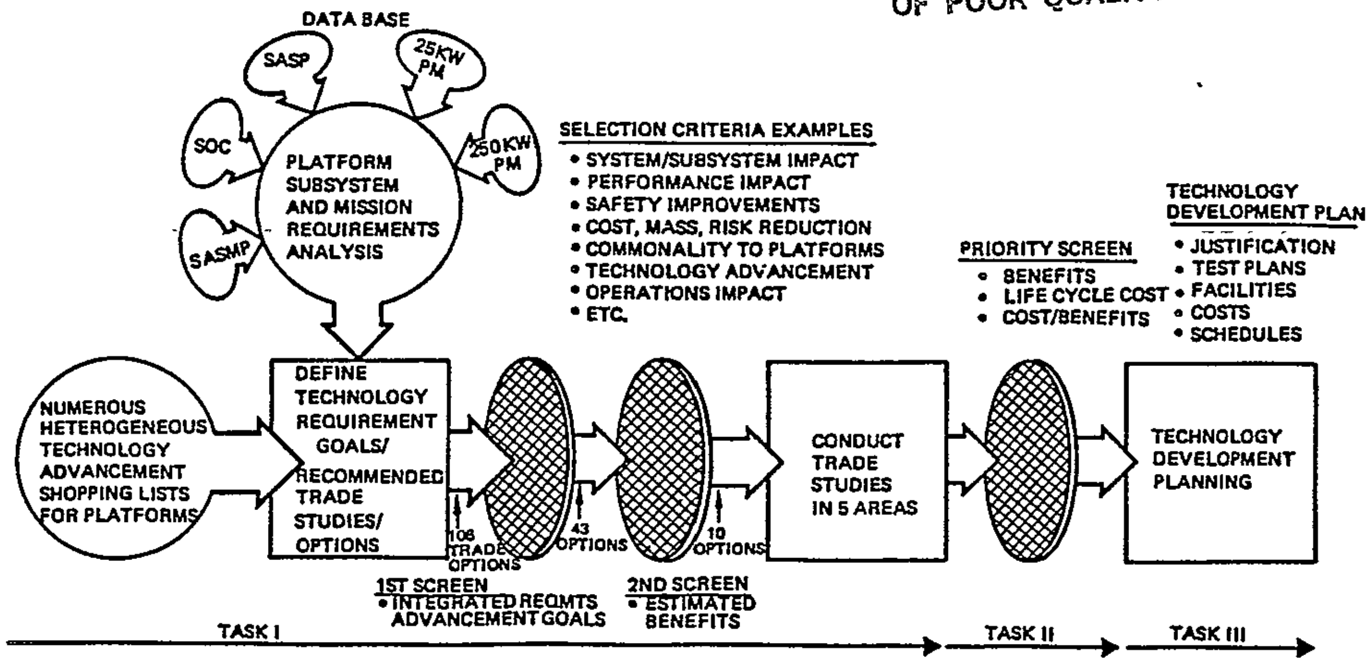

Figure 1.0-1. Study Concept Features Multiple Evaluation and Selection Screening to Identify Most Promising Platform Technologies

The study flow is shown in figure 1.0-2. As stated, the study started with space platform requirements, proceeded through trade study and cost benefits analysis, to technology advancement planning. The structured approach used in the study took advantage of a

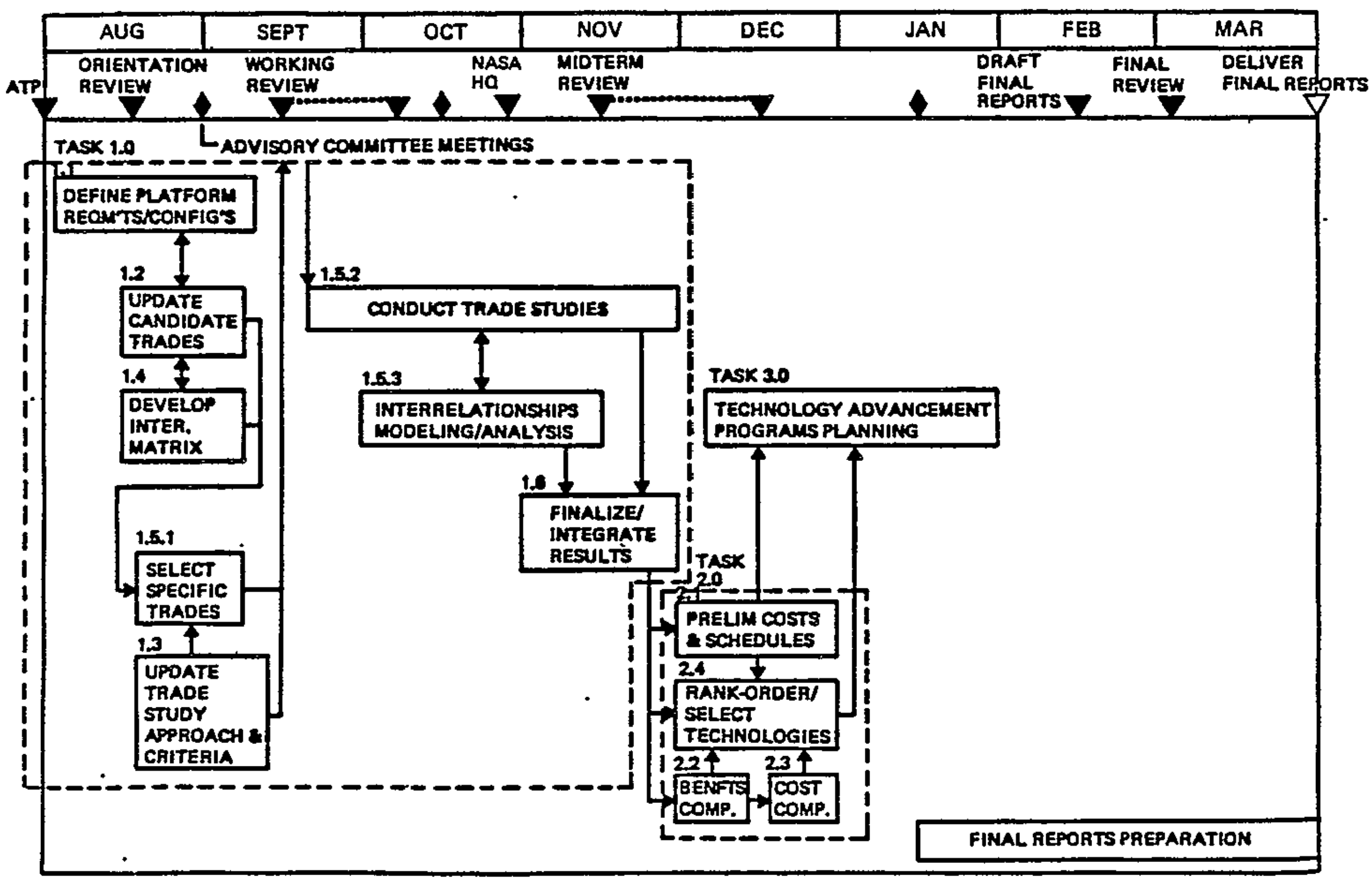

Figure 1.0-2. Study Logic Flow Accommodates All Study Requirements in Six Months

number of forms developed to ensure that a consistent approach was employed by each of the diverse specialists that participated in the study. These forms were an intrinsic part of the study protocol.

Example forms are shown in figures 1.0-3, -4, and -5. Form 1 was used to record and organize requirements. Form 2 was used to record trade study advancement goals and benefits and list technology options. Form 3 contained a listing of the initial selection criteria. Volume III of this report provides copies of the completed forms.

The task 2 objective was to evaluate the results of the trade studies performed in task 1, prioritize and select technologies with respect to comparative cost and benefit potential in the context of overall system compatibility. The task was accomplished in four primary steps in which advancement costs, schedules, comparative benefits and platform life-cycles costs were used to rank, order, and select the most promising technologies requiring advancement. The advancement steps were defined in task 3. Sections 4.0 and 5.0 of this volume reports on the results of task 2.

The primary objectives of task 3 were to provide the justification for technology advancement based on the detailed trade studies and benefit analysis and to prepare the test plans for each technology item identified. The advancement plan includes rationale, benefits, resources costs and schedules keyed to a platform program development schedule. Volume IV of this report presents the results of task 3.

REQM'T CODE NO	TECHNOLOGY DISCIPLINE / REQUIREMENT ** ** = MISSION ENABLING REQM'T	MANNED PLATFORMS: EARLY LEO: SASMP	MANNED PLATFORMS: EARLY LEO: SOC	MANNED PLATFORMS: ADVANCED LEO: SASMP	MANNED PLATFORMS: ADVANCED LEO: SOC	MANNED PLATFORMS: GEO: SOC	UNMANNED PLATFORMS: EARLY SASP	UNMANNED PLATFORMS: INTER-MEDIATE SASP	UNMANNED PLATFORMS: ADVANCED SASP	UNMANNED PLATFORMS: 250 KW PWR MOD	UNMANNED PLATFORMS: GEO: COM PLAT
	RADIATOR SYSTEM PM = POWER MODULE SM = SERVICE MODULE HM = HABITAT MODULE	PM • Deployable/ Constructable • 19.2 kW_T rejection • Non-toxic loop to HM • - - - - - - - • - - - - - - -	SM • Deployable/ Constructable • 18.2 kW_T rejection • - - - - - - - HM • Deployable • Integral w/ Meteoroid Shield • 13.2 kW_T max./HM • Non-toxic interior loop (dual loop) •	PM • Deployable/ Constructable • 32.4 kW_T Rejection • Non-Toxic Loop to HM • - - - - - - -	SM • Deployable/ Constructable • - - - - - - - HM • Deployable • Integral w/ Meteoroid Shield • 13.2 kW_T max./HH • Non-toxic Interior Loop (Dual Loop)	SM • Deployable/ Constructable • - - - - - - - • - - - - - - - HM • Deployable • Integral w/ Shield • Non-toxic Interior Loop (Dual Loop) •	• Deployable/ Constructable • - - - - - - - • - - - - - - - • - - - - - - -	• Deployable/ Constructable • 25 kW_T Nom. • - - - - - - -	• Deployable/ Constructable • 25 kW_T/ Payload • - - - - - - -	Not Defined	• Deployable/ Constructable • 0.2 kW_T per module (Comm Sys) • - - - - - - - • - - - - - - - 2 Constellation 6 Platform/ Constell. Only Others Not Defined

Figure 1.0-3. Form No. 1 — Platform Requirements Compilation Form

Technology Discipline / Technology Advancement Goal	Benefits	Applicable to: Manned Platforms: Early LEO	Manned Platforms: Adv LEO	Manned Platforms: Adv GEO	Unmanned Platforms: Early LEO	Unmanned Platforms: Int. LEO	Unmanned Platforms: Adv LEO	Unmanned Platforms: GEO	Technology Criticality Category	Specific Trades	Options	Current Technology Readiness Level	Technology Context
DEVELOP THERMAL MANAGEMENT SYSTEM CAPABLE OF ACCOMMODATING INTER CHANGEABLE PAYLOADS/VARYING THERMAL LOADS	• More Efficient Energy Use • Higher Reliability • Reduced Hardware Requirement • Reduced Weight • - - - - - - - • - - - - - - -	●	○	○	●	●	●	●	Tech Adv. Req'd	Decentralized vs Centralized Thermal Management Systems Centralized System • Evaluate Competing Thermal Bus Concepts • Identify PM/Bus Heat Exchanger Link • Evaluate Applicable Radiator Systems • Evaluate Applicable P/L Interfaces	• Single Centralized • Multiple Centralized • Decentralized (P/L) • Single Phase Pumped Loop • 2 Phase Pumped Loop • High Capacity Heat Pipe • - - - - - - • Deployable • Constructable • Forced Flow • Heat Pipe • Fixed • Moveable	- - - - - - - - - - - - 8 6 3–5 3 - - - - - - - - - - - - 4–6 -	

Figure 1.0-4. Form No. 2 — Technology Advancement Identification Form

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TECHNOLOGY DISCIPLINE	THERMAL CONTROL
TECHNOLOGY ADVANCEMENT GOAL	DEVELOP THERMAL MANAGEMENT SYSTEM CAPABLE OF ACCOMMODATING INTERCHANGEABLE PAYLOADS/VARYING THERMAL LOADS
SPECIFIC TRADE	DECENTRALIZED VS CENTRALIZED THERMAL MANAGEMENT SYSTEM

CRITERIA	ESTIMATED BENEFIT
• SYSTEM IMPACTS	REDUCED ENERGY REQMTS (INSTR. HEATING & ACTIVE ELEMENT CONSUMPTION)
• SUBSYSTEM IMPACTS	> 50% REDUCTION IN S/S HARDWARE
• PERFORMANCE IMPROVEMENTS	68–92% INCREASE IN P/L HEAT REJECTION CAPABILITY
• OPERATIONS IMPROVEMENTS	
• SAFETY IMPROVEMENTS	
• LIFETIME IMPROVEMENTS	
• MAINTAINABILITY IMPROVEMENT	
• RELIABILITY IMPROVEMENTS	ALL ACTIVE ELEMENTS REPLACED BY PASSIVE COMPONENTS
• COST REDUCTION	
• MASS REDUCTION	
• RISK REDUCTION	
• COMMONALITY AMONG PLATFORMS	
• TECHNOLOGY ADVANCEMENT REQUIRED	
• SCHEDULE REDUCTION	
• DESIGN SIMPLIFICATION	
• SYNERGISM	
• LONG RANGE POTENTIAL	
• MISSION ENABLEMENT	
• SHUTTLE IMPACTS	
• PACKAGING IMPACTS	

Figure 1.0-5. Form 3 — Specific Trade Benefits Estimate

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2.0 TRADE SELECTION

This section covers the process and rationale that was used to reduce the initial 106 topics that were candidates for trade study to the five areas that were studied.

2.1 PROCESS

The process used to select five trade study candidates through a systematic evaluation process is shown by the flow diagram of figure 2.1-1. Initially the list of topics for trade study included 106 candidates. These candidates resulted from a compilation of topics

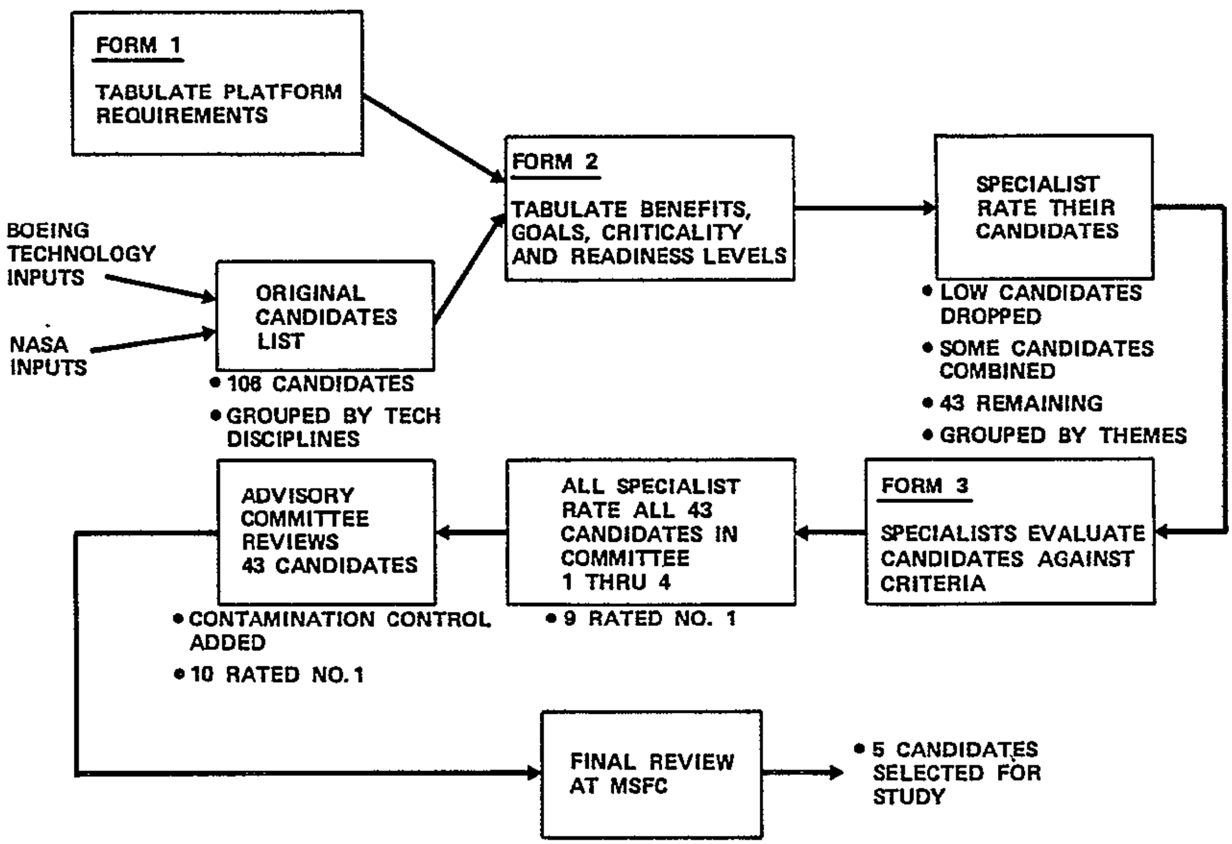

Figure 2.1-1. Candidate Selection Flow

suggested by National Aeronautics and Space Administration-Marshall Space Flight Center (NASA-MSFC) and by the team of Boeing technical evaluators after they had reviewed the baseline documentation for the study. Tables 2.1-1 through 2.1-11 list the titles of the initial 106 candidates according to the eleven technology disciplines which were used to organize the candidate topics.

Table 2.1-1. Systems Technology Original Candidates

- o Technical System Analysis Across Disciplines
- o Man and Automatic Task Allocation
- o Interface Commonality and Evaluation
- o Space Station Autonomy
- o System Maintenance Technology
- o Crew Station Human Factors
- o Teleoperator
- o Human Capabilities
- o Contamination Prediction and Protection
- o Orbit Atmosphere Environment Dynamics
- o Manufacturing Assembly, Test, Checkout Interface Verification
- o Simulation and Training
- o Automated Aids to Design, Integration, Configuration Management, and Interface Control
- o Collision Protection and Avoidance

Table 2.1-2. Thermal Technology Original Candidates

- o Long-Life Heat Rejection
- o Thermal Acquisition Transport
- o Thermal Berthing Interface
- o Movable, E.G. Subplatform, Interface
- o Radiator Packaging: Deploy Versus Construct
- o Coatings - Controllable, Long-Life Refreshable
- o Centralized Versus Decentralized TCS
- o Transient or Special Load Handling, E.G.
- o Automated Thermal Management

Table 2.1-3. Structures Technology Original Candidates

- o Structural System Identification
- o Structural Concepts
- o Dynamics and Control Analysis
- o Definition of Contamination Sources
- o Metal Matrix
- o Composites Lifetime and Properties Prediction Technology
- o Dynamics Prediction Through Analysis Models
- o Damping Active and Passive

Table 2.1-4. Environmental Control and Life Support Technology Original Candidates

- o Life Support Technology Demonstration
- o Advanced EC/LSS
- o Integrated and Accelerated Development
- o Accelerated Habitability Improvements
- o Life Support Technology Testing
- o Higher Pressure EVA Suit
- o Water Quality Monitor
- o Backpack Regenerable Heat Sink

Table 2.1-5. Operations Technology Original Candidates

- o Launch Support
- o Formation Flying and Differential Drag
- o Approach Rendezvous and Docking Methods
- o Technology for On-Orbit Maintenance
- o Satellite Servicing and Basing
- o Refueling Operation
- o Housekeeping Operation
- o Continuous Operations
- o Operations with Teleoperators and Robots
- o Construction Equipment and Tools
- o Reliability, Availability and Maintainability
- o Autonomy of Operations

Table 2.1-6. Data Systems Technology Original Candidates

- o Microprocessor Selection
- o Language Selection
- o Software Writing Automation
- o Man and Machine Interface
- o Voice Communication
- o Application of Computer Generated Imagery
- o Software Production Automation
- o Fiber Optics Data Buses
- o Information Network Architecture
- o Network Simulation and Analysis
- o Expert Systems
- o Fault Tolerant Computer Modules
- o Automation Technology for Subsystems

Table 2.1-7. Communications Technology Original Candidates

- o Telecommunications System Studies
- o Forward Error Correction
- o Spread Spectrum
- o Baseband Structure and Modulation
- o High-Speed Digital Processing
- o Spherical Antenna Coverage
- o Earth-to-Space and Space-to-Earth Communications
- o Space-to-Space Data Links
- o Traffic Control Radar
- o High Gain Antenna

Table 2.1-8. Electrical Power Technology Original Candidates

o	Plasma Characterization
o	Bulk Power Transfer
o	N H_2 Battery
o	High Voltage Components
o	H_2 0_2 Regenerative Fuel Cell
o	Solar Cell Welding
o	Distributed Voltage and Power Processors
o	Automated Power Management
o	Solar Array Concentrators
o	Power Conductors

Table 2.1-9. Propulsion Technology Original Candidates

o	H/O Auxiliary Propulsion System
o	Cryogenic Fluid Resupply
o	Resisto Jet
o	Fluid Leak Detection
o	Cryogenic Zero Gaging

Table 2.1-10. Guidance and Navigation Technology Original Candidates

o	On-Orbit Timekeeping
o	Automatic Rendezvous and Docking Control
o	Orbit Track Control
o	Relative Navigation
o	Autonomous On-Board Navigation

Table 2.1-11. Attitude Control Technology Original Candidates

- Distributed Control
- Applied System Identified and Adoptive Control
- Intervehicle Control and Docking
- Attitude Determination
- Instrument Pointing
- Micro-Gravity Control
- Control System Blending
- Advance Algorithms
- Variable Attitude Strategy
- Platform and Subplatform Figure Measurement and Control
- Disturbance Supression
- Advance Attitude and Inertial Sensors

The individual Boeing technical evaluators reviewed the candidates in their discipline areas according to technology advancement benefits, technology availability status, and existing advancement activities being conducted by NASA. This information was recorded on the Option Benefit Survey form 2. (These completed option benefit survey forms are presented in section 3.0 of volume III of this report.) This process which is the first screening shown on figure 1.0-1, eliminated 63 of the original 106 candidates. The candidates eliminated and a brief statement of the reason for elimination of each are listed on table 2.1-12.

After reducing the list to 43, the remaining candidates were arranged according to the seven theme areas listed on table 2.1-13. Each of the technical evaluators filled out form 3, Specific Trade Benefits forms for those candidates remaining in their area of technical discipline. See section 4.0 of volume III for the completed forms. During this process, some rephrasing of the candidate topics occurred; table 2.1-14 shows that rephrasing. With this information in hand, the technical evaluators attended a conference meeting where each evaluator presented their trade candidates with supporting data and rationale for evaluation and ranking. The process included deliberation and voting by all evaluators to rank all of the remaining 43 candidates, one through four. A number one ranking is the most desirable for trade study. After the meeting, each evaluator considered the voted ranking independently and forwarded comments where they disagreed with the majority opinion. These comments in fact did elevate the topic of "Developing a Space Qualified Traffic Control Radar" to a number one ranking. Table 2.1-15 shows the ranking of candidates which are listed according to technology theme areas. This ranking was then reviewed by the Management Advisory Committee and a final selection of the top candidates for presentation to NASA was made. Table 2.1-16 is the prioritized list of the top ten candidates with the highest ranked candidate listed first. The reasons for eliminating 33 candidates to reach this set are listed on table 2.1-17. Table 2.1-18 shows a technology interaction matrix for the topics listed on table 2.1-16. This matrix was used to check for technology impacts which could change the prioritization of the top topics prior to presenting them to NASA. No changes were considered necessary because of this comparison of interrelationships. At this point, the second screening on figure 1.0-1 was complete.

The final list of 10 candidates was then reviewed with NASA and 5 candidates were selected for study. The selection of candiates was based on NASA's own prioritization of the list and a need to keep the studies within the available resources. The final five technology trade areas are given by table 2.1-19.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Man and-automatic task allocation.	This is system design and does not require technology advancement.
System maintenance technology.	As a general topic, this becomes a design trade.
Teleoperators.	Technology advancement is not new unless automatic traffic control is used.
Human capabilities.	Technology advancement is being pursued on shuttle program.
Simulation and training.	Sufficient attention is already being given to advancing this technology.
Automated aids to design, integration, configuration management and interface control.	Benefits of this technology are not critical to the early space station.
Thermal berthing interface.	Technology advancement studies are already underway.
Moveable, e.g., subplatform thermal interface.	This is not a new technology.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Radiator packaging; deploy versus construct.	This is a design issue at the component level rather than a new technology.
Coatings - controllable, long-life, refreshable.	Technology advancement studies are already underway.
Transient or special load handling.	This is a design study in thermal control not a new technology.
Dynamics and control analysis.	Recent IAC work makes this technology current.
Definition of contamination sources.	This is a sub-set the contamination prediction and protection candidate which was selected by Boeing.
Life-support technology demonstration.	Technology advancement studies are underway.
Integrated and accelerated development.	Technology advancement studies are underway.
Accelerated habitability improvements.	Technology advancement studies are underway.
Life support technology testing.	Technology advancement studies are underway.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Water quality monitor.	Technology advancement studies are underway.
Backpack regenerable heat sink.	Technology is being advanced and is not required for early space station.
Metal matrix.	Combine with candidate on composites lifetime and properties prediction technology.
Formation flying and differential drag.	This technology is well defined; new operations are part of system design.
Approach rendezvous and docking methods.	Except for automatic functions which are not necessary for an early space station, this technology is well defined.
Dynamics prediction through analytic models.	This methodology is well established.
Satellite servicing and basing.	Not needed for an early space station.
Refueling operations.	This candidate is a system design topic rather than a new technology topic.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Housekeeping operations.	Technology being pursued.
Continuous operations.	Technology being pursued.
Operations with teleoperators and robots.	Processes are definable through system design.
Reliability, availability and maintainability.	These are design issues which do not require new technology.
Micropressor selection.	Selection process does not require new technology.
Software writing automation.	Significant DOD advancement effort is already being applied.
Man and machine interface.	Much effort is already being expended in this field.
Application of computer generated imagery.	This technology is being pursued already.
Software production automation.	Much DOD effort is already being applied to this technology.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Network simulation and analysis.	This technology is being pursued already.
Expert systems.	This technology is only needed to perform functions and not as an end in itself. It is being recommended for advancement effort as part of the integration of automated housekeeping function.
Fault-tolerant computer modules.	This technology is being pursued already.
Automation technology for subsystems.	This candidate is part of a larger function, the Integration of Automated Housekeeping.
Telecommunications system studies.	This is a system design function and does not involve new technologies.
Forward error correction.	The technology for this communication function is being pursued already.
Spread spectrum.	This technology is already being pursued.
High-speed digital processing.	This is not an independent topic from those covered under data management.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Spherical antenna coverage.	For a specific space station this would be required as a design process but not as a technology advance.
Space-to-space data links.	This is a well developed technology except for antenna pointing which is an attitude control program.
High-gain antenna.	Antenna technologies are well in hand.
Plasma characterization.	Specific issue which is already being studied.
Bulk power transfer.	Not a new technology.
H_2O_2 regenerative fuel cell.	This topic was combined with NiH_2 battery and others to form the energy storage topic.
Automated power management.	This candidate was combined with Space Station Autonomy which was eventually selected.
Power conductors.	Design trades only are involved with this candidate - not new technology.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
H/O auxiliary propulsion system.	This technology is already being advanced by studies that are underway.
Resisto jet.	This concept does not provide high leverage benefits - the cost benefits depend on missions and orbit altitudes - not a high risk technology.
Fluid leak detection.	This is a very specific topic which does not lend itself to trade studies.
Cryogenic zero-G gaging.	Specific study which is already being pursued.
On-orbit timekeeping.	Technology is well understood.
Orbit track control.	Design trades are involved with this candidate - not new technology.
Relative navigation.	This is a well-defined technology whose implementation involves data management design trades.
Attitude determination	Technology is already pursued.

Table 2.1-12. Technology Candidates Eliminated by the First Cut

Candidate Eliminated	Reason
Variable attitude strategy.	Studies of this technology are already underway.
Platform and subplatform figure measurement and control.	This candidate was combined with the instrument pointing topic which was included in the final selection by Boeing.
Advance attitude and inertial sensors.	This candidate is a specific topic that is already being advanced.
Autonomous on-board navigation.	This technology is being pursued - for example the IUS program.
Disturbance supression.	On-going contracts exist to develop this technology.

Table 2.1-13. Technology Theme Areas

Autonomous Station Operation. The routine operations of the space station should be conducted as much as possible without human attention either on the ground or within the station itself.
Enhance Man's Role in Space. Technology advancement will support manned operations and manned functions on the space station.
Evolution of the Space Station. The space station is expected to grow on-orbit from the initial configuration to one which is much more complex. Initial concepts should accommodate this growth with minimum redesign.
Combine System Functions. To save on-orbit weight and make operations more efficient, every advantage should be taken of functions which can be combined in the same hardware.
Long Life Capability. The space station is expected to operate with maintenance for several decades as a minimum. Technology needs to be considered with that in mind.
Control of Large Flexible Structures. Because of the large size of the station and need to keep on-orbit weight at a minimum, the space station will be unusually flexible; attitude control as well as thrust vector control need to be considered.
Subsystem Performance Improvements. Unique characteristics of the space station indicate need for technology improvements in the subsystem area.

Table 2.1-14. Rephrasing Guide to Candidates Remaining After the First Cut

Original Form	Rephrased Form
Voice communication.	Develop and evaluate voice communication techniques for manned compartment as well as other areas such as platform maintenance and EVA.
Earth-to-space and space-to-Earth communications.	Develop a lightweight-low cost voice and voice bandwidth communications system for intercom, EVA proximity and space/ground communications.
Baseband structure and modulation.	Develop a high data rate communication link capable of handling up to 4 digitized color TV channels along with other high rate data.
Advanced EC/LSS.	Regenerative LSS development and testing.
Interface commonalty and evaluation.	No change.
Centralized versus decentralized TCS.	TCS modularity.
Structural system identification.	Evolutionary structural concepts.

Table 2.1-14. Rephrasing Guide to Candidates Remaining After the First Cut

Original Form	Rephrased Form
Collision protection and avoidance.	No change.
Space station autonomy.	Non-automated integration of electrical power, EC and LSS thermal control, ACS, and propulsion.
Automated thermal management.	Automated housekeeping subsystems.
Intervehicle control and docking.	Automated terminal phase rendezvous and docking guidance and control.
Automatic rendezvous and docking control.	Automated traffic control system.
Launch support.	Space-based launch control system.
Autonomy of operations.	Autonomous mission planning and contingency operations.
Higher pressure EVA suit.	Develop improved EMU, EVA suit.
Crew station human factors.	Develop and evaluate multi-function controls and displays for human space environment.

Table 2.1-14. Rephrasing Guide to Candidates Remaining After the First Cut

Original Form	Rephrased Form
Construction equipment and tools.	Develop improved performance manipulator.
Information network architecture.	Develop and evaluate process for applicability of microprocessor in a distributed architecture.
Fiber optics data buses.	Develop and evaluate types of data buses applicable to distributed architecture, including fiber optics.
Applied system identified and adaptive control.	Develop control system which is robust with respect to changing control and structural interaction.
N H_2 battery.	Energy storage.
Damping active and passive.	Advanced algorithms for structural mode control and damping active vs. passive and structural damping.
Instrument pointing.	Develop control techniques for precision instrument pointing.
Advanced algorithms.	Develop control techniques for thruster operation on flexible structures

Table 2.1-14. Rephrasing Guide to Candidates Remaining After the First Cut

Original Form	Rephrased Form
Long-life heat rejection.	Long lifetime TCS.
Orbit atmosphere environment dynamics.	Orbit makeup propulsion selection.
Cryogenic fluid resupply.	Develop system for in-space gas liquid and cryogen resupply and leak proof change.
Manufacturing, assembly, test, checkout, interface verification.	Manufacturing technology, assembly checkout, test and interface verification technology.
Composites lifetime and properties.	No change.
Technology for on-orbit maintenance.	Deployment mechanisms.
Structural concepts.	Alternate materials development.
Contamination prediction and protection.	Control space station contamination.

Table 2.1-14. Rephrasing Guide to Candidates Remaining After the First Cut

Original Form	Rephrased Form
Language selection.	Develop and evaluate high order language and software tools.
Traffic control radar.	Develop space qualified traffic control radar.
Distributed voltage and power processors.	Develop high power and high voltage power conditioning equipment.
Solar array concentrators.	No change.
Solar cell welding.	Solar array reduction.
Control system bleeding.	Attitude control thruster selection.
Micro-gravity control.	Develop techniques to provide micro-G environment.
Thermal acquisition transport.	Constant temperature thermal bus.
Technical system analysis across disciplines.	RFI free space platform.

Table 2.1-15. Rating of Technology Candidates Within Theme Areas

		Rating
Autonomous Station Operation		
a.	Collision protection and avoidance.	2
b.	Non-automated integration of electrical power, EC/LSS, thermal control, ACS, and propulsion.	3
c.	Automated housekeeping subsystems.	1
d.	Automated terminal phase rendezvous and docking guidance and control.	2
e.	Automated traffic control system.	2
f.	Space based launch control system.	2
g.	Autonomous mission planning and contingency operations.	3
Enhance Man's Role in Space		
a.	Develop improved EMU, EVA suit.	2
b.	Develop and evaluate multi-function controls and displays for human space environment.	4
c.	Develop and evaluate voice communication techniques for manned compartment as well as other areas, such as platform maintenance via EVA.	4
d.	Develop a lightweight-low cost voice and voice bandwidth communication system for intercom, EVA proximity and space/ground communications.	4
e.	Develop a high data rate communication link capable of handling up to four digitized color TV channels along with other high rate data.	3
f.	Regenerate LSS development and testing.	2

Table 2.1-15. Rating of Technology Candidates Within Theme Areas (Cont'd)

		Rating
Evolution of the Space Station		
a.	Interface commonality and evaluation.	4
b.	TCS modularity.	2
c.	Evolutionary structural concepts.	3
d.	Develop improved performance manipulator.	2
e.	Develop and evaluate process for applicability of microprocessors in a distributed architecture.	1
f.	Develop and evaluate types of data busses applicable to distributed architecture including fiber optics.	1
g.	Distributed vs. centralized sensing and control action.	2
h.	Develop control system which is robust with respect to changing control/structural interaction.	1
Combined System Functions		
a.	Energy storage.	3
Control of Large Flexible Structures		
a.	Advanced algorithms for structural mode control and damping active vs. passive and structural damping.	2
b.	Develop control techniques for precision instrument pointing.	1
c.	Develop control techniques for thruster operation on flexible structures.	2
Long Life Capability		
A.	Long lifetime TCS.	1
b.	Orbit makeup propulsion selection.	2
c.	Develop system for in-space gas, liquid and cryogen resupply and leak proof change out of LRU's.	1

Table 2.1-15. Rating of Technology Candidates Within Theme Areas (Cont'd)

		Rating
Subsystem Performance Improvements		
a.	Manufacturing technology, assembly checkout, test, and interface verification technology.	4
b.	Composites lifetime and properties prediction.	3
c.	Deployment mechanisms.	4
d.	Alternate materials development.	2
e.	Control space station contamination.	1
f.	Develop and evaluate high order language and software tools.	3
g.	Develop space qualified traffic control radar.	1
h.	Develop high power and high voltage rotary joint.	2
i.	Develop high power and high voltage power conditioning equipment.	1
j.	Solar array concentrators.	3
k.	Solar array reduction.	3
l.	Attitude control thruster selection.	3
m.	Develop techniques to provide micro-G environment.	2
n.	Constant temperature thermal bus.	3
o.	RFI free space platform.	2

Table 2.1-16. Ranking of Top 10 Trade Study Candidates

1. Develop and evaluate types of data buses applicable to distributed architecture including fiber optics.

2. Develop control system which is robust with respect to changing control and structure interaction.

3. Long lifetime TCS.

4. Develop system for in-space gas, liquid and cryogen resupply and leak proof change out of LRU's.

5. Develop and evaluate process for applicability of microprocessors in distributed architecture.

6. Develop space qualified traffic control radar.

7. Develop techniques for controlling contamination of the space station.

8. Automated housekeeping subsystems.

9. Develop high power and voltage conditioning equipment.

10. Develop techniques for precision instrument pointing to minimize space disturbances.

Table 2.1-17. Technology Candidates Eliminated to Select the Final 10

Candidate	Reason for Elimination
Collision protection and avoidance.	Important, but studies have shown that the technology is too complex for practical advancement.
Nonautomated integration of electrical power, EC/LSS, thermal control, ACS and propulsion.	Effort is already underway at JSC on space station integration.
Automated terminal phase rendezvous and docking guidance and control.	Development of this technology needs to be encouraged for space stations, after the initial mission, when unmanned vehicles will be docked with the station - not necessary for early missions.
Automated traffic control system.	Key safety issue which is not being developed in U.S. - not necessary for early missions.
Space based launch control system.	Will require development only for later generation missions.
Autonomous mission planning and contingency operations.	This technology is not complex and is not mission enabeling.
Develop improved EMU, EVA suit.	This development is enabling to the space station, but studies are already underway.

Table 2.1-17. Technology Candidates Eliminated to Select the Final 10

Candidate	Reason for Elimination
Develop and evaluate multi-function controls and display for human space environment.	This technology is already being advanced.
Develop and evaluate voice communication.	Current technology will suffice for early techniques for manned compartment as well as other areas such as platform maintenance via EVA.
Develop a light-weight, low-cost voice and voice bandwidth communication system for intercom EVA proximity and space ground communications.	Current technology will provide an adequate.
Develop a high data rate communication link capable of handling up to 4 digitized color T V channels, along with other high rate data.	Except for millimeter wave requirements, the technology is well developed.
Regenerative LSS development and testing.	Needed technology but many trades have already been run and need has been enunciated.
Interface commonality and evaluation.	The technology already exists and the remaining issues are in system design.

Table 2.1-17. Technology Candidates Eliminated to Select the Final 10

Candidate	Reason for Elimination
TCS Modularity.	TCS can be made to operate without modularity, but technology needs to be developed for later generation space station.
Evolutionary Structural Concepts.	This is a natural outgrowth of other developments which are underway.
Develop improved performance manipulator.	Available designs should evolve to produce needed improvements without technology push.
Distributed vs. centralized sensing and control action.	The technology already exists to make this a system design issue.
Energy storage.	Energy storage technology drives space station weight - technologies are being developed.
Advanced algorithms for structural mode control and damping active vs. passive and structural damping.	There are on-going contracts which should give the required results.
Develop control techniques for thruster operation on flexible structures.	Required function - technology under development needs to be demonstrated.

Table 2.1-17. Technology Candidates Eliminated to Select the Final 10

Candidate	Reason for Elimination
Orbit makeup propulsion selection.	Trades are between LOX and H_2 motors. Studies are being conducted on Lewis contract.
Manufacturing technology, assembly, checkout, test, and interface verification technology.	KSC study contract to be let on this topic.
Composites lifetime and properties prediction.	Data are already being generated from operational use and experimental work - effects of space aging and outgasing need further study.
Deployment mechanisms.	This is only a design issue; the technology exists.
Alternate materials development.	Standard technology which is being developed should provide weight savings.
Develop and evaluate high order language and software tools.	Technology is being developed across industry, NASA and DOD.
Solar array concentrators.	Technology development is being pursued.

Table 2.1-17. Technology Candidates Eliminated to Select the Final 10

Candidate	Reason for Elimination
Solar array reductions.	Studies are underway in several areas related to reducing the size of arrays.
Attitude control thruster selection.	Further development of this technology is not necessary unless LOX-H_2 motors were used; selection technique would be part of the development of such motors.
Develop techniques to provide micro-G environment.	This is an extremely difficult technology-development is necessary for advanced missions where materials processing might need very low disturbances - early missions do not appear to require this.
Constant temperature thermal bus.	A lot of development money is already being applied to this area.
RFI free space platform.	Work has already been done (e.g. the Viking program) and further studies are underway.

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Table 2.1-18. Interrelationships Matrix

	AUTOMATED THERMAL, ELECT POWER AND EC/LSS SYSTEMS	DEVELOP/EVALUATE PROCESS FOR APPLICABILITY OF MICROPROCESSORS IN DISTRIBUTED ARCHITECTURE	DEVELOP/EVALUATE TYPES OF DATA BUSSES APPLICABLE TO DISTRIBUTED ARCHITECTURE INCLUDING FIBER OPTICS	DEVELOP ATTITUDE CONTROL SYSTEM WHICH IS ROBUST WITH RESPECT TO CHANGING CONTROL/STRUCTURAL INTERACTION	LONG LIFETIME TCS	DEVELOP IN-SPACE GAS, LIQUID AND CRYOGEN RESUPPLY AND LEAK PROOF CHANGE OUT OF LRU S	DEVELOP TECHNIQUES FOR CONTROLLING CONTAMINATION OF THE SPACE STATION	DEVELOP HIGH POWER/HIGH VOLTAGE POWER CONDITIONING EQUIPMENT	DEVELOP/EVALUATE SPACE QUALIFIED TRAFFIC CONTROL RADAR	DEVELOP TECHNIQUES FOR PRECISION INSTRUMENT POINTING WITH MANNED SPACE STATION DISTUHBANCE
1 AUTOMATED THERMAL, EC/LSS AND ELECTRICAL POWER SYSTEMS		THE AUTOMATED SYSTEMS WILL REQUIRE DATA PROCESSING WHICH MAY BE DISTRIBUTED	THE AUTOMATED SYSTEMS WILL REQUIRE THE TRANSFER OF DATA BETWEEN DISTRIBUTED CENTERS		THE EASE OF AUTOMATING THE TCS WILL BE RELATED TO THE LONG LIFE TECHNIQUES EMPLOYED	AUTOMATED THERMAL OR EC/LSS SYSTEMS MAY RESULT IN REMOTELY LOCATED LRU S FOR CHANGE OUT OR STATIONS FOR RESUPPLY		AUTOMATED POWER SYSTEM REQUIRE-MENTS MAY INFLUENCE THE DESIGN OF HIGH VOLTAGE EQUIPMENT	DUTY CYCLE OF SPACE RADAR AS POWER USER AND THERMAL SOURCE MAY INFLUENCE DESIGN OF THESE AUTOMATED SYSTEMS	
2. DEVELOP/EVALUATE PROCESS FOR APPLICABILITY OF MICROPROCESSORS IN DISTRIBUTED ARCHITECTURE	THE TYPE* OF MICROPROCESSOR ARCHITECTURE COULD SET REQUIREMENTS ON AUTOMATED SYSTEM DESIGN		DESIGN OF MICRO-PROCESSORS IN DISTRIBUTED ARCHITECTURE MUST BE INTEGRATED WITH DATA BUS TYPE	THE TYPE* OF MICROPROCESSOR USAGE AND DATA SYSTEM ARCHITECTURE MAY AFFECT ACS DESIGN					THE TYPE* OF MICROPROCESSING AND DATA SYSTEM ARCHITECTURE WILL IMPACT RADAR DESIGN	THE TYPE* OF MICROPROCESSING WILL IMPACT THE DESIGN ON PRECISION POINTING ACS
3. DEVELOP/EVALUATE TYPES OF DATA BUSSES APPLICABLE TO DISTRIBUTED ARCHITECTURE INCLUDING FIBER OPTICS	THE TYPE* OF DATA BUS USED COULD SET REQUIREMENTS ON AUTOMATED SYSTEM DESIGN	DATA BUS TYPE WILL BE RELATED TO THE DATA RATE & VOLUMES ASSOCIATED WITH THE MICRO-PROCESSOR DESIGN		THE TYPE* OF DATA BUS ARCHITECTURE USED MAY AFFECT ACS DESIGN					DATA BUS* TYPE AND ARCHITECTURE MAY IMPACT THE DESIGN OF THE RADAR	DATA BUS* TYPE MAY IMPACT DESIGN OF PRECISION POINTING ACS
4. DEVELOP ATTITUDE CONTROL SYSTEM WHICH IS ROBUST WITH RESPECT TO CHANGING CONTROL/STRUCTURAL INTERACTION	THE TYPE OF ACS USED WILL INFLUENCE THE DUTY CYCLE OF AUTOMATED THERMAL & ELECT POWER CONTROL SYSTEMS	ACS FOR CHANGING SPACE STATION WILL UTILIZE MICRO-PROCESSING IN DISTRIBUTED CONTROL CENTERS	ACS DATA WILL HAVE TO BE TRANSFERRED BETWEEN DISTRIBUTED CONTROL CENTERS & CENTRAL STATION PROCESSING		THE TYPE OF ATTITUDE CONTROL USED (ACCURACY & DUTY CYCLE) WILL AFFECT THE LIFETIME CAPABILITY OF TCS	ACS THRUSTER & TANKS REMOTELY LOCATED MAY REQUIRE CHANGE OUT OR RESUPPLY	ACS THRUSTER USAGE WILL AFFECT CONTAMINATION	ACS TYPE WILL EFFECT POWER SYSTEM DUTY CYCLE AND THUS THE EQUIPMENT REQUIREMENTS	THE ACS TYPE WILL CONSTRAIN THE DESIGN OF ANY SCANNING ANTENNA	THE TYPE OF OVER ALL ACS MAY IMPACT THE CAPABILITY FOR PRECISION POINTING
5. LONG LIFE TCS	THE TECHNIQUE USED FOR LONG LIFE TCS WILL AFFECT THE AUTOMATION DESIGN USED	LONG LIFE TCS MAY REQUIRE CAPACITY & SPEED FROM MICRO-PROCESSING EITHER REMOTE OR CENTRAL	LONG LIFE TCS MAY REQUIRE DATA TRANSFER BETWEEN DISTRIBUTED CENTERS & THE CENTRAL PROCESS-ING			LONG LIFE TCS MAY REQUIRE RESUPPLY AND CHANGE OUT CAPABILITY				
6. DEVELOP IN SPACE GAS, LIQUID AND CRYOGEN SUPPLY AND LEAK PROOF CHANGE OUT OF LRU'S							TYPE OF RESUPPLY OR CHANGE OUT TECHNIQUE WILL AFFECT CONTAMINATION			
7 DEVELOP TECHNIQUES FOR CONTROLLING CONTAMINATION OF THE SPACE STATION		THE TYPE OF CONTAMINATION CONTROL MAY REQUIRE DATA PROCESSING CAPABILITY	THE TYPE OF CONTAMINATION CONTROL MAY UTILIZE DATA BUSSES IN DISTRIBUTED ARCHITECTURE	THE LEVEL AND METHODOLOGY FOR CONTAMINATION CONTROL WILL SET CONSTRAINTS ON ACS THRUSTING	THE LEVEL OF CONTAMINATION ALLOWED MAY IMPACT DESIGN REQUIREMENTS FOR TCS LIFETIME	THE LEVEL OF CONTAMINATION ALLOWED WILL IMPACT THE TECHNIQUES USED FOR RESUPPLY AND CHANGE OUT		CERTAIN TYPES OF CONTAMINANTS WILL BE CONCEN-TRATED AROUND HIGH POWER/ VOLTAGE EQUIPMENT		
8. DEVELOP HIGH POWER/ VOLTAGE POWER CONDITIONING EQUIPMENT	TYPE OF POWER CONDITION EQUIP MENT MAY DRIVE DESIGN OF AUTOMATED POWER CONTROL SYSTEM									
9. DEVELOP/EVALUATE SPACE QUALIFIED TRAFFIC CONTROL RADAR	TYPE OF RADAR AND ASSOCIATED POWER USAGE COULD DRIVE POWER CONTROL DESIGN	USE OF RADAR IN TRAFFIC CONTROL WILL IMPACT DATA PROCESSING		TYPE OF RADAR WILL IMPACT DISTURBANCES ON ACS				TYPE OF RADAR MAY IMPACT HIGH VOLTAGE REQUIREMENTS		TYPE OF RADAR MAY IMPACT DISTURBANCES ON ACS
13. DEVELOP TECHNIQUES FOR PRECISION INSTRUMENT POINTING WITH MANNED SPACE STATION DISTURBANCES		INSTRUMENT POINTING ACS MAY REQUIRE CAPABILITY FROM DATA PROCESSING	INSTRUMENT POINTING ACS MAY REQUIRE CAPABILITY FROM DATA BUS	PRECISION POINTING MAY REQUIRE SOME FUNCTIONS FROM GENERAL ACS					PRECISION POINTING ACS MAY CONSTRAIN RADAR DESIGN	

* THE REQUIREMENTS LEVIED BY USER SUBSYSTEMS ON THE DATA PROCESSORS AND DATA BUSSES SHOULD BE MUTUALLY DEFINED SO THAT THEY ARE COMPATIBLE WITH BOTH.

Table 2.1-19. Final Selected Trade Study Areas

a.	Data management architecture.
b.	Data management data bus.
c.	Long-life thermal management.
d.	Integration of automated housekeeping subsystems.
e.	Adaptable attitude control system for manned space station.

2.2 RATIONALE

The selection criteria listed on form 3, figure 1.0-5, was used during the initial screening phase. These criteria were modified somewhat to reflect a greater emphasis on availability, advancement, practicality, and advancement timelines. The upgraded selection criteria and rationale follow:

a. Does the identified technology topic require development?
   1. What is current level of development?
   2. Is technology area already being developed?
   3. Has the technology been developed to a point where it is operationally usable on space platforms?
b. Is the identified technology required to support development of current large space platform concepts or evolutions from those concepts or is it only enhancing technology?
c. Does the envisioned advancement of technology produce a benefit to the space platform concept in any of the following areas:
   1. Does the technology advancement facilitate a reduction in the cost of producing, launching, or operating the platform?
   2. Does the technology advancement extend the operational lifetime of the platform?
   3. Does the technology advancement facilitate a necessary operational aspect of the platform or does it simplify operation of the platform?
   4. Does the technology advancement reduce the mass of the platform of the Airborne Support Equipment (ASE) required to deliver the platform components to orbit?
   5. Does the technology advancement reduce the volume of the platform components for transport to orbit, i.e., does it allow for more efficient packing of the platform components in the shuttle bay?
   6. Does the technology advancement facilitate repair and/or maintenance of platform elements on orbit?
   7. Does the technology advancement facilitate a necessary performance aspect of the platform such as pointing accuracy for science appendages or antennas; orbit adjust capability, communications or tracking capability, power generation, or thermal control of the platform?
   8. Does the technology advancement improve the safety or comfort of human habitation of a manned platform?
   9. Does the technology advancement facilitate evolutionary expansion of the platform on orbit?

10. Does the technology advancement facilitate development of future platform use concepts and platform configurations?

d. Is the technology advancement possible in the time frame of the envisioned large space platform usage (between now and the mid-1990's)?

For each of the screening steps, significant reliance was placed on the judgment of the specialist in applying the criteria to their particular candidates. Using these criteria then, along with the methodology of evaluation against the formats of forms 1, 2, 3, and 3A, (see volume III) the technical specialists in each discipline performed their selections. In committee the interaction of all of the specialists and later the management advisors drove out cross-technology issues. Finally the judgment of the NASA reviewers was brought to bear for the final selection of five topics.

3.0 TRADE STUDIES

This section presents the results of the trade study effort conducted in the Advanced Platform Systems Technology Study.

3.1 INTRODUCTION

The trade study effort conducted on the Advanced Platform Systems Technology study considered cost versus benefits for options with respect to the following selected topics: data management architecture, data management data bus, long-life thermal management, and integration of automated housekeeping. The results focus within each topic to specific technology items that require advancement in order to support a 1990 initial launch of an early space station. The results also consider some technology advancements to support evolutions from that early space station.

The adapted attitude control topic was selected for a study which was more focused on characterizing the space station control problem then on a trade between options. The study conducted is reported in section 3.6 under this trade study heading, but the approach was actually an investigation of the conditions for attitude control of the space station.

The trade studies conducted were generally structured to start with the identification of issues which motivated high-priority consideration of the topic. A definition of requirements based on space station needs and constraints was then developed. These requirements were either from space station related documentation or were derived from requirements known to exist for similar missions. These requirements are largely functional or conceptual, but in a few cases, specific design considerations have been isolated. The next step was to develop characterizations of options within the trade topic. In the long lifetime thermal management and integration of automated housekeeping, these options were defined in a classical trade study sense. In the two data management areas, the global level trade results were assumed, and the options were drawn at the component levels. Based on life cycle costs and benefits, the options were then evaluated and technologies necessary to support the more promising options were identified.

The two data management topics are presented first. Data architecture leads the presentation because it sets some of the characterization for the data bus topic. The next topic is the long lifetime thermal management, followed by integration of automated housekeeping functions. The attitude control topic is placed last because of the unique nature of the study.

3.2 DATA MANAGEMENT ARCHITECTURE

This study addresses the problems of interconnecting and integrating all space platform subsystems needing digital data processing, storage and communications support. This is a critical technology area for space platform development. Most, if not all, space platform subsystems are involved, as described in the Boeing Space Operations Center (SOC) study, yielding an extremely broad and diverse set of requirements.

Section 3.2.1 addresses some of the general issues, such as performance, modularity, and reliability to be considered in the design of a system that fulfills these requirements (see sec. 3.2.2). The trade studies used to select the technologies needing development are then described in section 3.2.3. Briefly, a distributed architecture, more commonly known as a local area network (LAN) was selected as the best approach, very early in the study. The LAN has developed over the past ten years as a replacement for the centralized computer system architectures of the 60's and early 70's. It consists of multiple, distributed computers, frequently specialized for particular applications, plus a distributed data base and a set of display and keyboard terminals or microprocessor-based workstations. These network resources are interconnected by means of a communications medium, usually over distances of a kilometer or less. The LAN has evolved because it combines features such as high performance, modularity, fault tolerance, and evolutionary growth capability into an integrated data management system. The primary requirements are (1) a means for connecting equipment to the network, (2) an organized set of software control functions, and (3) a means for communicating with the outside world. The last feature implies that a local network provides specialized capabilities at different locations. For space station applications, this data management network architecture is ideal for meeting the evolutionary growth requirements at a reasonable cost.

In this context, the technology area recommended for development is a LAN specialized for space platform data management, consisting of three major components, as follows:

a. Network interface module: an electronic unit that interconnects the various subsystems.
b. Network operating system: the associated control and communications software used in the network.
c. Gateways: special interfaces to other systems, both present and future (e.g., Space Shuttle).

Based on the preliminary results of the data bus study, it was generally assumed that fiber optic interconnections would be used to interconnect the space platform modules. This, and use of a standardized microcomputer, would be of great value in developing a viable data management system; these features are included in section 3.2.5 as development categories.

3.2.1 Issues

The data management architecture technology area deals primarily with systems integration, and therefore plays a key role in the development of an advanced space platform. As envisioned here, the data management network combines the many space platform instruments, sensors, processors, and other subsystems and components into a fully integrated system. This approach gives rise to several issues that are grouped into four main areas for the purposes of this report. These are:

a. Performance.
b. Reliability and fault tolerance.
c. Modularity.
d. Evolutionary development.

The first two areas deal primarily with mission requirements, while the other two are approaches that will help meet the requirements in a timely and cost-effective manner. The following sections explore these considerations in greater detail.

3.2.1.1 Performance

The data management network must integrate a wide variety of equipment types, ranging from environmental sensors with data rates of less than one bit/sec, to synthetic aperture radars (SARs) with data rates of hundreds of millions of bits/sec (MBPS). In the later stages of development (post 1995), significant amounts of scientific computer hardware and signal processing equipment will be required, with correspondingly high requirements for onboard data storage and communications. It is difficult to estimate the total requirements; however, table 3.2-1 lists some of the major subsystems that will likely be found aboard an operational space platform, including estimates of processing requirements, mass storage requirements, and data communications bandwidths. Figure 3.2-1 gives estimates of the total data communications bandwidth requirements for the platform. It is readily apparent that a space platform used for experimental work, with advanced video, processing, and communications capabilities, will require a very high performance data management system. Considering the rapid growth in microelectronics technology, an advanced space platform system of the late 1990s will probably have a processing capability greater than any computer installation in existence today.

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Table 3.2-1. Major Subsystem Requirements

SUBSYSTEM	PROCESSING CHARACTERISTICS	STORAGE REQUIREMENTS	COMMUNICATIONS BANDWIDTH
ATTITUDE	32-BIT MATH	SMALL ARCHIVE	< 1 KBPS
THERMAL	SENSING AND CONTROL	SMALL ARCHIVE	< 1 KBPS
POWER	SENSING AND CONTROL	SMALL ARCHIVE	< 1 KBPS
ENVIRONMENTAL	SENSING AND CONTROL	SMALL ARCHIVE	< 1 KBPS
PROPULSION	SENSING AND CONTROL	SMALL ARCHIVE	< 1 KBPS
COMMUNICATIONS	SWITCHING/MULTIPLEXING	LARGE BUFFERS	> 100 MBPS
SPACECRAFT TEST	SIMULATION	LARGE ARCHIVE	> 100 MBPS
MANIPULATOR	CONTROL	SMALL BUFFERS	< 1 MBPS
DISPLAYS	SYNTHESIS AND SWITCHING	LARGE BUFFERS	> 100 MBPS
DATA BASE	SEARCH AND SORT	LARGE ARCHIVE	< 100 MBPS
MAINTENANCE	AUTO TEST AND SIMULATION	LARGE ARCHIVE	< 10 MBPS
EXPERIMENT *	SENSING AND CONTROL	LARGE ARCHIVE	> 100 MBPS
AUDIO	A/D AND D/A CONVERSION	SMALL BUFFERS	< 10 MBPS
VIDEO (ANALOG)	ANALOG SWITCHING	NONE	> 100 MHZ

* E. G., MULTISPECTRAL SCANNER, THEMATIC MAPPER, ETC.

BUFFER: TEMPORARY STORAGE – DISK, BUBBLE, SEMICONDUCTOR
ARCHIVE: PERMANENT STORAGE – SIZE DEPENDS ON AMOUNT OF INPUT DATA OR REFERENCE MATERIAL

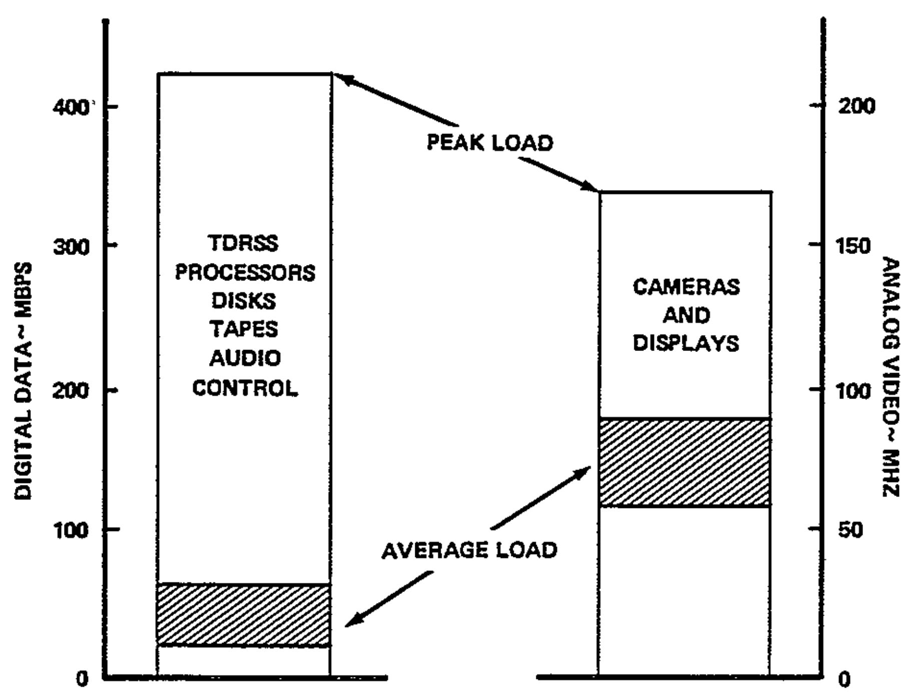

Figure 3.2-1. Estimated Bandwidth Requirements

3.2.1.2 Reliability and Fault Tolerance

The data management system will require a high degree of reliability and fault tolerance, like any other manned spaceflight system. This requirement is strongest in the core flight control subsystems, including attitude, power, thermal, communications and environmental control. The scientific and mission-oriented subsystems are not as critical, so a smaller investment in fault detection, hardware redundancy and system verification would be acceptable. Because the time of crew members is quite valuable, and should be devoted to experiments and platform operations rather than equipment troubleshooting and repair, it is a goal that most subsystems should have the capability to continue operating in the presence of single-point failures. When time is found for repairs, built-in test (BIT) techniques and computer aided testing should be utilized to minimize the mean time to repair.

The use of digital equipment is desired wherever possible, as opposed to analog or electromechanical equipment. Digital equipment typically requires no calibration or adjustment, uses inherently reliable components, lends itself to microelectronic integration, and uses established BIT, error correcting, and testing methods. Programmable digital computers, rather than hard-wired controllers should be used wherever possible. This approach permits the use of fault-tolerant architectures and topologies; it also permits work around procedures to be instituted by ground control during periods when the platform is unmanned. A data management architecture based on embedded microprocessors linked by a local network, appears very attractive from the standpoint of reliability and fault tolerance.

3.2.1.3 Modularity

The space platform will be assembled from modules carried in the cargo bay of the shuttle. The baseline configuration used in this study, shown in figure 3.2-2, calls for six basic types, as follows:

a. Habitation.
b. Service.
c. Docking.
d. Logistics.
e. Hangar.
f. Laboratory.

In addition, the shuttle will be docked with the platform, and will have to be interfaced to the data management system.

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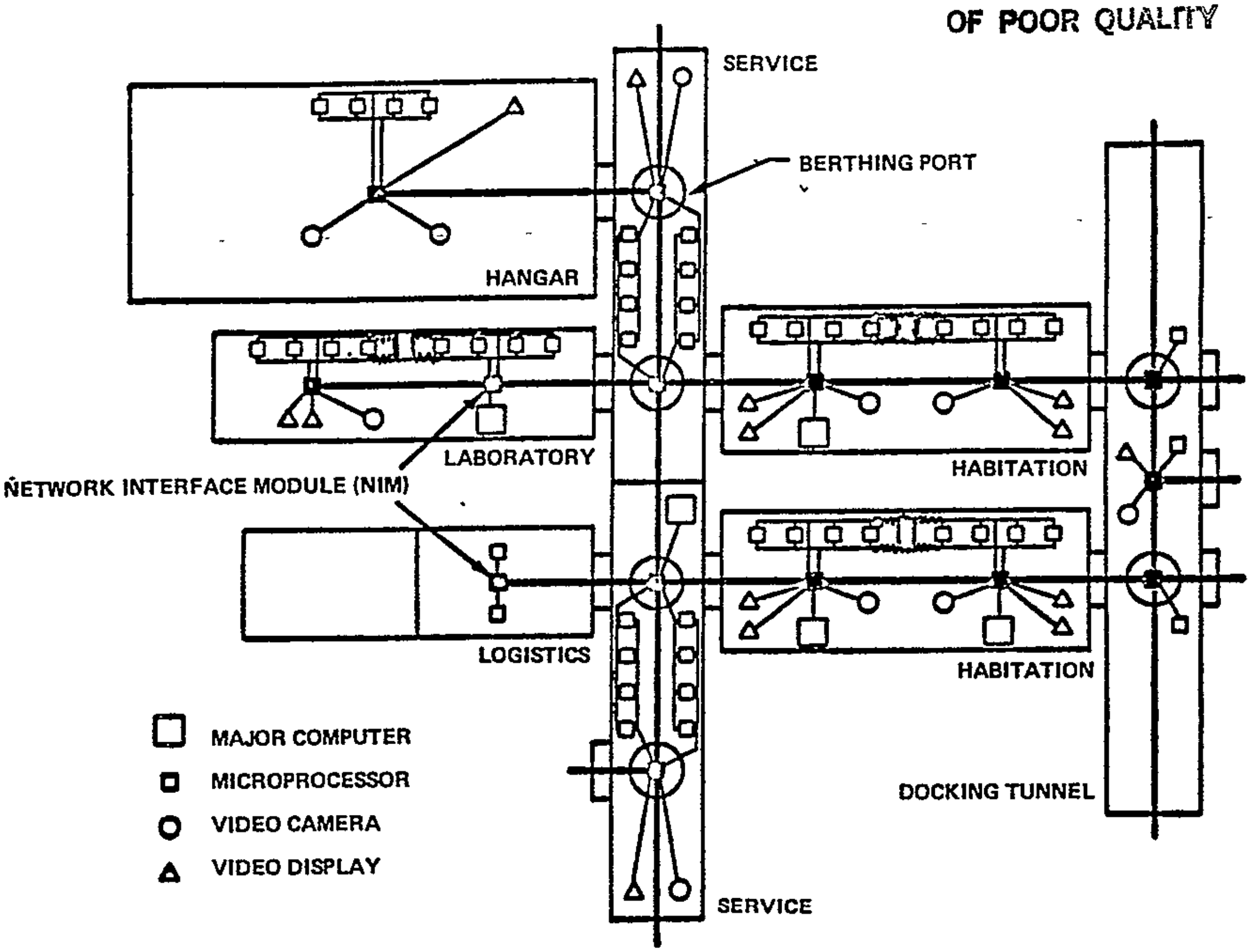

Figure 3.2-2. Study Results: Network Example

In later phases of development, other types of modules may be constructed and attached to the platform, depending on mission requirements. Technology will continue to evolve, and new types of equipment will have to be accommodated. The new modules could have functions such as—

a. Power.

b. Propulsion.

c. Communications.

d. Manufacturing.

e. Military systems.

f. Remote sensing.

g. Space science.

In addition, satellites and spacecraft will probably have to be accommodated periodically. Also, multiple platforms could be configured, each with a different complement of modules and missions.

It seems obvious that modularity is an important factor in the design of the data management system. It will be necessary to consider a number of issues in the development of a modular system, as follows:

a. Berthing port uniformity.
b. Data rates.
c. Data formats.
d. Communication protocols.
e. Functional partitioning.
f. Electrical isolation.
g. Equipment standardization.
h. Software standardization.
i. Growth capability.
j. Technological change.

Local networks have developed over several years as the preferred solution to such interfacing and intercommunication problems. However, no existing architecture appears to meet the requirements as described in section 3.2.2. Therefore, development of a high performance, fault tolerant, fiber optic network architecture, referred to as a backbone network, is represented as a heavy line drawn through the space platform modules in figure 3.2-2. Conceptually, it consists of multiple optical fibers linked by means of electronic units called network interface modules (NIMs). Equipment is attached to the NIMs, which handle all data multiplexing and distribution. The NIMs also provide fault tolerance by monitoring the equipment interfaces and fiber optic links to detect failures, with automatic selection of redundant units and data paths when reconfiguration is required.

3.2.1.4 Evolutionary Development

This issue is very important to the development of the space platform, in terms of cost and schedule. NASA has a large investment in ongoing research projects and existing systems that will be in use well after the initial deployment of the space platform. However, technology is advancing so rapidly, particularly in computers and electronics, that new equipment is frequently obsolete even before it reaches operational readiness. Figure 3.2-3 illustrates the trends in integrated circuit performance that contribute to early obsolescence. With this in mind, it seems necessary that the space platform data management system development proceed in an evolutionary fashion, beginning with the design of a ground-based prototype network and its installation in one or more NASA laboratories. Existing or developing equipment would be selected and interfaced to the network early in the development cycle, forming the basis for the eventual production of flight hardware. This system would provide at least the following capabilities:

a. Evaluation testbed
b. Software development

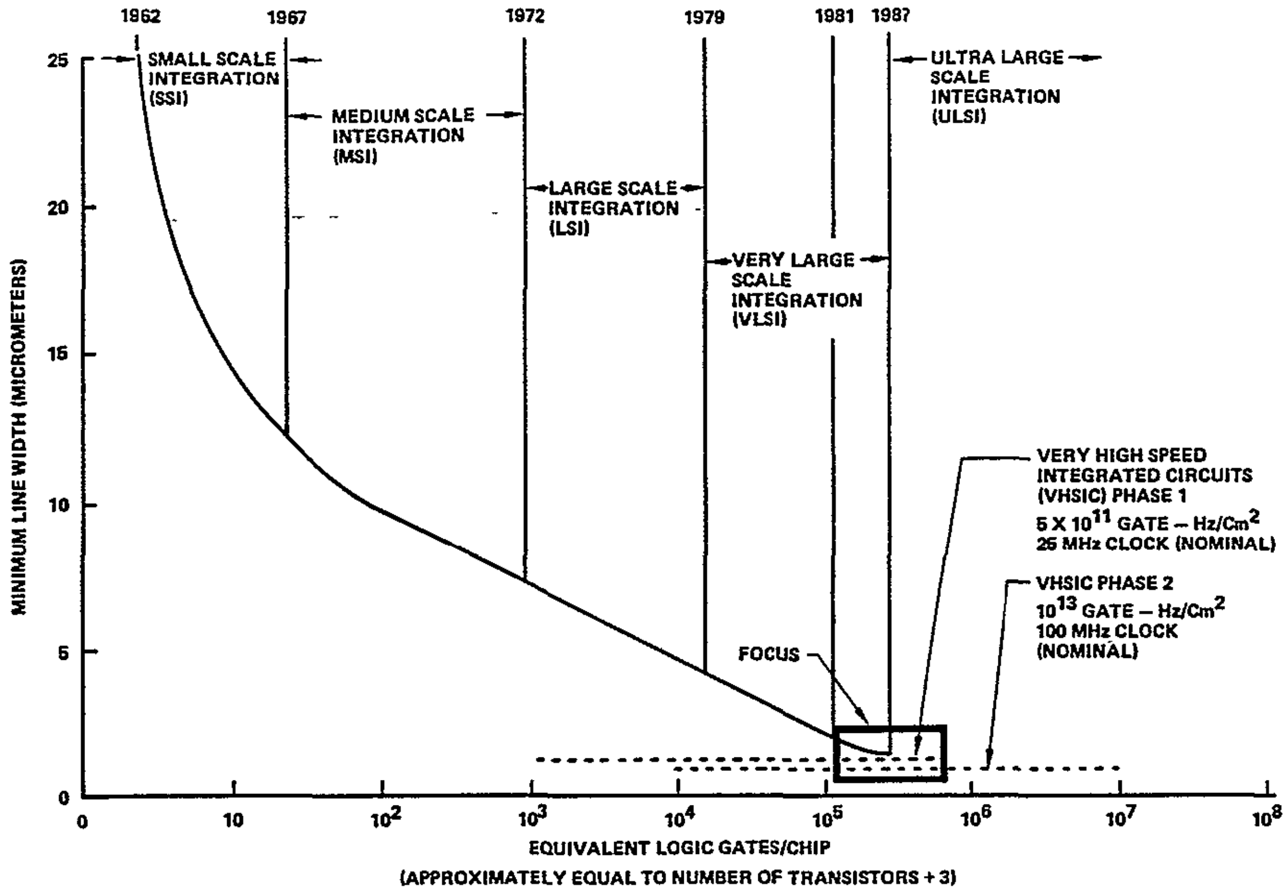

Figure 3.2-3. Integrated Circuit Trend Example

c. Interface standardization

d. Simulation

e. Experimental support

f. Verification

g. Training

This approach allows new equipment to be tested and evaluated directly on the system in laboratory breadboard form. Testing, optimization and verification would be carried out in stages as flight hardware evolved. Eventually, an all-up configuration would be reached for the initial operational capability. The flight hardware could then be installed in the platform modules for final checkout before launch. This approach provides a basis for the phased development and insertion of new equipment over the lifetime of the platform. Gradually, the system configuration would evolve as new technology became available, without major retrofits or unnecessary returns and relaunches of space platform modules.

3.2.2 Requirements

The main purpose of this study was to identify key technologies that must be developed to provide a space platform operational capability. It was assumed that orbital operations would begin in 1990, with design commencing in 1986. In order to define key technologies, a feasible mission model, or baseline, was needed first. This was used to identify a set of requirements, which are satisfied by appropriate use of technology. Technology areas needing development were determined from that data.

The following list summarizes the assumed space platform data management requirements described in table 3.2-1 and figure 3.2-1, as determined from a review of Boeing's mission model, the SOC.

a. Real-time control (i.e., attitude, power, thermal).
b. Instrument data collection.
c. Digital voice communications.
d. High bandwidth video distribution.
e. High speed bulk data communications.
f. Interprocessor communications.
g. Online and archival mass storage.
h. Scientific computations.
i. Signal and image processing.

This is a list of generic requirements which may apply to various kinds of systems, particularly where modern electronics are involved. The data management system will have to satisfy all these at some point in its lifetime, although the early system may be fairly modest, with built-in growth capability. The specific requirements of an operational space platform are discussed in greater detail in the following sections.

3.2.2.1 Realtime Control Functions

The data management system must provide digital control capabilities for subsystems and experiments. It is anticipated that most of these functions will be provided by a NASA standard microcomputer, embedded in each subsystem, such as power, thermal, communications or attitude control. The microcomputers will acquire data from sensors, calculate the appropriate control responses, and send digital control messages to transducers, actuators, indicators and displays. Use of a standard microcontroller allows independent subcontractors to develop each subsystem without replicating the development costs of the basic control hardware and software. Most control functions are critical to the operation of the space platform. The development, integration, and verification costs of such critical functions can be quite high, so use of standardized approaches could have a large impact. This is discussed in greater detail in section 3.2.4.

3.2.2.2 Instrument Data Collection

The space platform will be equipped with a number of science and engineering instruments used to collect operational data. Some examples are microgravity forces, skin temperature, and air pressure. Sensors and transducers associated with these instruments will be distributed about the platform, and will likely be under the control of NASA standard microcomputers, as with the control system. The data acquired by the distributed microcomputers will be transmitted to the data base management subsystem for archival storage, to the communications subsystem for a downlink to ground stations, and to the control and display subsystems for onboard use.

3.2.2.3 Digital Voice Communications

It will be necessary to provide an intercom system for the use of crew members working in various modules. Some of this equipment will also be used for communications with ground stations, the shuttle, an orbital transfer vehicle, and for EVA's. The intercom could also be used for recreational purposes, carrying recorded music and sports or news programming from the ground. Audio can be digitized and distributed fairly easily, as a basic function of the data management network.

3.2.2.4 High Bandwidth Video Distribution

The rationale for video distribution is similar to that for audio, except that the video displays would tend to be located at only a few crew stations. Television cameras would be located in several areas, such as the shuttle docking ports, in the hangar, on the manipulator arm, and on teleoperator and EVA units. Video jacks might be located in many other areas, for use with portable cameras and displays. The portable units could be very useful in maintenance activities. Imagery could be transmitted to ground control or contractor facilities for consultation purposes, while diagrams and troubleshooting procedures could be viewed on portable displays by crew members. High resolution would be required in some cases, especially for graphics. This translates into a high bandwidth requirement if the video is to be displayed as real-time and time-varying imagery. The video can be distributed in analog or digital form, perferably the latter. However, digital video equipment will likely require complex, bulky electronics during the 1986-1990 time frame. Therefore, some combination of digital and analog video equipment will probably be used for early platform deployment.

3.2.2.5 High Speed Bulk Data Communications

The space platform, especially in advanced versions, may carry a number of sensors used for remote sensing and astronomy. Search and tracking radars may also be carried, for docking, satellite tending, deep space search and space debris avoidance. Some imaging sensors and radars have data rates in the hundreds of millions of bits/sec. This data will have to be transferred from the sensors to the processing, display, data storage and communications equipment located in other modules. In addition, data will have to be transferred from temporary storage to the communications subsystem. As a result, the data management network will have to provide for high speed data communications, at least at the maximum TDRSS downlink rate of 300 MBPS.

3.2.2.6 Interprocessor Communications

It is assumed that the distributed architecture of the space platform will comprise standard computers with specialized software for major tasks such as attitude control, data base management, and scientific computations. It will be necessary to provide a means for communications between these processors and the rest of the system, for file transfers, program loading, data display, telemetry and testing. This type of computer-to-computer communication is a major function of the data management network.

3.2.2.7 Online and Archival Mass Storage

As data are collected from station instruments and science experiments, it will be necessary, at least part of the time, to provide temporary storage facilities. At other times, when TDRSS capacity is available, the data could be transmitted to ground stations for storage and processing. The storage requirement for imaging sensors is particularly high, so video tape recorders will probably be needed. It will also be necessary to carry operations and maintenance information aboard the platform, and recreational materials such as books, films, and television programming may be provided as well. Most such information is archival; that is, it is recorded or written once, and is then saved for future reference. Temporary (online) storage devices may have their contents modified or overwritten frequently. Magnetic disks and bubbles are strong candidates for the online storage function, while video and laser disks and fiches should be available for archival storage in the 1986-1990 time frame.

3.2.2.8 Scientific Computations

As the space platform matures, more and more scientific experiments will be carried onboard. Many potential experiments, such as crystal growth, exotic alloys, drug processing, and solar observation may require a significant amount of scientific computing power. Examples are control state equations, process control, fast fourier transforms (FFTs) and spectrum analysis. Since much of that processing will take place in realtime, the associated computers will have to be carried aboard the platform. In some cases, the computers may be attached to specific experiments. However, it may be more cost-effective to share one or more scientific computers among several experiments. In this case, the computers may be located away from the experiments, with the data management network used for high speed transfers. Raw data would be sent to the computers, and control information would be fed back after processing. This kind of interprocessor communication is an essential part of any distributed architecture used for scientific purposes.

3.2.2.9 Signal and Image Processing

Signal and image processors are typically specialized for particular applications. For example, a synthetic aperture radar (SAR) can generate high resolution radar imagery but requires a very high speed signal processor, especially for realtime applications such as aerospace vehicle detection and tracking. Imaging sensors, such as CCD telescopes, also require specialized processors to perform pattern recognition, noise filtering, or feature extraction. In some cases, it may be advisable to provide such processors for general use aboard the platform. In this way, new sensors could be transported to the platform and attached to the shared processors by means of the data management network. The sensors would then be less complicated, massive and expensive, than if each were provided with a dedicated signal or image processor.

3.2.3 Characterization of Concepts

The concepts described in the following paragraphs all pertain to local area network (LAN) technology. Figure 3.2-2 shows a baseline space platform floorplan, with a fiber-optic backbone network represented by a heavy line drawn through the center of the space platform modules. This architecture was selected as a result of the trades and analyses conducted during this study, as described in the following pages. Conceptually, the backbone consists of at least two fiber optic cables. Each cable consists of multiple optical fibers, giving redundant pathways for data communications, audio and video distribution, and other such functions. The cables are physically separate, to give greater survivability in case of fire, explosion, collision or other accident. Some of the fibers are reserved for future expansion. The equipment and instruments contained in the modules are interfaced to the fiber optic backbone by means of electronic units called network interface modules (NIM's). The NIM's contain digital and analog switching and control circuitry for data, audio and video distribution. Each NIM provides connection points for the processors, instruments and other space platform equipment.

The intelligent devices attached to the NIM's must conform to interfacing standards and use a set of standard protocols for communications. Other devices, such as audio or video units have their outputs switched from place to place within the space platform under software control. Collectively, the software system used to control communications throughout the network is known as a network operating system.

The following pages describe the basic local network concepts in greater detail, along with decision rationale and trades, covering the topics listed below:

a. Local area network topologies.
b. Packet communications.
c. Layered protocols.
d. Interface standards.
e. Gateway architecture.
f. Network operating system.

Configuring the data management network as described will provide a high performance, fault tolerant and flexible system. Sufficient capacity will be provided for expansion over many years, by means of standard interfaces at the berthing ports, and at the network interface modules. Nonstandard equipment will be interfaced to the system by means of gateways; however, the use of standards for all new devices and subsystems should greatly reduce the development, integration, verification and life-cycle costs of the data management system, as described in section 3.2.4.

3.2.3.1 Local Area Network Topologies

Figure 3.2-4 shows diagrams of eight topologies that have been proposed or utilized for data networks of various types. The bus, ring, and star are the most common approaches. Examples of the bus include MIL-STD-1553B, the MMS multiplex data bus, Ethernet, Sytek and Hyperchannel. Examples of the ring include the Cambridge Ring and Ringnet; also, IBM has recently adopted this topology for their new office products. The star is actually the most common approach, since any centralized computer complex with remote stations can be considered a star network. The tree is a similar concept, with the hierarchy expanded to an arbitrary number of levels. Multiple buses have been used in fault-tolerant systems to provide alternate paths for data transfers. The chordal ring and threaded tree are variants of the ring and tree respectively, with redundant links added for survivability. The graph is the most general approach, since all topologies except the bus structures are actually specialized versions of the graph.

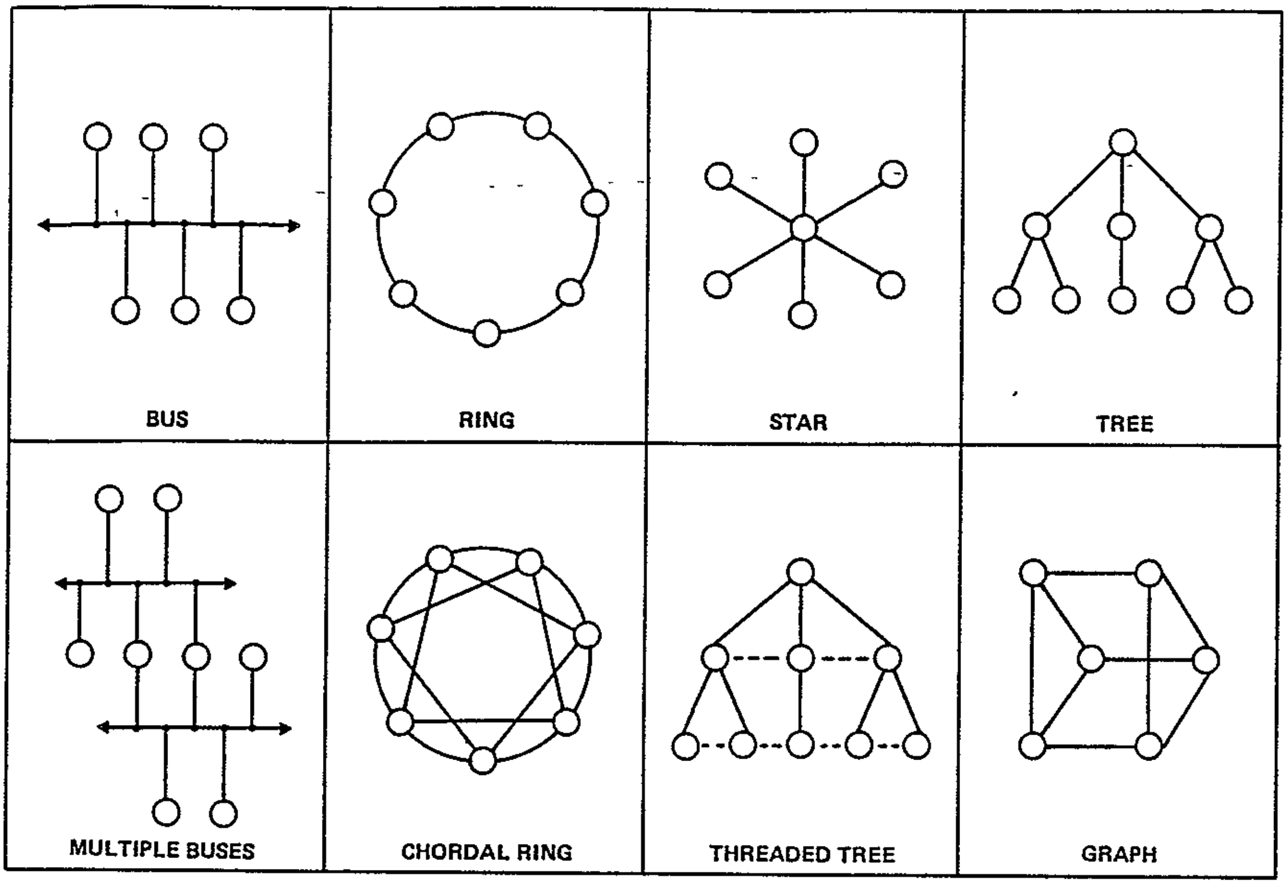

Figure 3.2-4. Network Topologies

Table 3.2-2 is a trade matrix, developed to aid in the selection of a data management network topology. Given the varied requirements decribed in section 3.2.2, simple buses, rings and other "single string" topologies will not provide adequate throughput or fault tolerance. The chordal ring and threaded tree are of theoretical interest, but do not appear to fit the physical structure of a modular space platform; that is, they are difficult to expand without reconfiguring the entire system. Multiple buses appear to be a viable approach, with a choice of contention, polling, or broadcast access techniques. However, these all involve complex electronics, including dedicated controllers for polling (master/slave) and broadcast buses. Dedicated controllers are vulnerable to single-point failures. Also, a bus is a shared medium and can be jammed by the failure of any attached device.

Therefore, a backbone graph structure, consisting of simple point-to-point links between network interface modules has been selected as the most viable approach, particularly for a fiber-optic implementation. This is the type of network topology depicted in figure 3.2-2. The term graph is used because the topology can assume many different structures, depending on the configuration of the space platform modules. It is flexible, modular, and reconfigurable to suit specialized requirements. This approach uses multiple

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Table 3.2-2. Network Architecture Trade Matrix for Data Distribution

	RELATIVE COMPARISON										
	FAULT TOLERANCE			PERFORMANCE			COST		SCORE		
TOPOLOGIES* / CRITERIA	CONNECTIVITY	SIMPLICITY	RECONFIGURATION	BANDWIDTH	ACCESSABILITY	EXPANDABILITY	MAINTAINABILITY	MATURITY	WITH FAULT TOLERANCE	WITHOUT FAULT TOLERANCE	
BUS	0	10	0	0	5	5	10	10	40	30	CONTENTION AND POLLING
RING	0	10	0	0	0	0	10	10	30	20	TOKEN PASS
STAR	0	10	0	5	0	5	5	5	25	20	CENTRALIZED CONTROL
MULTIPLE BUSES	5	5	5	5	10	10	5	5	50	35	SEMI-AUTONOMOUS INTERCONNECTED BUSES
CHORDAL RING	5	10	10	5	5	0	5	0	40	15	BIDIRECTIONAL WITH DOUBLE ALT. LINKS
THREADED TREE	5	5	10	10	5	10	5	5	55	35	HIERARCHICAL WITH CROSS LINKS
GRAPH	10	5	10	10	10	10	5	10	70	45	FULLY DISTRIBUTED

* NON-REDUNDANT NODAL INTERCONNECTS

optical fibers in a high performance, redundant data trunk, with local networks and buses provided within each of the space platform modules. The backbone network makes use of circuit switching to provide reconfigurable high-speed channels, on a fairly long-term basis. Some of these channels are then utilized for high speed bulk data transfers and video. Others are used for interprocessor communications and audio, by means of digital packet switching, as described in the next section.

3.2.3.2 Packet Communications

Packet switching is the most commonly used method for transferring data from place to place within a network. As shown in figure 3.2-5, packets are organized into a format that is recognized by all data communications devices in the network. The diagram shows a typical packet format, including fields for the header, data, and trailer. The header includes subfields for source (transmitter) and destination addresses, and for control information such as packet type, priority, or sequence number. The data field for packets has a fixed maximum length, depending on type. The trailer usually consists of a single field containing a checksum or an error detecting code such as a cyclical redundancy check (CRC).

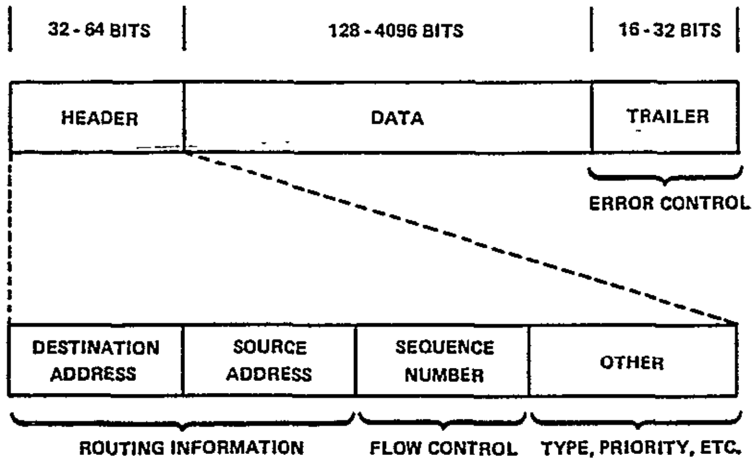

Figure 3.2-5. Example Packet Format

The extra information contained in the packet header and trailer is used for routing, flow control and error control. Packets may be transmitted directly to a receiver on a data bus or by means of a point-to-point link. They may also be routed indirectly to their destinations through intermediate nodes. Such store-and-forward networks generally maintain routing tables at each node to define the fastest path through the network from a given source to a given destination. In the event of failures, these tables are modified to reroute the packets along alternate paths. When packets are received correctly, they are typically acknowledged by the receiver. Errors are detected by examination of the trailer, and a negative acknowledgement is returned to the sender, causing a retransmission. Similarly, packets that are lost or delivered out of sequence can be detected by examination of the header information, followed by negative acknowledgement and retransmission.

Packet switching technology is well developed, having been used in data communications for nearly twenty years. Many variations and techniques are used, as described in volumes of research papers and textbooks. As the data management network matures, specific techniques and formats will have to be selected and standardized. This will be a very significant effort, but should result in a flexible and efficient system, with capacity for expansion over many years.

3.2.3.3 Layered Protocols

Protocols are rules used by data communications equipment to regulate the transfer of data. For example, if an error is detected in a packet, a protocol is used to control recovery from the error. In this case, a negative acknowledgement could be sent back to the source, or the destination might simply neglect to return a positive acknowledgement. In either case, the source would be expected to detect that the positive acknowledgement for that packet had not been received, and would be required to take corrective action. The protocol for error recovery must be defined in advance for both the source and destination.

Many different protocols are used in data communications systems. They may determine how channels are set up and torn down, the rate at which packets may be transmitted, the format of packets, and the methods by which applications programs utilize the functions of a network operating system, to name a few of the major concerns. A system of protocols can be extremely complicated, and correspondingly difficult to implement, use, and verify. This is especially true when systems using incompatible or nonstandard protocols are interfaced to each other. This situation has long been recognized, and standards organizations have attempted to reduce the complications by establishing standard protocols. Local networks are relatively new, however, and only guidelines have been adopted so far. These include the IEEE-802 and the ISO/OSI. (International Standards Organization/Open System Interconnect, also known as the Reference Model: ISO/RM.)

Figure 3.2-6 shows the basic structure of the ISO/OSI reference model. This is a layered structure, in that different types of protocols are defined for different functions, ranging from the control of hardware at the physical layer, to support for user programs and keyboard commands at the application layer. Each device attached to a network would

LAYER		A POSSIBLE IMPLEMENTATION
7	APPLICATION	USER INTERFACE, KEYBOARD HANDLER, COMMAND INTERPRETER, ETC.
6	PRESENTATION	DATA STRUCTURES AND UTILITIES (MAKES NETWORK LOOK LIKE A FILE SYSTEM)
5	SESSION	SYSTEM CALLS PROVIDED BY O S. AND NETWORK DEVICE DRIVER
4	TRANSPORT	NETWORK DEVICE DRIVER (O.S. SYSTEMS PROGRAM - PHYSICAL I/O)
3	NETWORK	SEMAPHORE-PROTECTED QUEUING SYSTEM (WITH EMBEDDED MICROPROCESSOR)
2	DATA LINK	MICROPROGRAMMED CONTROLLER, ECC AND ADDRESSING/ROUTING LOGIC
1	PHYSICAL	HIGH SPEED FIBER-OPTIC LINKS AND MEMORY BUFFERS

Figure 3.2-6. International Standards Organization (ISO) Open Systems Interconnection (OSI) Implementation

utilize a similar protocol structure. This permits the data link layer in each device to handle all error control functions, for example, so that error control is transparent to the layers above and below. Similarly, the presentation layer might handle file transfers between devices, while layers below deal only with packets, bits, or electrical signals.

The layered approach seems more complicated than necessary, at first. However, it provides a highly organized set of functions that can be implemented on different types of devices. This kind of a structured organization makes networks easier to implement and ensures compatibility throughout. In turn, this increases reliability and flexibility, while reducing integration and verification costs. Although it is recommended that the protocol structure of the space platform data management network resemble the ISO/OSI reference model, it does not follow that the methods used will be identical to the approaches taken with ground-based business and scientific systems. The performance and reliability requirements of the space platform are very high, and the network organization will necessarily be specialized. This means that considerable systems engineering work will have to be performed before the data management network and its protocols can be fully characterized.

3.2.3.4 Interface Standards

Interface standards are similar to standard protocols, and there may be an overlap in some cases. However, standards typically are concerned with electrical and mechanical compatibility, rather than logical control and software compatibility. Interfaces are usually designed to provide signaling and data transmission capabilities, while protocols deal with data formats, information content, and operational procedures.

Many standard interfaces have been defined and are in use today. Examples are RS-232, 422, 423 and 449 for serial data transmission, RS-170 and 330 for video distribution, IEEE-488 for parallel input and output, and IEEE-796 for microcomputer data buses. NASA's multiplex data bus and the DOD MIL-STD-1553B are other examples. The varied space platform requirements preclude the use of any existing interfacing standard throughout. However, some of the existing standards may have to be accommodated if development costs are to be held down. For example, video displays might use the RS-330 closed circuit TV (CCTV) standard, while some military equipment might use MIL-STD-1553B.

The data management network can accommodate such varied requirements by means of the Network Interface Modules (NIM's) mentioned in section 3.2.3. The purpose of the NIM is to provide an interface between subsystems and the data management network. Data is transferred from NIM to NIM throughout the platform by means of dedicated and switched circuits for video and bulk data; and by means of packet switching for interprocessor communications and audio. Standards will have to be selected or defined to cover the interconnections between existing or new space hardware and the NIM's. Adoption of standardized approaches should greatly reduce the integration, verification and life cycle costs of the space platform data management system, as described in section 3.2.4.

3.2.3.5 Gateway Architecture

A gateway is a special type of network interface module that interconnects two or more systems of different types. For example, a gateway would be needed between the space shuttle avionics system and the space platform data management system. The requirements for the two systems are different, and the technologies used in the space platform will be ten years more advanced than shuttle technology. The space platform system will likely include other gateways. Examples are the interfaces between the multiplex data bus of the multimission modular spacecraft and the platform's spacecraft checkout system, and gateways between the platform's core data management system and modules developed for foreign, commercial, and military interests over a period of many years.

The use of a gateway architecture ensures that many different missions can be accommodated by the data management network, resulting in a very powerful and flexible system. Gateways also provide for modularity, since different technologies can be incorporated in the various space platform modules if desired. This naturally allows for growth and technological change. The early space platform can make extensive use of existing technology. However, existing technology will rapidly become obsolete and will be gradually replaced over the lifetime of the platform. This does not mean that the early platform modules will have to be replaced or refurbished. Rather, gateways can be incorporated in new modules to accommodate the interfaces, protocols, and other characteristics of the early platform. Gateways are a natural solution to the space platform requirements of modularity, flexibility, and growth capablity.

3.2.3.6 Network Operating System

The software used to control a network is generally called a network operating system (NOS). A NOS is similar in many ways to conventional microcomputer, minicomputer and mainframe computer operating systems, such as Unix, VMS, RT-11 or CP/M. However, a NOS integrates the functions of several distributed computers instead of one. For example, a NOS might allow a terminal physically attached to a computer in one location to be logically connected to a computer at a remote location. This permits a large set of differing computer resources to be used for a wide variety of applications, eliminating needless waste and duplication.

In the context of a space platform, a NOS organizes the many subsystems, such as thermal, power, environmental, communications, and attitude control into an integrated system. For example, telemetry data must be transmitted from many of the subsystems, through communications transmitters, via the TDRSS, to NASA ground stations. The NOS provides the capability to select a particular sensor and transmitter, and to store such information temporarily, until the satellite comes in view of the platform's antennas. This could be accomplished by a telemetry system that is almost completely separate from the space platform operational systems. However, great savings in development time and cost, mass, bulk, and power consumption could be gained by means of systems integration. The network operating system is a name for the software control system that provides these integrated capabilities.

3.2.3.7 Summary

The primary trades done in this study pertain to local area network options and topologies, as shown in figure 3.2-4 and table 3.2-2. The topologies were rated in section 3.2.3 according to the issues discussed in section 3.2-1 and the requirements covered in section 3.2.2. No single approach fit space station needs perfectly, so a hybrid graph structure, called a backbone, was evolved. This hierarchical structure includes redundant fiber optic links for high speed intermodule communications, with more ordinary buses and networks used within the various space platform modules. The next major sections describe costs and benefits of the network development approach, and the technologies and components that need development if a space platform data management network (and the platform itself) is to be constructed.

3.2.4 Cost Benefits of Options

The local area network approach to space platform data management requires systems engineering at the outset. This involves defining the mission requirements, as was done in section 3.2.2, followed by analysis and selection of the approach that best meets the requirements, with continued system development through use of a testbed facility. The alternative is to develop all subsystems more or less independently, and then to follow-up with systems integration to overcome the incompatibilities. This approach makes little use of standardization in the processors or software used in the various subsystems. Therefore, systems integration by hindsight is expected to be far more expensive than the selected approach, which calls for standard interfaces, protocols, and processors.

The RCA price model was used to calculate the development costs of typical hardware and software components that are required for a space platform data management system. The estimated costs are based on the approximate weight, size, complexity and level of technology of the electronics used. It was assumed that off-the-shelf 1986 integrated circuit technology would be used throughout the system. The estimated development costs are (in thousands of 1986 dollars):

Network Interface Module:	$9,409
Standard Microcomputer:	$6,192
Gateway Interface Unit:	$20,183
Network Operating System:	$5,985
Systems Integration Cost:	$13,681

Hardware production adds to the total somewhat, giving a total of about $64 million for the development, production and integration of a data management network to interconnect 20 subsystems. In contrast, the integration cost of 20 nonstandard subsystems is estimated at almost $240 million in 1986 dollars, if networking is not used. This means that a special interface would have to be built and integrated for all subsystems, at a cost of about $12 million each.

This represents a first-order cost estimate, so the actual numbers should be used primarily as a guideline. It is the ratio between the totals (almost 4:1) that is important. Even if the actual ratio were much smaller, (e.g. 1.5:1), the development cost savings would be very significant. This illustrates one benefit to be derived from the use of local network technology and standardization. Other benefits, besides development cost reductions, are improved flexibility, modularity and growth capability. These features should also reduce life-cycle costs, as well, an area requiring extended studies. All equipment is basically plug-in compatible, and most of the control and communications software can be developed once by the systems integrator, for use (by agreement) by all subcontractors. The cost advantage is primarily the result of doing the basic development once, versus doing the same job many times, once for each subsystem.

3.2.5 Technologies Needing Advancement

The preceding sections have discussed space platform requirements, and concepts that allow the requirements to be met. The basic approach chosen is the local area network (LAN), a technology that provides a powerful, flexible, and modular approach to systems integration. A number of network components need development if a space platform LAN is to be ready in the 1986-1990 time frame, as follows:

a. Network interface module (NIM).

b. Network operating system.

c. Gateways to existing systems.

These components, in conjunction with fiber optic transmitters, receivers, cables and connectors will provide a high performance, fault tolerant network, with enough flexibility for growth into the next century. Additionally, it is believed that selection or development of a standardized microcomputer would be of great benefit in an early space platform. An analysis of the requirements, as described in section 3.2.2, indicates that almost all space platform data processing needs can be met with projected 1986 microelectronic technology, as summarized in table 3.2-3. The exceptions are in the areas of scientific computations and signal and image processing, which demand processing capabilities that are almost unlimited, especially for realtime operation.

Table 3.2-3. Standardized Microcomputer

• IC TECHNOLOGY:	CMOS/SOS, CMOS, BIPOLAR
• MEMORY:	64K - 128K BITS (STATIC CMOS)
• GATE ARRAY:	10K - 20K GATES (CMOS, BIPOLAR)
• VLSI CHIPS:	100K - 150K GATES (CMOS)
• MICROCOMPUTER:	~32-BIT CMOS (SINGLE BOARD/100 IC'S)
	~2 MIPS THROUGHPUT
	~1 MEGABYTE CMOS STATIC RAM
	~10 W POWER CONSUMPTION
	~2 KG WEIGHT (WITH PACKAGING)
• RELIABILITY:	0.006%/THOUSAND HOURS/COMPONENT
	20 YEAR MTBF COMPUTER (WITHOUT FAULT TOLERANCE)
	>100 YEAR MTBF COMPUTER (WITH FAULT TOLERANCE)

The basic platform requirements such as control, data collection and digital voice communications can be satisfied by use of microcomputers. Given the cost and time required for the development and space qualification of computer hardware and software, it is readily apparent that needless duplication of effort should be avoided if possible. Training, logistics, maintenance and other computer-related life-cycle costs can also be very high if great care is not taken in the design of the data management system. These considerations are far more important in the case of a permanent manned space platform than for any other type of system because of the cost and difficulty of on-orbit support. Therefore, selection or development of a standardized microcomputer for use in the core space platform subsystems is recommended. However, exceptions may be permitted, particularly if existing equipment is adapted to space platform needs in order to reduce development costs. Additional study of these issues is recommended.

3.2.5.1 Network Interface Module

The network interface module (NIM) is an electronic unit that connects instruments, telemetry transceivers, experiments, processors, data storage devices, and other equipment to the fiber optic backbone network, as shown in figure 3.2-7. The local buses shown

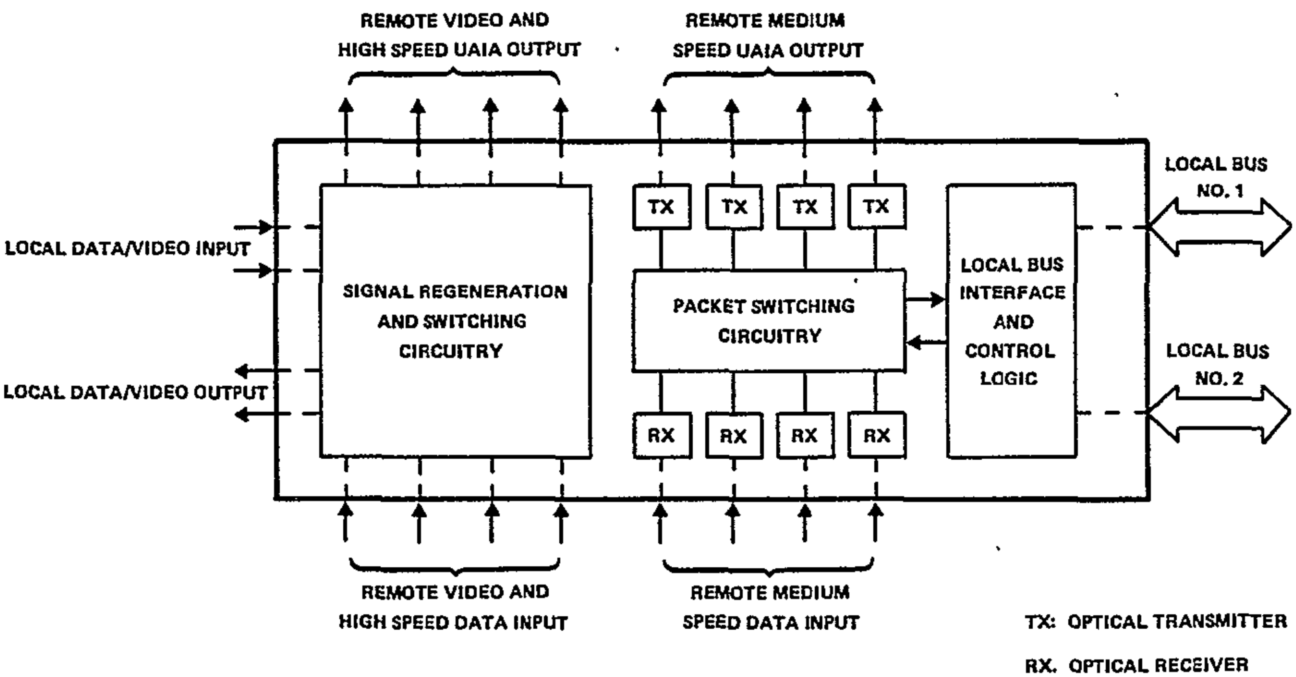

Figure 3.2-7. Network Interface Module (NIM) Example

in the figure could be multiplex serial buses like those used in the shuttle or MMS, or they could be based on the MIL-STD-1553B specification for military applications. However, it is even more likely that a new high performance bus will have to be developed for advanced equipment. The local video circuitry might conform to the RS-330 closed-circuit TV standard, or possibly a NASA standard, depending on requirements. Because the NIM is a key network element, its requirements need to be defined in greater detail, to provide a baseline for subsystem integration. Development or selection of new interface standards, communications protocols, or special integrated circuits to achieve satisfactory performance, mass, bulk, and power consumption characteristics may be required to complete this task.

3.2.5.2 Gateways to Existing Systems

Figure 3.2-8 depicts a gateway between the data management network and the shuttle avionics system. The MMS, spacelab, and the TDRSS are examples of other systems that may require gateways for interoperability. This approach permits the development and use of new technology, without constraint by obsolete hardware, software, or concepts. Even the data management backbone network will eventually be obsolete, but it can be used until phased out by means of gateways between it and systems of the future.

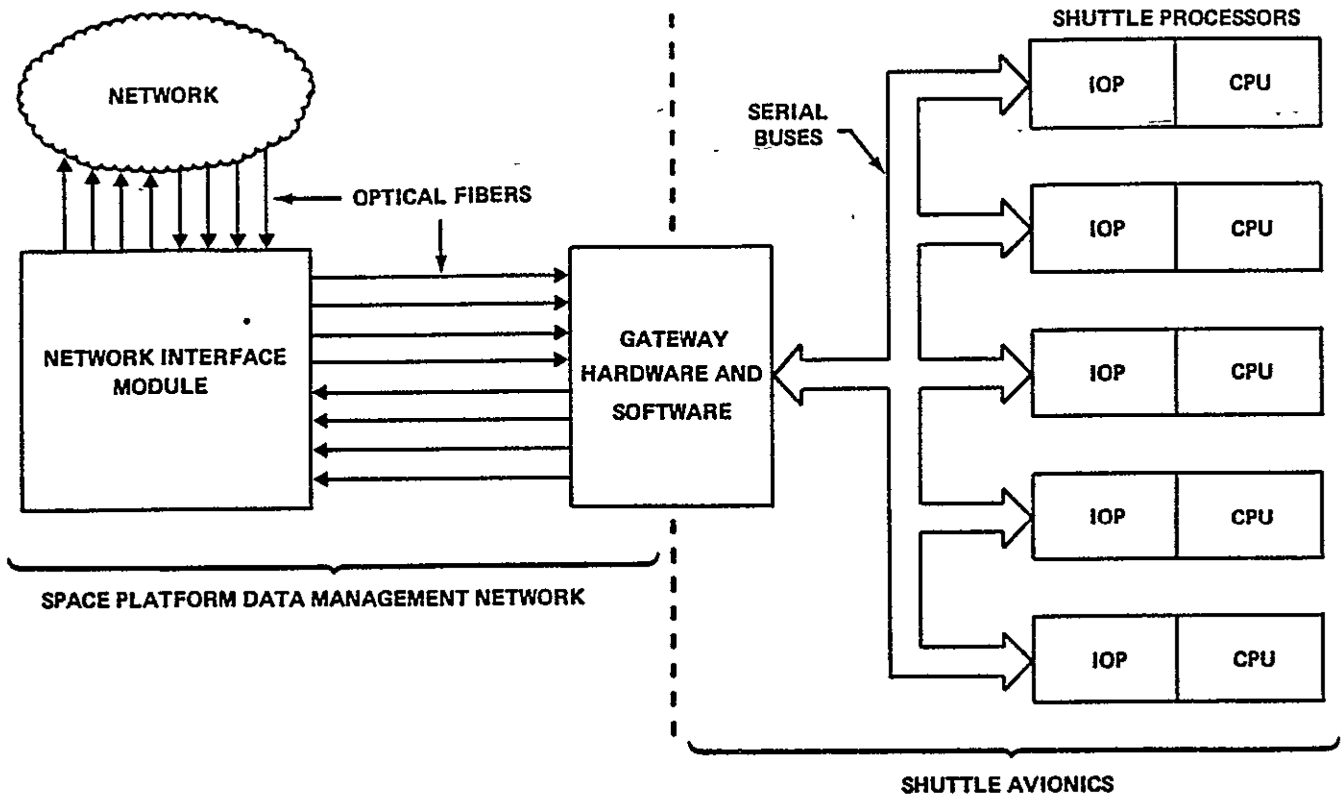

Figure 3.2-8. Gateway to Space Shuttle Avionics System

3.2.5.3 Network Operating System

A network operating system is the collection of software that provides control and communications services for the equipment attached to a data management network. It generally does not include applications software that resides in specific devices, but provides support for such functions. The control of an instrument is an example of an application, while the storage of data from all platform experiments is an example of an operating system function.

As shown in figure 3.2-9, a network operating system consists of one or more executive programs to provide integrated control of the network, plus manager or server programs for each device. Thus, the system has a hierarchical structure. For example, an executive program might control all telemetry through TDRSS, while a server program running on a microprocessor might control a single antenna multiplexer. Additional capability must be provided for nonspecific computational tasks, as depicted by the boxes labeled job processing.

The space platform network operating system will have critical control functions involving many devices. Equipment used for attitude, thermal, power, and environmental control will all be involved, since the data management network will provide the interconnections to these subsystems. Some functions will require fault tolerance,

(EACH BOX REPRESENTS SOFTWARE RUNNING ON A SEPARATE PROCESSOR)

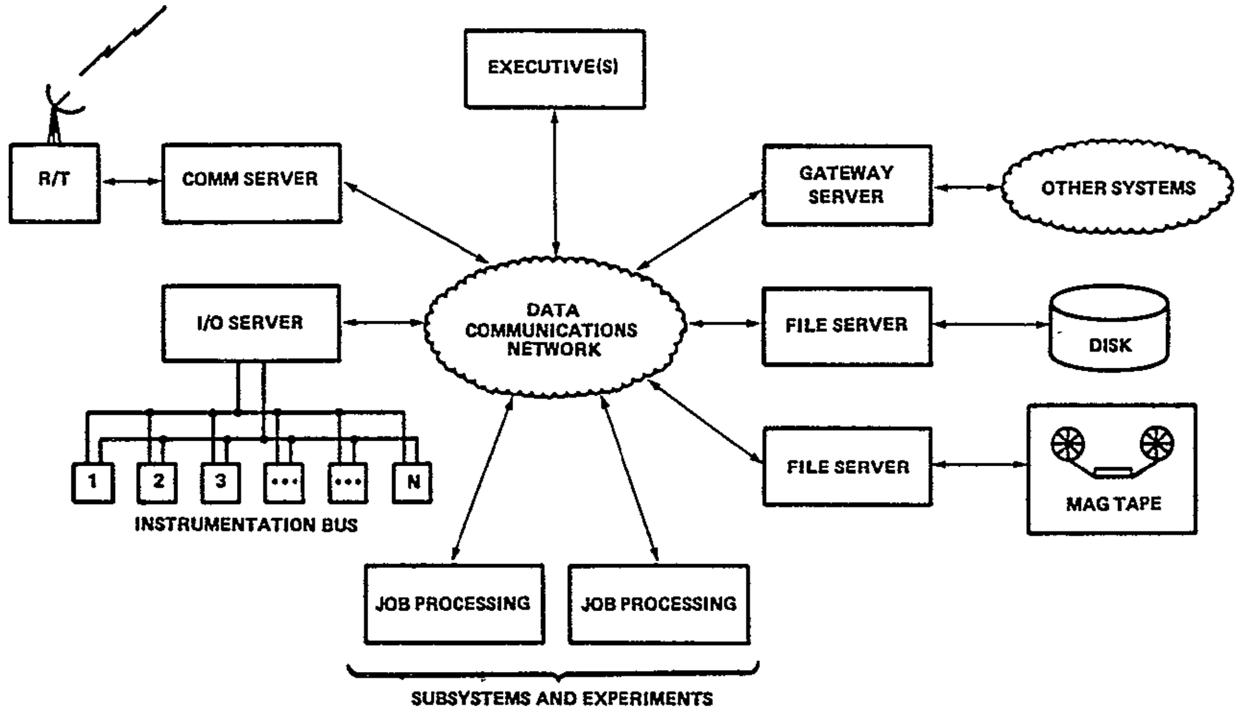

Figure 3.2-9. Network Operating System

implying that multiple executives may be needed. In any case, extensive simulation, testing, and verification is required for system development, and a systems integration facility will undoubtedly be necessary. The next major section discusses this development concept in greater detail.

3.2.6 Technology Development Cost and Schedule Considerations

This section summarizes a baseline approach for the space platform data management architecture, with an emphasis on the technology development schedule and costs. Briefly, this approach is to adapt computer network technology to space platform needs. This would take the form of a fiber optic backbone network, (a specialized local area network), consisting of multiple fibers encased in at least two physically separate cables. The cables would run through the space platform modules, connecting them at the berthing ports by means of standardized connector assemblies. Devices such as instruments, sensors, processors, data storage units, video displays, transducers, and controllers of various types would be connected into the network by means of network interface modules (NIM's).

The NIM's are electronic units containing optical receivers and transmitters for inter-module communications. They also contain interfaces for equipment such as NASA multiplex data bus instruments or RS-330 closed circuit television monitors. The NIM's might control a single antenna multiplexer. Additional capability must be provided for nonspecific computational tasks, as depicted by the boxes labeled job processing.

The space platform network operating system will have critical control functions involving many devices. Equipment used for attitude, thermal, power, and environmental control will all be involved, since the data management network will provide the interconnections to these subsystems. Some functions will require fault tolerant provide electronic circuit switching and data packet switching capabilities for control and communications. These functions are orchestrated by a set of computer programs, collectively known as a network operating system.

The most important components of the fiber optic backbone network, except for the optical fiber cables, connectors, transmitters, and receivers are:

a. Network interface module.
b. Network operating system.
c. Gateways to other systems.

Gateways allow the devices organized by the backbone network to "talk" with other systems, such as the shuttle, that use different interfaces and protocols.

Most space platform subsystems will utilize digital electronics controlled by microcomputers. The difficulty and cost of subsystem development, testing, integration, logistics support, and maintenance would be greatly reduced if a standard microcomputer could be developed or selected. A family of processors, memories and I/O interfaces could be produced by a single contractor for use by all other space platform subsystem contractors. In this way, a small set of components could be utilized in many applications, yielding great savings in developmental and life-cycle costs.

The following sections recommend an approach for developing the space platform data management network for a 1990 initial operational capability. This is an early platform, while development in the post-1995 time frame would be considered a late platform. Before the early platform can be constructed, however, it is believed that a systems integration facility should be developed, as described in the next section.

3.2.6.1 Systems Integration Facility

It is recommended that a space platform systems integration facility (SIF) be selected, equipped and staffed as early as possible in the space platform development cycle. The first task would be to initiate requirements definition studies for the various subsystems supported by the data management system. This includes any subsystem with a requirement for computer processing, data storage, digital control or data communications capabilities. This includes or involves almost every electronic device or essential subsystem aboard the platform.

The general requirements should fit into one of the nine categories listed near the beginning of section 3.2.2. However, the requirements must be determined quantitatively at some point, considering at least the following areas:

a. Data rate.
b. Data format (frame size).
c. Storage requirements.
d. Processing requirements.
e. Reliability requirements.
f. Delay tolerance (for control functions).
g. Display requirements (how/where/when).

In many cases, it will not be possible to calculate such requirements directly. However, specifications must be issued before equipment can be designed. Therefore, it is recommended that the SIF be equipped for computer simulations in its initial testbed configuration. This will require multiple scientific computers with advanced video display capabilities.

After requirements are defined, specifications can be issued for selection or design of equipment breadboards. It is recommended that all such breadboards adhere to a set of standards for processors, interfaces and communications protocols. Therefore, these standards will have to be defined as an early task for the SIF.

The equipment breadboards would be connected into a prototype data management network for testing and verification. Brassboard units would be developed soon after, and after validation in the testbed, could be carried aboard the shuttle for space testing. That is, brassboards would be carried in a shuttle-compatible module in a subset configuration, which would also have to be equipped with a functional network.

Therefore, it is recommended that a prototype data management network be developed at the SIF very early in the program. This network would—

a. Interconnect simulation computers.
b. Provide video displays for simulation.
c. Provide a data base management system.
d. Serve as a prototype space platform network.
e. Support laboratory breadboards.
f. Help develop flight hardware.
g. Serve as a training model.
h. Become the SIF network for flight configurations.

Most NASA facilities have scientific computers available for simulation, as well as laboratories for subsystem testing and evaluation. The prototype data management network is the only missing component required for early development. It is therefore recommended that the SIF be equipped with a prototype data management network as an initial task.

It was estimated that a space qualified network could be developed at a cost of about $64 million, as an approximation. Also, it is estimated that a ground-based system could be implemented for a fraction of that total. Such ground-based system costs could then be recovered as part of the flight hardware development cost. The ground-based system probably could be built for $10-15 million, with initial funding at the $2-3 million level in 1984 dollars. Volume IV of this report discusses the development plan in greater detail.

3.3 DATA MANAGEMENT DATA BUS

The purpose of this study was to identify potential fiber optic data network approaches to the advanced space platform data communication requirements and evaluate them in order to select the most promising for technology advancement and eventual use on a space station. Fiber optic component capabilities for space application were also to be considered. Fiber optics was selected for study because of its known advantages in bandwidth, insensitivity to EMI, and security and weight benefits compared to wire-based interconnections. These benefits have been proven in ground applications, but are still basically unproven in space. A major output of the study was to be identification of any technology requiring advancement in order to allow or enhance use of fiber optic data networks in 1986 design of the advanced platform.

No enabling technology barriers to the use of fiber optics technology in the Advanced Platform application were identified. Unconstrained reconfiguration and modular growth requirements of the advanced platform resulted in elimination of passive optical bus approaches and appear to require use of data networks utilizing point-to-point interconnection of system nodes. Preliminary evaluation favors use of a graph point-to-point network structure. Discussion and evaluation of approaches follows in section 3.3.3.

Several technological problems related to the fiber optic portions of the advanced platform data communication system were identified. While of importance to meet identified requirements for operation of the data systems studied, the technological problems are of an enhancing rather than enabling nature. Since fiber optics is still relatively immature compared to conventional electronics technology, a number of technological advances are underway in commercial and DOD work that will benefit the space application. Two areas were identified that justify NASA development funding at this time. Both are related to improvement of fiber optic system reliability and reduction of life cycle costs. One is the development of fiber pigtailed hermetic optical sources and detectors, and the second is the development of integrated circuit optical transmitters and receivers to replace discrete/hybrid approaches currently used. Technology advancement items are discussed in section 3.3.5.

3.3.1 Issues

The technological feasibility of fiber optics communication links has been proven for a number of ground, sea, and air applications. Its benefits in bandwidth and distance capability, interference immunity, security, and low cost and weight compared to metallic conductors of equivalent bandwidth are very attractive for application to the advanced space platform. However, there are a number of peculiar requirements inherent in the advanced platform application that require examination and resolution to enable use in the space environment. The main issues are technological maturity, reliability, and radiation. These items are discussed in section 3.3.5.

3.3.2 Requirements

The principal purpose of this study was to evaluate potential for fiber optic implementation of data network interconnects for a manned space platform and to identify key technologies requiring development to meet the requirements for this application. It was assumed that design would start in 1986 in order to provide an initial operating platform in the early 1990's. For this study, a set of requirements based generally on the study data base was used. This data base resulted primarily from previous Boeing work on the Space Operations Center concepts and was used in order to provide a basis for comparison between approaches. These requirements included—

a. Provision for modular build up of the advanced platform in module increments allowed by space shuttle capacity. The assumed initial manned operating configuration would consist of three modules as shown in figure 3.3-1. Growth over a period of years to the configuration shown in figure 3.3-2 was assumed. Based upon previous work, the growth configuration represents an upper limit for personnel and habitat and work modules. A maximum crew size of 8 to 12 is assumed. Additional laboratories, hangars, etc., together with external structures related to in-orbit build up and repair of spacecraft would probably be added, but would have a relatively small impact on the data network requirements. A laboratory containing a multispectral scanner or other high data rate device would constitute an exception. However, this type equipment would typically require a dedicated interconnection to prevent gross overload of the normal data network. The figures also identify assumed per-module data system equipment quantities and types assumed for this study to provide a common basis for comparison of approaches.

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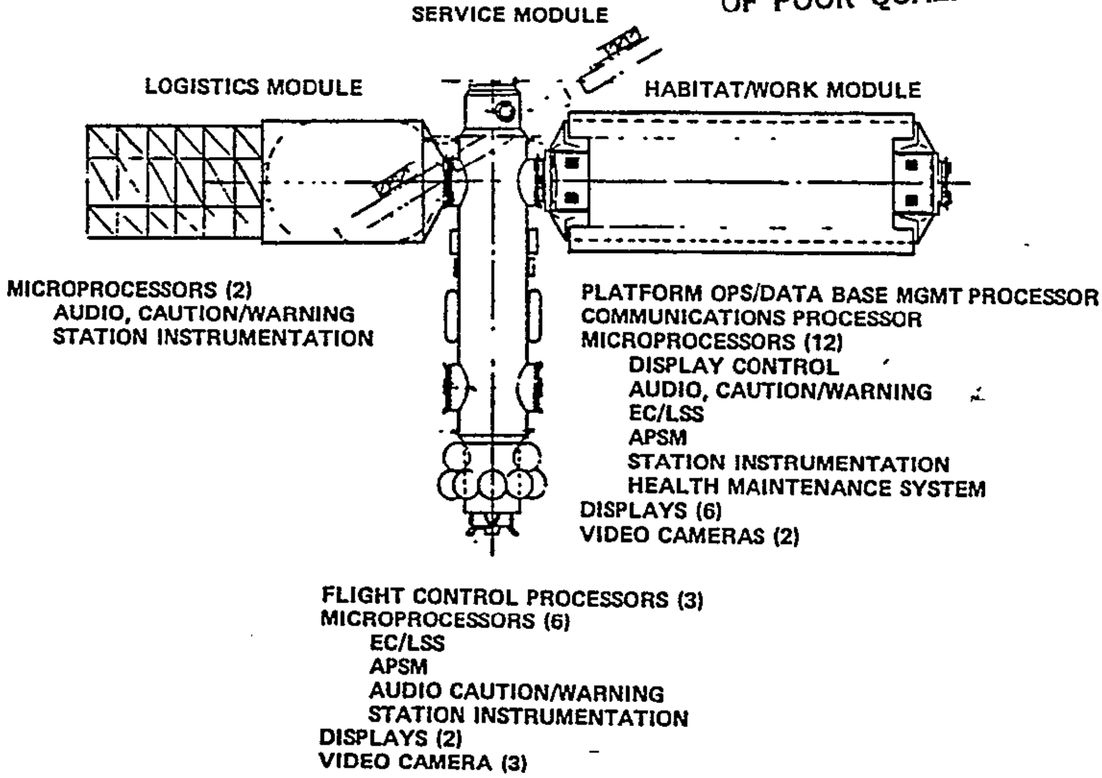

Figure 3.3-1. Initial Manned Station Configuration

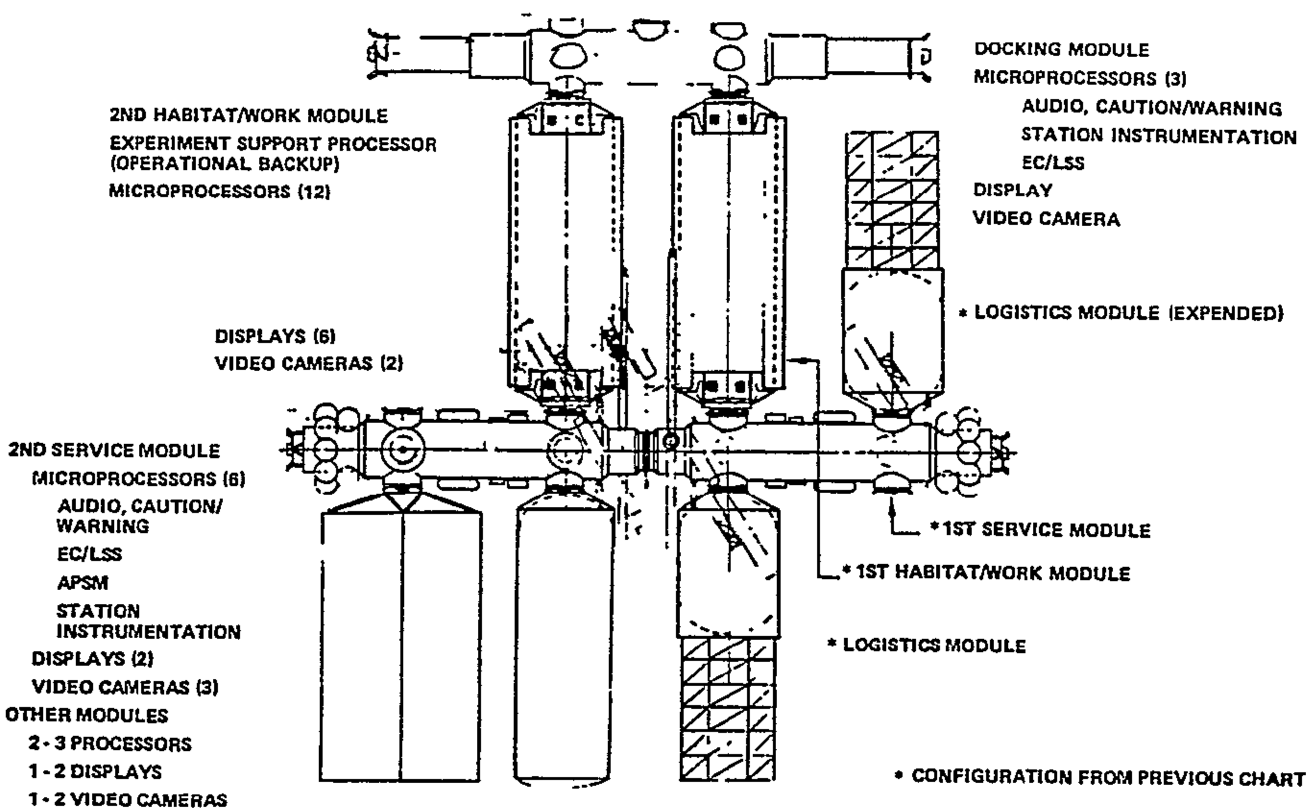

Figure 3.3-2. Evolutionary Growth Station Configuration

b. Data network capabilities to handle communication requirements in support of tasks identified as part of the Data Management Architecture Study are discussed in section 3.2.2. These include—
   1. Real time control functions.
   2. Instrument data collection.
   3. Digital voice communications.
   4. High bandwidth video distribution.
   5. High speed bulk data transfers.
   6. Interprocessor digital data communications.
   7. On-line and archival mass storage data transfers.
   8. Scientific computations for experiments.
   9. Signal and image processing.

The majority of this data would require transmission in a serial digital form. It is desirable to handle all data transfers in digital form, including the high bandwidth video. However, because of the exceedingly high data rates (greater than 5 GBPS) that would result for digitized video handling, it is probable that initial video data transfers will be in analog form.

The Data Management Architecture Study made preliminary estimates of peak and average data rates that would occur. These estimates, (identifed in figure 3.2-1) were used in evaluations of data bus concepts in this part of the technology study program.

3.3.3 Characterization of Concepts

The following paragraphs identify and discuss various fiber optic data network configurations which were considered for the advanced platform application. Approaches considered included passive bus concepts, several point-to-point concepts, and a hybrid network using passive buses interconnected by broadband active repeater modules.

3.3.3.1 Passive Networks

Three different passive coupled network configurations were considered. All passive networks have a number of features in common. The most important are—

a. The ability to operate in broadcast mode. That is, any message sent may be received by all other nodes on the network without intervention by any other node.

b. The ability to operate with baseband direct modulation or broadband modulation utilizing frequency division multiplexing (FDM) or with combined baseband and FDM operation. With baseband operation, time division multiplexing in some form must be used to handle more than a single pair of nodes. This requires a network control protocol of some type to apportion data communications among the terminals on the bus. The type of protocol selected is influenced by the type of operation to be carried out by the bus. Many different protocols exist, ranging from contention to command and response. With FDM, simultaneous bus operations may be carried out on different FDM subcarriers using baseband modulation of each subcarrier. In this case, each FDM subcarrier would require control by a network control protocol in the same manner as with direct baseband operation of the network. However, in the FDM case, the subcarrier itself would require on-off control by the protocol so that only a single transmitting node at each subcarrier frequency was on at one time. FDM operation would allow simultaneous hierarchical bus operations on the same set of interconnecting optical paths by using different subcarrier frequencies for each hierarchical group and would result in increased effective total date rate capability compared to baseband operation of the network.

c. The ability to support use of optical wavelength division multiplexing (WDM), which can greatly expand the total data rate of the network without any change in optical paths other than addition of optical wavelength multiplexers and demultiplexers. This assumes that adequate optical signal power margins to accommodate the additional optical insertion loss (5 to 6 dB) of the mux/demux units. Use of WDM techniques also requires the provision of optical sources at the nodes capable of operation at each wavelength selected. This mode of operation also allows simultaneous operation of essentially independent data networks on the same set of interconnecting optical paths.

Support of FDM and WDM techniques would allow the data handling capacity of initially installed optical interconnecting paths to be greatly expanded, without change in interconnecting cabling, as increasing data requirements necessitate increased system capability. However, both FDM and WDM techniques are more costly (perhaps $1,000 to $3,000 per network node) than baseband direct modulation approaches. This is due to added costs of multiplexers and demultiplexers at each network node. For the relatively short communication path lengths required in the advanced platform application, it would probably be more cost effective to provide excess data rate capacity in the network by including unused fibers in the initial station design and construction to handle projected growth. For example, to cost effectively quadruple the data capacity of a single fiber using WDM techniques, the path length would have to exceed about 700 meters based on current fiber and WDM component costs. Cost effective use of FDM would similarly require longer path lengths than are likely to occur in the advanced platform. The cost-benefit cross over point would depend on a number of design factors and could not be determined until completion of a preliminary design to meet specific requirements was complete. However, FDM mux/demux electronics is estimated to cost more than passive optical WDM mux/demux units, therefore the cross over would require even longer path lengths.

For the number of terminals and extremely high data rates necessary to handle the initial and growth requirements of the advanced platform, it would be necessary to use solid state laser diode optical sources to achieve satisfactory operating optical signal margins in any passive bus configuration. This adds significantly to circuit complexity (40% to 60%) in optical transmitters because temperature stabilization and optical feedback techniques are needed to hold optical output power variations within acceptable limits. As discussed in section 3.3.5, use of solid state laser diode optical sources also imposes a significant penalty in terminal operational reliability compared to terminals using spontaneous light emitting diode sources.

All passive bus configurations would require special control circuitry in the optical transmitters to prevent blockage of the bus by a babbling transmitter or node. Babbling is uncontrolled transmission by a node. Babble protection circuitry would consist of an activity monitor at each node which would act in conjunction with a transmission timer. The timer would reset at the conclusion of each message, and restart at the beginning of the next message. If the timer exceeds a predetermined count, the control circuit assumes that the transmitter is babbling and turns it off. The time interval at which this would occur could either be determined as part of the initial design process, or set by the system depending on the type of operation at a particular time. The babble control timer could also be set at a standard network value, or it could be set on an individual node basis if desired.

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The following paragraphs examine three different passive network configurations relating to the requirements established in section 3.3.2.

3.3.3.1.1 T-Coupled Bus

Figure 3.3-3 shows the T-coupled bus configuration. This configuration uses the least fiber of any of the passive configurations for a given number and spacing of terminal nodes. It looks similar to a tapped wire bus, but does not operate in a similar fashion

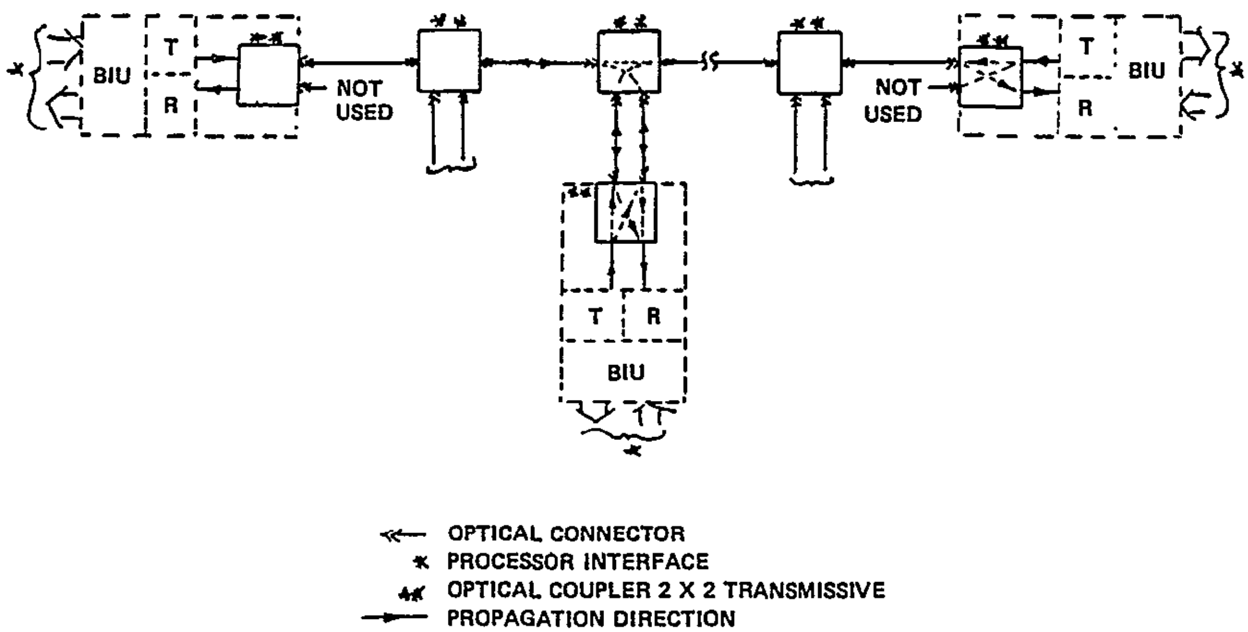

Figure 3.3-3. T-Coupled Optical Bus

since there is no way to tap an optical bus in the high-impedance bridging manner used in a wire bus. In the version shown, a single optical fiber is operated in a bidirectional mode using 2X2 transmissive biconical taper optical couplers as bus tap elements and to provide the required optical transmitter and receiver coupling at each node. A T-coupled optical bus exhibits a rapid increase in bus propagation loss as the number of terminals is increased. The series loss components of optical connectors and the optical tap couplers add rapidly to produce the increase in propagation loss. Each connector pair typically adds 1 to 2 dB loss, and the 2X2 tap elements are typically 4 to 6 dB each. In a similar fashion, optical dynamic range requirements on the bus receivers increase rapidly with the number of terminals. Bus dynamic range in the T-coupled bus is the dB ratio of the signal power from the most distant node to the signal power from the nearest node as measured at the end nodes. With uniform ratio tap couplers, the T-coupled bus is useful for about 4 terminals before loss and dynamic range requirements exceed system capabilities. Use of non-uniform tap ratios can extend the number of terminals slightly. With non-uniform couplers, 5 to 6 terminals are feasible. However, the tap ratios of the tap couplers must be selected for their location in the system and for the total number of terminals. This results in peculiar requirements for each coupler element, which prevents modular growth and results in low production volumes and attendant high cost. Adding or deleting a terminal would require replacement of all tap couplers in the system in order to achieve the benefits of nonuniform couplers. This is completely impractical.

Optical propagation loss and system dynamic range characteristics versus number of terminals for both uniform and nonuniform couplers are discussed in comparison to the other passive bus configurations in section 3.3.3.1.4.

This bus configuration is not suitable for the advanced platform application since it will not support the required number of bus nodes. This statement is valid even if the nodes were contained in the same platform module (i.e., habitat-work module or service module). Distribution of the nodes among station modules makes the problem even more severe.

3.3.3.1.2 Star or Radial Coupled Bus

Figure 3.3-4 shows the basic star or radial coupled bus configuration. Each terminal node is connected to a passive central optical coupling element. This central coupling element interconnects all terminals. In the example shown, the central coupling element is a

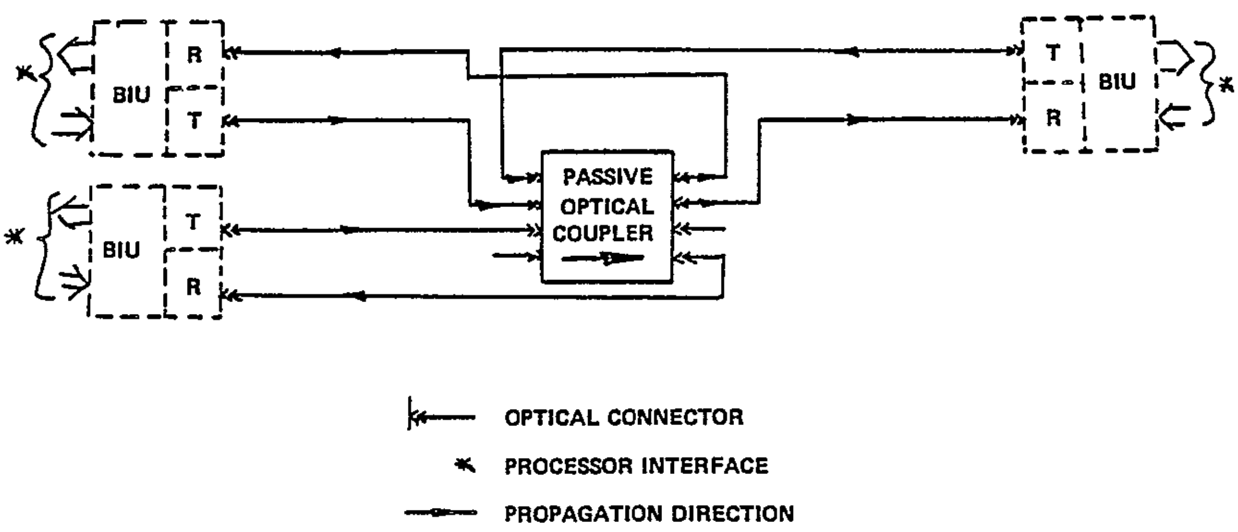

Figure 3.3-4. Passive Star Coupled Bus

transmissive type with two interconnecting fibers for each terminal node. One connects to the node transmitter, and the other to the node receiver. At the central coupling element, transmit fibers from all nodes are connected to the coupler input end and all receive fibers are coupled to the output end. This results in the input signal from any transmit fiber being divided, approximately uniformly, between all receive fibers. The currently favored fabrication technique for this type coupler involves fusing, twisting and drawing a group of fibers to produce the optical mixing action required. Couplers produced in this manner are known as biconical taper couplers. Couplers with over 100 input and 100 output fibers have been successfully produced in this manner.

The passive star coupled approach is characterized by a very gradual increase in coupling path loss as the number of terminals is increased and by a moderate dynamic range characteristic. Dynamic range variations result from nonuniformities in the coupler itself, differences in optical path length and connector quantities between terminals in the network, by connector loss variations, and node transmit power variations.

A major negative factor for the star-coupled approach is the single point failure potential inherent in the central coupling element. In addition, the central coupler location requires use of a rather large quantity of fiber to interconnect the system. The distribution of data network nodes throughout the advanced platform modules, in combination with the uniform berthing port interface and modular growth requirements prevents application of star-coupled passive networks that extend beyond the boundries of a single station module. Use of redundant buses would be required to reduce potential for data network failure.

Dynamic range and bus coupling loss versus number of terminals for this configuration are shown in figure 3.3-6 in comparison to the other passive network configurations.

3.3.3.1.3 DISCO Bus

Figure 3.3-5 shows the configuration of the DISCO bus. DISCO is an acronym for distributed star coupled. This configuration replaces the central star coupler with a group of interconnected transmissive star couplers. Interconnection in this manner limits the effect of star coupler failure to those terminals accessing the bus through that coupler. This represents a significant improvement in bus operational reliability. Use of redundant buses would still be required to achieve the high bus reliability required in the advanced platform application.

Compared to the basic star coupled bus configuration, the DISCO configuration exhibits slightly higher coupling path losses for a given number of terminals and a stepped rather than gradual increase. The stepped increase is the result of the N^2 relationship between the number of coupling elements and the number of terminal nodes that is inherent in this

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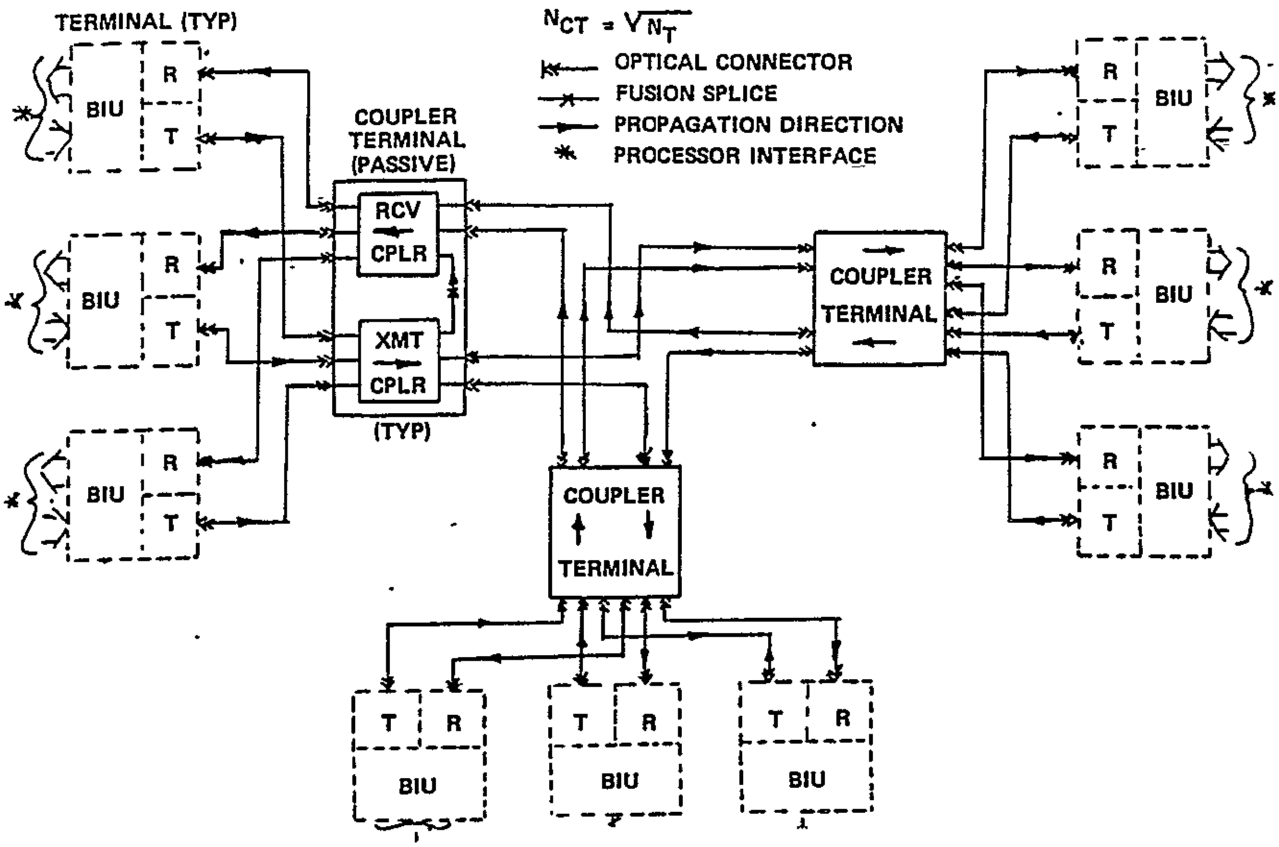


Figure 3.3-5. Distributed Star Coupled Bus (DISCO)

configuration. Coupling path loss and dynamic range characteristics for the DISCO bus are given in figure 3.3-6.

The uniform berthing port and modular growth requirements also prevent using the DISCO bus, except in individual modules of the advanced platform.

3.3.3.1.4 Comparison of Passive Bus Configurations

Figure 3.3-6 shows the coupling path loss versus number of terminals for each of the three configurations. The viability of a particular approach depends to some extent on the loss and dynamic range requirements imposed by the optical coupling network in relation to the achievable optical link margins provided by the system transmitters and receivers and the dynamic range capabilities of the receivers. Optical link margin is determined by the optical source output power and the receiver sensitivity for a given data rate and bit error rate. Optical link margins in the range of 30 to 45 dB have been demonstrated for 100 MBPS data rates and 10^{-9} bit error rate. The maximum link margin requires use of avalanche photo diode (APD) optical detectors and solid state injection laser diode optical sources. Both devices tend to degrade system reliability compared to spontaneous light emitting diode (LED) sources and PIN diode optical detectors. PIN detectors in

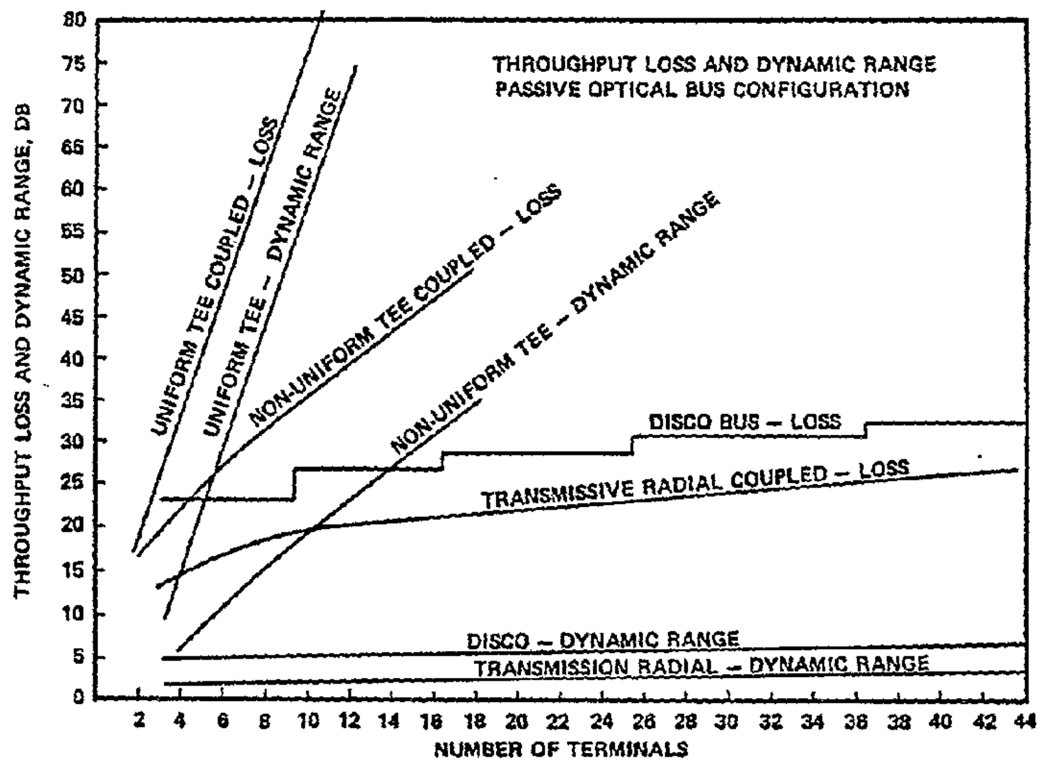


Figure 3.3-6. Passive Bus Comparison Path Loss & Dynamic Range vs Terminal Quantity

conjunction with ILD sources can produce optical link margins in the range of 35 to 40 dB. Use of PIN detectors results in simpler receiver design since the high voltage bias power supply required for the APD can be eliminated. Receiver dynamic range capability of about 25 dB has been demonstrated. As can be seen from the figure, only the T-coupled networks exceed this value. Based on the demonstrated transmitter-receiver performance at 100 MBPS, uniform T-coupled networks would be limited to 4 to 6 terminals. More than 80 terminals could be supported in a conventional star-coupled network operating at 35 dB link margin. At least 25 terminals could be accommodated under the same conditions by a DISCO configuration. Inclusion of link margin safety factors to allow for device aging and environmental variations would reduce this to 3, 4, 5, and 16 terminals respectively.

For the advanced platform application, the most difficult problem relating to application of any of the passive bus approaches is satisfaction of the uniform berthing port-modular growth requirement. It might be possible to establish a large star or DISCO configuration in the first service module with enough bus terminal ports to provide the required number of bus interconnects at each berthing port. Based on the equipment quantities and locations selected to provide a basis for comparison between network approaches (section

3.3.2) this would require at least 22 terminal capability to accommodate the first habitat-work module. Allowing about a third for growth would require a standard berthing port interface to accommodate 30 nodes and necessitate a star or DISCO coupler set capable of about 250 node capacity. This might be feasible and would satisfy the uniform berthing port-modular growth requirement for the first service module. However, the second service module also has seven berthing ports, each of which would also be required to have at least 30 terminal capacity. Clearly, this cannot be accomplished by passive splitting from the 30 terminal capacity interface between the two service modules. Consequently, in light of this difficulty, it was concluded that none of the passive bus configurations can be made to satisfy the overall station data network requirements. Passive networks must therefore be limited to data networks contained within a single station module. Some form of active interface, such as a gateway node, would then be required to communicate across the berthing port interfaces between modules.

3.3.3.2 Hybrid DISCO Bus Networks

The hybrid DISCO bus configuration shown in figure 3.3-7 is a modification of the standard DISCO configuration shown in figure 3.3-5. It differs by inclusion of additional

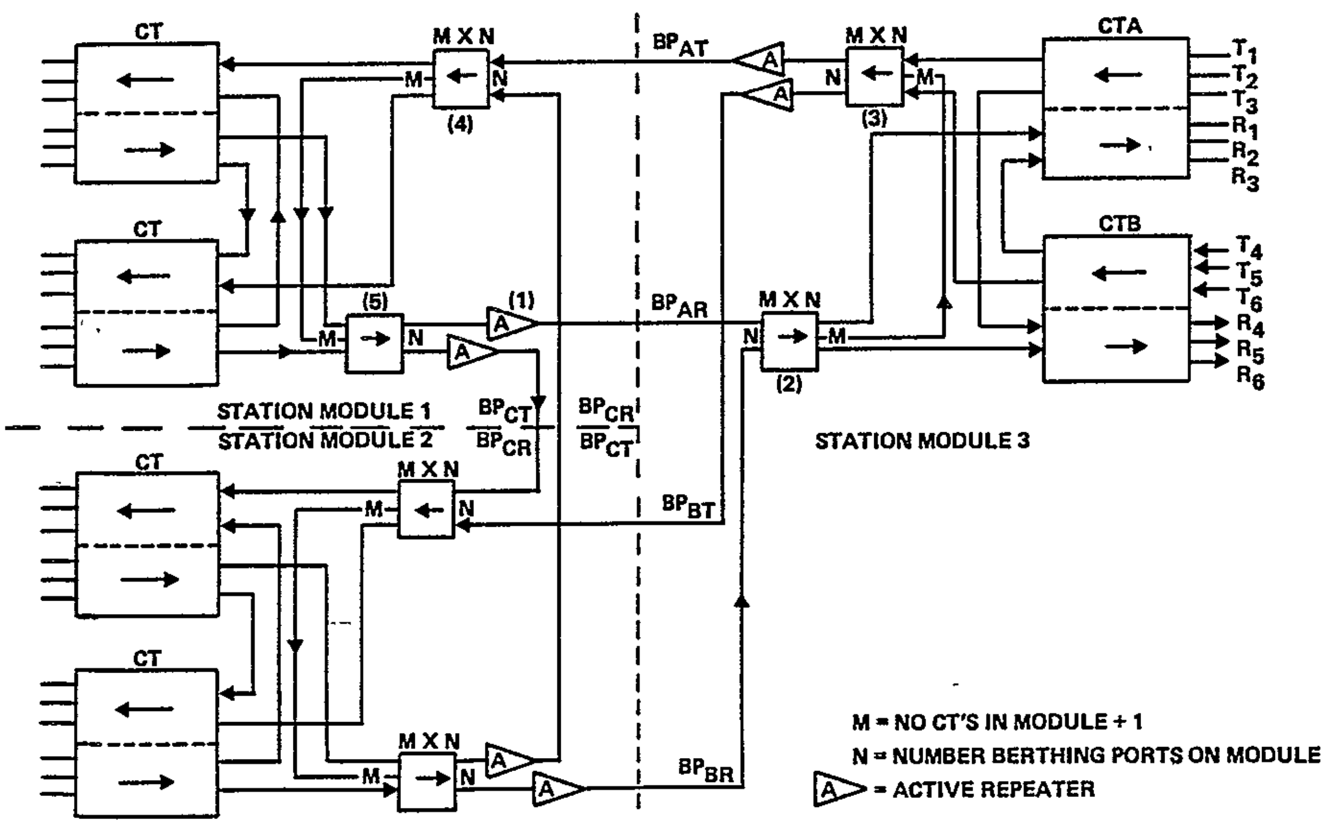


Figure 3.3-7. Hybrid DISCO Bus Configuration

transmissive star couplers and broadband repeater amplifiers to enable coupling across the berthing port interfaces in a uniform manner. This configuration was postulated shortly before the contract midterm oral briefing, and was presented as a possible solution to the uniform berthing port-modular growth problem. Further examination shows the configuration will not perform as originally expected. The basic DISCO configuration takes great pains to prevent multiple propagation paths through the network, which could cause data degradation due to multipath interference. Inclusion of the additional optical couplers to serve and interconnect the berthing ports results in multiple path propagation, and with the broadband repeater amplifiers would in all probability result in a severe case of oscillation which would totally block the network. This can be seen by examining the configuration shown in the figure. Starting at the active repeater (1) in module 1, follow the path to the incoming optical coupler (2) in module 3. The output of this coupler is fed as an input to the berthing port feed coupler (3) and active repeater in module 3, where it is fed back to the input coupler (4) in module 1. The output of this coupler is similarly fed to the input of the berthing port feed coupler (5) in module 1 which results in its being connected right back as an input to active repeater (1) which was the starting point in the loop. Conditions for oscillation are thus established, depending only on feedback phasing which cannot be controlled. Even if phasing were such that oscillation did not occur, multiple data path interference would still result in improper operation. Operation would look like a contention-type bus with 100% guaranteed message collisions.

3.3.3.3 Point-to-Point Network Configurations

Local area networks can be configured in many different ways using point-to-point links to interconnect network nodes. These links could be either wire or fiber optic, but the bandwidth, interference immunity, and other features of fiber optics would not be available if wire were used. The use of point-to-point fiber optics links offers some very significant system benefits compared to use of passive bus configurations. They are—

a. Optical path losses between nodes would be a small fraction (less than 1/4) of those that would be present in any of the passive buses. With current technology, losses in all probability would be less than 8 dB between nodes. Providing that data rate requirements do not exceed about 250 MBPS, this would enable the use of LED optical source diodes instead of ILD sources and would result in significantly higher system reliability. Lower costs would also result due to circuit simplifications. Similarly, PIN diode optical detectors could be used.

b. The optical receivers could be greatly simplified since their dynamic range performance would only have to accommodate slow, long term optical power variations instead of the fast intermessage optical signal variations which typically occur in a passive bus configuration.

c. Long-life radiation performance of the links would be improved since the high optical signal margins obtainable in point-to-point links would allow a much higher allowance for radiation degradation. In addition, receiver AGC performance would tend to compensate for the long term, very gradual, fiber loss increases due to radiation.

d. The optical transmitters could eliminate the babble prevention provisions that are required in any of the passive bus configurations. This can be done since a babbling transmitter or node would affect only those nodes receiving data directly from it. The receiving node could recognize the problem and ignore input from that source. No general network blockage would occur.

e. Network operating protocols can be greatly simplified since they are not required to allocate network access among the connected nodes. Each node only has to examine all incoming messages, determine whether it is the addressed node and then either accept the message traffic or pass it on to the next node. For some of the configurations, routing information is used to determine which of several available links is optimum for outgoing traffic.

f. Synchronization of incoming message traffic with local clock timing to enable its proper processing is greatly simplified since gaps in message traffic can be filled with clock to retain synchronization between messages. In passive buses, clock resynchronization is a significant problem at high data rates since all nodes are asynchronous, and it is not possible to transmit a continuous synchronization signal. In high rate passive buses, it is common to see 40- or 50-bit preambles on every message to allow clock resynchronization. This is undesirable since it increases system overhead.

As is usually the case, benefits on one hand are obtained only at the cost of penalties on the other. This is the case for point-to-point networks. The principal penalties are briefly discussed below:

a. The ability to operate in a broadcast mode is lost, since any message typically must be repeated through a number of nodes prior to receipt at the destination node. This increases message propagation time compared to passive bus configurations with the same number and spacing of nodes. However, there is no possibility of contention between nodes as can occur in a passive bus configuration with some protocols.

b. System data rate is limited by the processing rates of the network node electronics, and can only be increased by setting up parallel interconnection paths. Available fiber bandwidth typically would not be used. It is not feasible to utilize FDM or WDM techniques to increase the data rate capacity of the interconnections since the paths are too short for this approach to be cost effective.

c. Current data rate capabilities of the node electronics will not allow handling of continuous high rate data such as originates in a multispectral scanner, long messages formatted for 300 MBPS TDRSS satellite transmission, or data transmission for high-resolution video systems. VHSIC program developments may change the capabilities sufficiently to allow handling of this data by active nodes. However, relatively sustained high-rate data of this type would tend to load a network unacceptably. Consequently, dedicated separate capabilities for this data should probably be provided for these functions.

The Data Management Architecture study identified a number of different local area network configurations in section 3.2.3.1 and considered their characteristics. From the point of view of the data bus study, the differences tend to disappear, except as they affect the number of point-to-point links required to interconnect the nodes in the network. Consequently, the data bus study limited evaluations to a relatively simple redundant ring structure and a highly redundant high-performance graph structure. These are discussed briefly from the point of view of the interconnection structure and their suitability for the advanced platform application in the following paragraphs.

3.3.3.3.1 Chordal Ring Network

The chordal ring local area network structure shown in figure 3.3-8 is the simplest form of point-to-point network that could be given consideration for a manned platform application. As can be seen from the figure, each system node is connected to four other nodes. A node can receive data from two different nodes and transmit data to two others. The ring will continue to function with any single interconnection path failure or node failure—except for loss of the failed node itself of course. If the primary path fails, the alternate is selected.

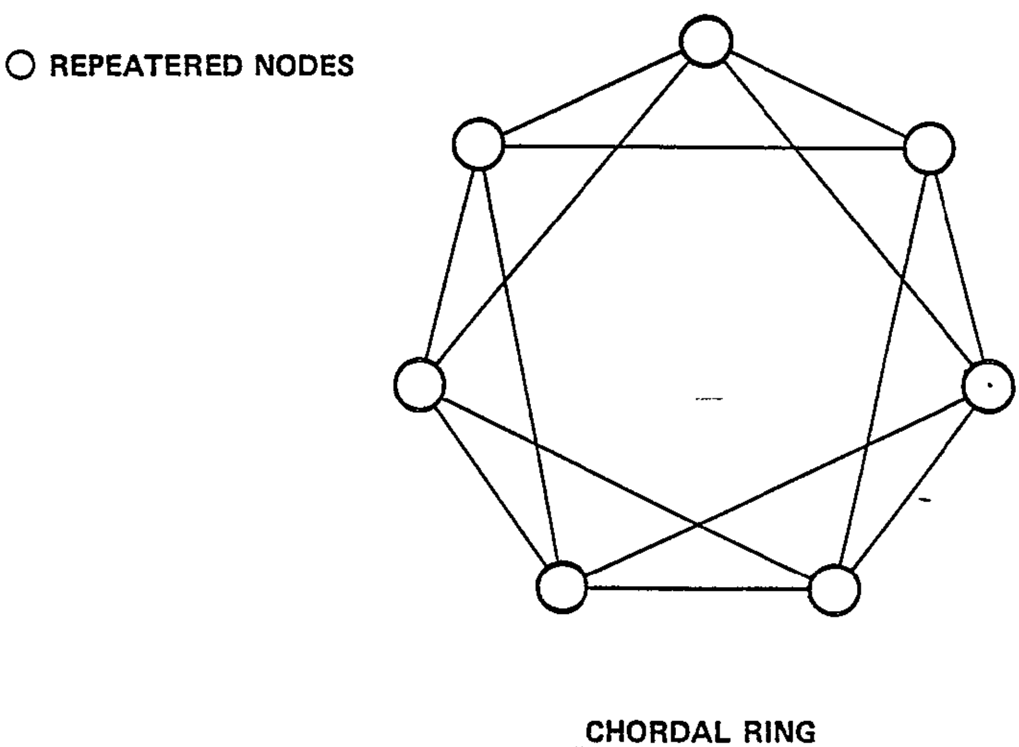


Figure 3.3-8. Chordal Ring Network

The chordal ring structure allows satisfaction of the uniform berthing port-modular growth requirement providing that capability is provided to bridge across unoccupied ports. Each port would have two sets of three optical paths, one set of which could be considered as entering a berthed module, and the other set as exiting. For any unoccupied berthing or docking port, entry cables would be connected to exit cables, maintaining ring continuity across the empty port. System nodes in the berthed module would be connected in series in the ring structure. Changes at the architecture level to accommodate new node addresses, etc., would be required. In the evolutionary growth station configuration shown in figure 3.3-2, it would be desirable to bridge across the berthing ports at one of the two docking tunnel to habitat-work module interfaces to prevent setting up an unintended shunt connection. A shunt connection could be accommodated, but at cost of additional complexity in the control structure of the network.

As previously discussed, the chordal ring network is not suitable for transmission of high rate continuous digital data nor for any form of analog data, video or otherwise. This is due to mode electronics limitations, not the fiber optics link limitations. Dedicated interconnections must be provided for these functions.

3.3.3.3.2 Graph Network

Figure 3.3-9 shows a partially connected graph network structure. A fully connected graph network has every node directly connected to all other nodes. This network form

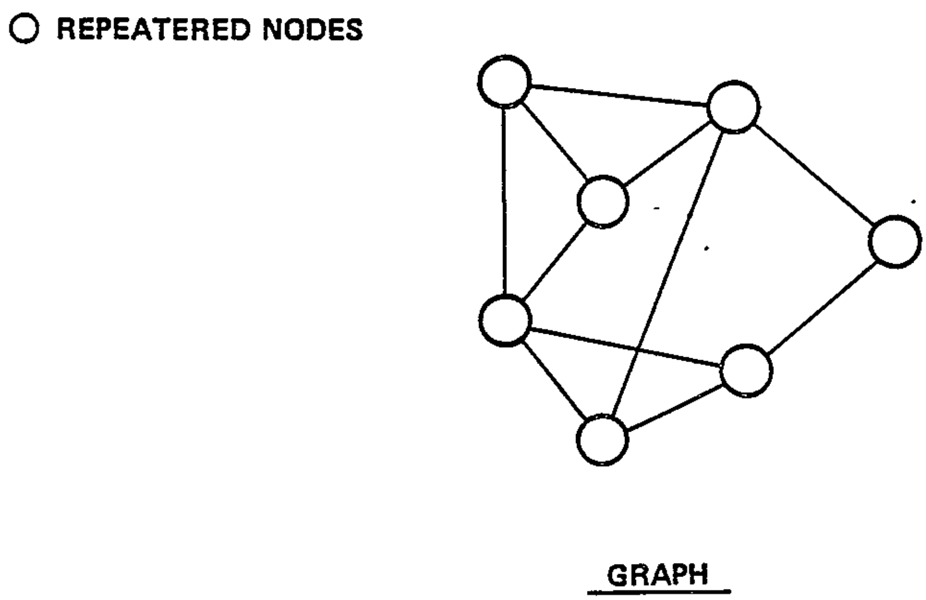


Figure 3.3-9. Graph Network

provides the highest total data rate capability of any of the point-to-point network configurations. It is able to do this by establishing simultaneous operation on a number of parallel or hierarchical networks within the overall network. Node complexity is increased by more complex routing and control functions and the necessity for additional interface connections. In practice, fully connected graph structures are seldom used due to complexity and cost.

The graph structure, in spite of its increased data rate potential compared to the chordal ring structure, still cannot accommodate dedicated path high-rate digital data, long TDRSS message transmission, or analog and real time video data. As before, the limitation is due to mode electronics capabilities.
Constraining the graph structure interconnects to a uniform berthing port interface to meet modular growth requirements requires providing all berthing ports with the number of paths needed to achieve adequate data rate capablity across the worst-case pair of ports. This would have to include growth allowances as well, and would result in many unused links at the unoccupied ports. This causes cost and weight penalties that may be unacceptable. For the growth configuration shown in figure 3.3-2, it is estimated that 25 to 30% of the network cost and weight would be devoted to serving unoccupied ports.

3.3.3.4 Comparison of Concepts

The chart of figure 3.3-10 was presented at the midterm briefing to show preliminary

RELATIVE RANKINGS ONLY

▷ QUANTITATIVE COMPARISONS TBD

	▷ ESTIMATED SYSTEM COST (TRANSMITTERS, RECEIVERS, OPTICAL PATHS ONLY)	▷ ESTIMATED SYSTEM WEIGHT	▷ ESTIMATED RADIATION LIFE, YEARS	RELIABILITY/FAULT TOLERANCE (RELATIVE RANKING)	COMPLEXITY (RELATIVE RANKING)	BANDWIDTH CAPABILITY (RELATIVE)	ACCESSABILITY (RELATIVE)	EXPANDABILITY (RELATIVE)	MATURITY (RELATIVE)	RECONFIGURABILITY (RELATIVE)	COMBINED RANKING
CHORDAL RING *	6	8	8	6	6	9	8	7	6	8	7.2
GRAPH *	5	7	8	7	6	9	9	8	6	9	7.4
HYBRID DISCO WDM, BASEBAND WITH REDUNDANT BUS	2	7	7	6	4	10	9	8	4	8	6.5
HYBRID DISCO FDM AND BASEBAND WITH REDUNDANT BUS	4	6	7	5	3	8	9	9	6	9	6.6

* WITH REDUNDANT HYBRID DISCO BUS FOR VIDEO

RELATIVE RANKING 10 = BEST
0 = WORST

Figure 3.3-10. Preliminary Bus Configuration Trade Results comparisons of network concepts believed viable for advanced platform application. Comparisons as presented are qualitative. As explained at the briefing, the concepts compared in the figure are not the only ones evaluated in the Data Bus Study. A preliminary evaluation of other approaches, including conventional wire interconnects, was made. The preliminary evaluation was made based on suitability for application to the system requirements stated in section 3.3.2. The approaches considered, together with brief reasons for inclusion or exclusion, are given below:

Twisted pair wire interconnects. Twisted pair wire interconnects were excluded from consideration due to bandwidth inadequacy, EMI sensitivity, weight, and potential security inadequacy.

Coaxial cable (wire). Use of coax was excluded based on weight, EMI sensitivity, and security considerations.

Passive T-coupled fiber optic bus. This configuration was excluded based on inability to support the required number of nodes in the data system.

Passive star-coupled fiber optic bus. This approach was eliminated due to inability to satisfy the uniform berthing port-modular growth requirement.

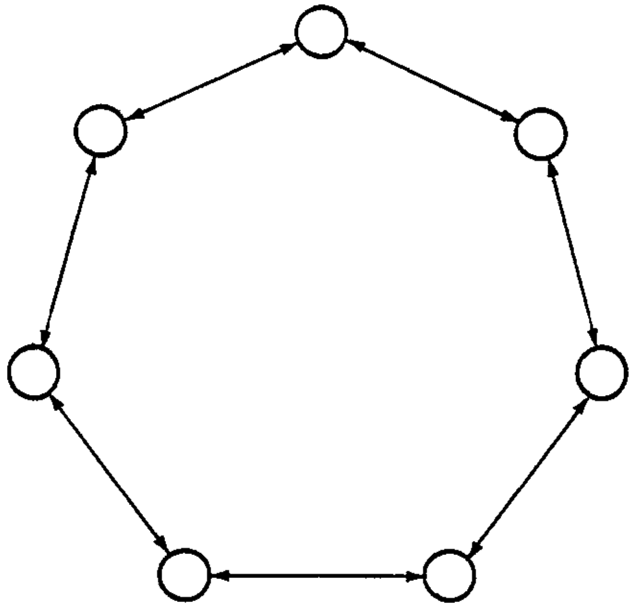
Passive DISCO fiber optic bus. This approach was eliminated due to inability to satisfy the uniform berthing port-modular growth requirement.

Hybrid DISCO fiber optic bus. This configuration was included since it appeared to meet uniform berthing port-modular growth requirements. As discussed in section 3.3.3.2, subsequent work has shown this preliminary judgment to be incorrect, and this approach is currently not considered viable.

Ring network. The simple nonredundant ring network, shown in figure 3.3-11(a), was excluded due to poor fault tolerance and modularity.

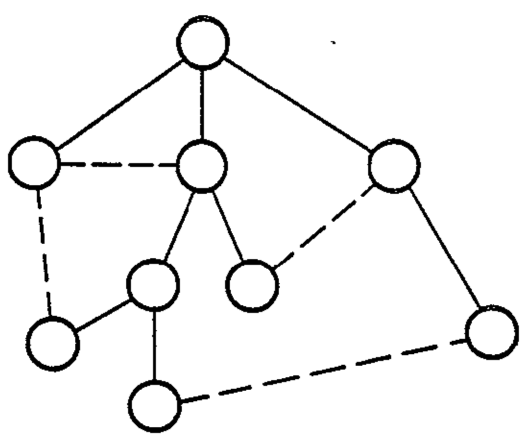
Chordal ring network. This network was included since it was the simplest form of point-to-point network which appeared to have viability in the advanced platform application.

Threaded tree network. The threaded tree network shown in figure 3.3-11(b) was excluded from the comparison since at the interconnection level, it is very similar to a graph structure, except that it is more hierarchical. Differences are primarily in protocol and operation.



RING

Figure 3.3-11 (a). Simple Ring Network



THREADED TREE

Figure 3.3-11 (b). Threaded Tree Network

Graph network. The graph network was included since it is highly fault tolerant and capable of supporting uniform berthing port-modular growth requirements.

The comparison factors used in the comparison are shown in figure 3.3-10. The combined ranking score for each approach given in the last column of the figure represents an unweighted average of the individual scores for that approach. A true ranking would necessitate using a weighted average since some of the factors are of greater significance than others. However, development of weighting factors was beyond the scope of the current study.

3.3.4 Cost Benefit of Options

Quantitative comparisons were to be provided wherever possible in the data bus study. At the midterm briefing, quantitative comparisons for the first three columns of figure 3.3-10 were identified as to be determined. Quantitative comparisons for the other factors were identified as beyond the scope of the study, principally because of their subjective nature. Figure 3.3-12 shows quantitative comparisons established since the midterm briefing, together with revised qualitative comparisons. As before, the combined rating column gives an unweighted average of the qualitative ratings. The hybrid DISCO

	ESTIMATED SYSTEM COST (TRANSMITTERS, RECEIVERS, OPTICAL PATHS ONLY)	ESTIMATED SYSTEM WEIGHT (LBS)	IN-ORBIT SYSTEM COST ($ x 10⁶)	ESTIMATED RADIATION LIFE, YEARS	RELIABILITY/FAULT TOLERANCE (RELATIVE RANKING)	COMPLEXITY (RELATIVE RANKING)	BANDWIDTH CAPABILITY (RELATIVE)	ACCESSIBILITY (RELATIVE)	EXPANDABILITY (RELATIVE)	MATURITY (RELATIVE)	RECONFIGURABILITY (RELATIVE)	COMBINED RANKING (RELATIVE SCORES ONLY)
CHORDAL RING*	$2.16M	698	2.84	1200	4	6	8	6	6	6	7	5.9
GRAPH*	$8.02M	2604	10.67	1200	7	4	9	9	8	6	9	7.4
HYBRID DISCO WDM, BASEBAND WITH REDUNDANT BUS	$2.30M	997	3.25	125	5	3	8	7	7	4	8	6.0
HYBRID DISCO FDM AND BASEBAND WITH REDUNDANT BUS	$2.96M	1926	4.91	125	4	2	5	7	8	6	9	5.9

*WITH SEPARATE PASSIVE NETWORK FOR VIDEO

RELATIVE RANKING 10 = BEST
0 = WORST

Figure 3.3-12. Bus Concepts Comparison configurations are based on use of gateway nodes between station modules. System cost and weight figures are based on interconnecting the equipment items identified in figure 3.3-2 and determining quantities of optical transmitters, receivers, connectors, and fiber and other optical components such as couplers, multiplexers and demultiplexers. Fiber lengths were estimated. Locations of equipment within modules were assumed based on limited information from previous Space Operations Center work. The equipment configuration and locations were standardized for all interconnection approaches to provide a constant baseline for comparison. It must be emphasized that the locations and node quantities used in the comparison are not necessarily representative of any particular manned platform configuration and were established only to provide a baseline for comparison of the data network approaches.

Quantities of components (i.e., transmitters, receivers, etc.) were identified for each of the configurations to be compared. From these quantities, estimated system weight and cost were determined. Where possible, procurement costs and weights were based on currently available components. For items where this was not possible, engineering estimates are given. In the case of the optical transmitters and receivers, the estimates were developed by the RCA cost estimating model used widely in the industry. The costs produced by this model appear high, but are based on factors for complexity, weight, similarity to existing designs, and other factors, which taken individually, seem to be reasonable. Table 3.3-1 identifies quantities and unit cost and weight values used in arriving at the quantitative comparison values given in figure 3.3-12. Relative ratios between concepts are perhaps more important than the absolute magnitudes given in the comparison.

The first two columns of figure 3.3-12 show system cost and weight for the component quantities identified in table 3.3-1 for each concept evaluated. The third column, in-orbit cost, is the result of summing system component cost, the product of system weight, and $718 per pound launch cost, and a value for cost of electrical power. The power cost is based on a launch weight of 100 pounds per kilowatt and the $718 per pound launch weight cost together with the estimated power requirements of each system. Cost, weight, and power values used to obtain the values given in figure 3.3-12 include only the node electronics necessary for the fiber optic communications links, not processors, microprocessors, or other equipment associated with the various nodes. The graph network structure has the highest in-orbit cost, but it also has the best capability. The chordal ring network has the lowest in-orbit cost, which is appropriate since it also has the lowest performance in terms of data rate. For the configurations compared, it is estimated that the useful bandwidth of the chordal ring configuration would be on the

Table 3.3-1. Network Comparison Cost/Weight/Power Data

A. GRAPH NETWORK

Item	Quantity	Unit Weight	Unit Cost	System Weight (lb)	System Cost (1000 $)
1. Optical Cable					
2 fiber	2200m	30 kg/km	$ 2.00/m	145	4.4
12 fiber	3060m	155 kg/km	$ 12.00/m	1,043	36.7
2. Optical Connectors					
Pins	2650	400/lb	$ 30.00	7	79.5
Shells	475	4/lb	$ 100.00	119	47.5
3. F/O Electronics					
Data T/R	2050	0.6 lb	3800.00	1230	7,790.
Video	60	1 lb	$ 2500.00	60	150.
			Total	2604	8,018.

Electrical Power Estimate

5 w/Data T/R =	10,250w	
10 w/Video =	600w	10,850 w Total

B. CHORDAL RING

Item	Quantity	Unit Weight	Unit Cost	System Weight (lb)	System Cost (1000 $)
1. Optical Cable	2640m	30 kg/km	$ 2.00/m	175	5.28
2. Connectors					
Pins	1060	400/lb	$ 30.00	3	31.8
Shells	320	4/lb	$ 100.00	80	32.
3. F/O Electronics					
Data T/R	380	0.6 lb	$ 5100.00	380	1,938.
Video	60	1 lb	$ 2500.00	60	150.
			Total	698	2,157.

Electrical Power Estimate

5 w/Data T/R =	1900w	
10 w/Video =	600w	2500 w Total

Table 3.3-1. Network Comparison Cost/Weight/Power Data (Continued)

C. HYBRID DISCO/WDM (with Redundant Bus)

Item	Quantity	Unit Weight	Unit Cost	System Weight (lb)	System Cost (1000 $)
1. Optical Cable					
2 Fiber	6200M	30 kg/km	$ 2.00/m	410	12.4
2. Optical Connectors					
Pins	2200	400/lb	$ 30.00	6	66
Shells	500	4/lb	$ 100.00	125	5
3. F/O Electronics					
Data T/R	260	1 lb	$6500.00	260	1,690
Video	60	1 lb	$2500.00	60	150
4. Passive Optical WDM					
Mux	136	1/3 lb	$1000.00	45	136
Demux	136	1/3 lb	$1000.00	45	136
5. Optical Couplers	136	1/3 lb	$ 800.00	46	108.8
			Total	997	2,304.2

10 w/Data T/R 260 x 10 = 2600 w
10 w/Video 60 X 10 = 600 w 3200 w Total

D. HYBRID DISCO/FDM (With Redundant Bus)

Item	Quantity	Unit Weight	Unit Cost	System Weight (lb)	System Cost (1000 $)
1. Optical Cable					
1 Fiber	6200m	30 kg/km	$ 2.00/m	410	12.4
2. Optical Connectors					
Pins	2200	400/lb	$ 30.00	6	66
Shells	500	4/lb	$ 100.00	125	5
3. F/O Electronics					
Data T/R	260	1 lb	$6500.00	260	1,690
Video	60	1 lb	$2500.00	60	150
FDM Mux/ Demux	260	3 lb	$3000.00	780	780
Repeaters	120	2 lb	$12,000.00	240	144
4. Optical Couplers	136	1/3 lb	$ 800.00	45	108.8
			Total	1926	2,956.2

Electrical Power Estimate

10w/Data T/R 260 x 10 = 2600
10w/Video 60 x 10 = 600
15w/FDM Mux/DMux 260 x 15 = 3900
8w/Repeater 120 x 8 = 960 8060 w Total

order of 200 MBPS. This limit is determined primarily by the node interface and processor electronics. The individual links of the graph network would also have essentially the same data transmission rate as the chordal ring, but the total network would have a potential data rate about 8 to 10 times that of the chordal ring. Thus, on the basis of data rate per dollar of cost, the graph network is the most cost effective. From a data management architecture standpoint, there are a number of other benefits to the graph structure as indicated by comparing the technical evaluation criteria qualitative ratings for each concept shown in figure 3.3-12.

The two hybrid DISCO configurations are useful primarily within any station module. With the necessity to use gateway nodes rather than broadband repeaters to communicate across the berthing port interfaces, their capabilities are significantly reduced compared to the values assumed in the contract mid-term presentation (fig. 3.3-10). As a result, they should not receive serious consideration for total station application. They could be of value within a single station module.

Quantitative radiation performance values have been derived for each configuration since the midterm presentation. As expected, the values are the same for the chordal ring and the graph networks since they are both basically point-to-point networks. Similarly, the two hybrid DISCO networks are the same insofar as their optical interconnection paths and other factors that affect their radiation performance and consequently have the same radiation life. Table 3.3-2 shows values assumed and the method used for evaluation of radiation life. Based on this data, the radiation life of the point-to-point links would be in excess of 1200 years and the life of the DISCO configurations would be on the order of 125 years. This assumes use of graded-index all-glass fiber, having a Ge-doped silica core and borosilicate glass cladding, and room temperature operation of the links at 820 nanometer optical wavelength. Fiber radiation performance data used in calculating these figures was based on a dose rate of 300 rads(si)/sec. The induced attenuation figures for high dose rates show the effects of fiber annealing occurring simultaneously with relatively long duration exposure. The fiber radiation performance data was obtained from a paper presented by E. J. Friebele, et al. at the Optical Fiber Communications meeting held in Washington, D.C. in March of 1979.

3.3.5 Technologies Needing Advancement

Fiber optic technology is still relatively immature in comparison to more conventional electronics technology. Consequently virtually every component of the technology will benefit from advancement in the next few years. Most of these advancements will occur in the natural course of development for commercial application of the technology.

Table 3.3-2. Radiation Life Determination

A. Configuration Factors:

Item	Point-to-Point Networks	Passive DISCO Bus
Path Length (Meters)	30	35
Optical Link Margin	30 dB (LED Source)	40 dB (ILD Source)
Source Degradation Allowance	3 dB	3 dB
Optical path Loss	10 dB max	28 dB max
Radiation Damage Allowance	17 dB	9 dB

B. Fiber Damage Characteristics

Total Dose (rads (si))	Induced Attenuation (dB/km)
700	20
1,500	50
2,600	70
6,000	100
26,000	200
63,000	300
600,000	500

C. Determination of Radiation Lifetime

1. Point to Point

$$\frac{17 \text{ dB}}{\frac{30}{100} \text{ km}} = 566.6 \text{ dB/km maximum fiber loss at radiation damage limit}$$

$$\frac{600{,}000 \text{ Rads}}{500 \text{ Rads/year}} = 1200 \text{ years}$$

2. Passive DISCO

$$\frac{9 \text{ dB}}{\frac{30}{100} \text{ km}} = 300 \text{ dB/km maximum fiber loss at radiation damage limit}$$

$$\frac{63{,}000 \text{ Rads}}{500 \text{ Rads/year}} = 125 \text{ years}$$

However, several specific areas that can benefit from NASA support have been identified. They are the development of space qualified fiber pigtailed hermetic optical sources and detectors, and the development of integrated circuit optical transmitters and receivers. These areas are discussed in the following paragraphs. Other fiber optic technology development areas of importance to space platform application of fiber optics are identified and discussed briefly in section 3.3.5.3 following discussion of the areas requiring NASA funding.

3.3.5.1 Pigtailed Optical Source and Detector Hermeticity

Each optical transmitter in a fiber optic system requires an electro-optic device to convert the electrical signal current being transmitted to a corresponding optical signal. Similarly, each receiver in the system requires an electro-optic device to convert the optical signal input into an electrical signal for use in the system. Efficient utilization of these electro-optic devices depends on achieving efficient coupling of the optical signal from the optical source to the optical fiber, and from the fiber to the detector. Various approaches have been used to accomplish this fiber-to-device coupling. However, none have been as effective as the pigtail approach. In this approach, a short length of fiber is physically butt-coupled directly to the optically active area of the electro-optice device. Positioning of the fiber relative to the device is done while monitoring the fiber-to-device coupling and is adjusted for maximum coupling. Following this adjustment, the relative positions are locked. The free end of the pigtail fiber is then the coupling point to the external fibers forming the system interconnections.

Currently, optical sources and detectors fabricated with integral fiber pigtails to optimize optical coupling of the fiber and devices are nonhermetic. This causes the device to be frequently unreliable. Since the failure rate of optical sources is already the principal determinant in the failure rate of a fiber optic communications link, a hermetic package can improve system reliability significantly.

Programs are in progress to develop hermetic pigtailed devices at a number of companies. However, recent discussions with several of the companies indicated that outside requirements and funding would significantly aid in completion of their efforts, particularly if space qualification in support of a 1986 design start is required. The current efforts are primarily related to commercial market applications, and it is not certain that current approaches will meet all requirements for space.

3.3.5.2 High Bandwidth and Data Rate Integrated Circuit Transmitters and Receivers

The optical transmitters and receivers required to use fiber optic internode system communications must operate at data rates on the order of 200-300 MBPS for the advanced platform. The transmitter and receiver are required to generate and detect the serial optical pulse train transmitted by the interconnecting fibers and perform the electrical signal processing required to interface to the node processing electronics. Electrical inputs to the transmitter from the node generally consist of a serial digital signal in NRZ format, together with a system clock signal. The transmitter then normally converts from NRZ to biphase Manchester before transmission in order to provide a signal with no dc component for optical transmission. This balanced signal is extremely important in proper detection and processing of the signal at the receiver. Depending on the design approach followed, the transmitter may also include the parallel to serial conversion circuitry required by the system. Thus, an optical transmitter consists of signal processing electronics together with an LED or ILD electro-optic source which provides a modulated optical output signal for transmission to the associated receiver(s). For best optical signal coupling efficiency, the LED or ILD should have an integral fiber pigtail to couple its output to the system interconnection fiber.

The optical receiver consists of an optical detector which converts the low-level optical to a low-level electrical signal, together with the required signal processing electronics to interface with the node electronics. Typical detector devices are silicon PIN diodes or silicon avalanche photo diodes (APDs). Detectors using galluim arsenide and other materials are now under development. Receiver processing electronics includes wide-band analog amplifiers to increase the low-level signal from the detector sufficiently to convert back to a serial digital logic level pulse train, clock recovery circuitry, and Manchester to NRZ conversion circuitry. Receiver outputs are a serial NRZ pulse train and a data synchronized clock signal. Serial to parallel conversion circuitry may also be included. The optical detector diode used in the receiver should also be pigtailed to achieve required optical coupling efficiency.

Optical transmitters and receivers are required at each system node, including NIMs used to interconnect to the backbone graph structure. Quantity of transmitters and receivers required at a particular location is dependent upon the system configuration chosen. The absolute minimum would be one transmitter and one receiver at each location.

High data rate optical transmitters and receivers have so far been fabricated using costly discrete component assembly techniques. Development of high data rate (greater than 100 MBPS) integrated circuit optical transmitters and receivers has not taken place. This is partially due to insufficient commercial or military demand to justify their development. It is also due to significant technological problems in the development of receiver

IC's. Principal among these are the necessity to combine analog and digital circuitry to form an integrated receiver. For the advanced platform application, which is expected to use point-to-point links, the analog portion of the receiver must have an exceedingly high-gain bandwidth product (microwatt optical input power, more than 200 MHz BW) to detect and process the low level optical signals. The problem is even more severe for networks using passive data buses, since path losses would be 20 to 30 dB greater. Receiver gain must then be increased. The receiver digital output stages tend to be very noisy as a result of nanosecond rise and fall times on the logic level signals. The fast rise and fall times of the logic signals when both analog and digital circuits are in close proximity results in both radiated and conducted noise problems in the system. This results in a very challenging, state-of-the-art, design task to combine these circuits while providing satisfactory isolation and decoupling between them. To date, this has been accomplished using special compartmented packaging techniques and extensive power system decoupling together with combinations of discrete or hybrid and LSI circuit techniques.

3.3.5.3 Other Fiber Optic Technology Developments

As previously indicated, due to the comparative youth of fiber optics technology, many developments in the technology are under way at this time. It is felt that the on-going work in these areas will satisfy NASA requirements for manned space platform applications. However, progress in these areas should be monitored and evaluated against NASA requirements to ensure that their technical and schedule progress does not lag behind. The following paragraphs identify several of these areas.

Radiation Performance. Radiation performance was identified as an issue of concern for manned space application of the technology. The radiation life analysis contained in section 3.3.4 showed that fiber radiation damage was not a significant concern for the orbital parameters of the currently planned advanced platform. Other orbital parameters having more severe environments must be evaluated as to their effect on the system.

Fiber optic cables, optical sources and optical detectors are known to be sensitive to radiation damage. Damage levels in each case are a function of environmental radiation level relative to the damage sensitivity levels of the particular components used. Radiation performance is a very significant problem in military applications where very high radiation levels due to nuclear events must be considered in system design and performance evaluation. A brief evaluation of radiation performance based on current fiber optics technology and estimated radiation environment for the advanced platform has been conducted. Based upon this preliminary evaluation, radiation performance of fiber optic components does not appear to pose a signficiant problem for the advanced platform application. Data links which will meet the system requirements as presently assumed can be produced providing proper attention is made to selection of components and system design. Technology improvements now under way are expected to provide further reduction in radiation damage sensitivity. This will provide an even longer system life in the assumed radiation environment. The following paragraphs identify the assumptions and factors leading to this conclusion.

In order to evaluate the magnitude of the potential radiation damage problem, it was first necessary to identify the applicable radiation environment. The external radiation environment is determined by the orbital altitude and inclination. The internal environment seen by the majority of the data network components is then a function of the shielding effectivity of the spacecraft. Links to external cameras, or other portions of the system which may be outside the shielding provided by the spacecraft, will require careful examination at the time of design to ensure adequate protection. For purposes of this evaluation, a non-polar orbit and an orbital altitude of 325 to 400 kilometers were assumed. A non-wartime environment was also assumed. Available data indicates an external radiation environment which would produce a total dose on the order of 10^7 to 10^8 rads(si) per year on the exterior of the spacecraft. The higher value would occur at the higher orbital altitude. Since the advanced platform must be manned, internal radiation must be held to approximately 5 rads(si) per year. Extensive spacecraft shielding will be required to achieve this level. For purposes of evaluation of fiber optics component radiation performance, a two orders of magnitude margin above the 5 rads(si) per year value was assumed. The assumed 500 rads(si) per year total dose corresponds to a dose rate of less than 20 millionths of a rad(si)/sec.

Components for optical data links fall into four categories when considering radiation sensitivity: emitters, detectors, fiber, and electronic parts.

Emitters

Typical solid state optical emitters have been found to be essentially unaffected by gamma radiation levels typical of nuclear event sources. Their principal problem is one of lattice damage due to neutrons and other high-energy particles. Emitters start to show lattice displacement damage, which degrades their output at neutron fluence levels on the order of 10^{13} n/cm^2. Levels experienced in the Advanced Platform environment are expected to be many orders of magnitude below the level at which damage would occur in emitters. Consequently, emitter performance will not be limited by the assumed radiation environment.

Detectors

Previous Boeing work related to radiation performance of fiber optic components has shown that typical PIN and avalanche photo diodes are less sensitive to lattice displacement damage than emitters. This is chiefly due to their smaller active volumes. However, detectors have also been shown to be sensitive to gamma radiation. Gamma dose rates in the range of 5 to 5000 rads(si)/sec are potentially serious since they can cause induced photo currents that can disrupt data links. Selection of detectors with small active areas, operation of data links with high-link margins that allow low-gain receivers, and optimizing receiver design for radiation result in the ability to operate at the higher radiation levels (500 rads(si)/sec). The dose rates (much less than 1 rad(si)/sec) expected in the advanced platform environment are far below those which could cause a problem, either from dose rate or neutron and other particle displacement damage. Use of point-to-point links as indicated by the comparisons of section 3.3.3.5 results in high signal margins and simplifies receiver design to provide good radiation performance.

Fiber

Fiber radiation sensitivity is a function of a number of factors. Fiber fabrication techniques, dose rate, total dose, temperature of operation, and previous radiation history of the fiber can all be of importance. When subjected to high-level prompt radiation such as results from a nuclear blast, fiber typically exhibits a number of different effects. Initially, during the period of prompt gamma exposure, the fiber will fluoresce due to the high initial dose rate. During this period, any data link using fiber communication paths would be interrupted. In addition to the fluorescence, the fiber attentuation is markedly increased as well during this interval. The increase in fiber attenuation is more dependent upon total dose received than on dose rate. Fiber recovery (annealing) starts at the incidence of radiation. Its recovery rate is dependent on temperature, fiber type, and photo-bleaching effects due to the optical signal of the operating system. Currently, the best fibers from a radiation standpoint are plastic clad silica (PCS) step index-types. However, PCS fiber is difficult to terminate reliably, and it typically has a relatively low bandwidth. Graded-index fibers fabricated from Ge-doped boirosilicate glass are being developed with relatively good radiation properties, low losses, and bandwidths approaching one gigahertz/kilometer. A similar, all-glass, radiation hard fiber should be selected for the advanced platform.

In order to determine an acceptable fiber damage level, the following assumptions were made:

a. Point-to-point data links as discussed in section 3.3.3.5.

b. Maximum individual link length of 100 meters.

c. Link allowance of 10 dB for radiation damage before falling below the specified maximum bit error rate (assumed to be 10^9).

d. Total dose of 5000 rads(si) accumulated in ten years as previously stated.

These assumptions would then allow radiation induced fiber damage up to 100 dB/KM before operation of the data links would be degraded below the specified bit error rate. Review of currently available fiber radiation test data shows a number of PCS fibers and several graded index, all-glass varieties which can have induced loss values in this range for 5000 rad(si) total dose. Even fibers having significantly larger induced damage readings based on most tests would probably be suitable for the advanced platform when the effects of fiber annealing and photo-bleaching are considered. Most fiber radiation tests are accomplished with dose rates many orders of magnitude higher than the assumed advanced platform environment. Consequently, fiber annealing and photo-bleaching over the much longer period would greatly reduce the total net damage to the fiber.

Electronic Parts

Electronic parts are generally considered radiation hard at radiation environmental levels suitable for manned operation of the systems in which they are used.

Several other environmental factors essentially peculiar to space applications require consideration. These are the effects of cosmic ray radiation and dielectric charging of data system components located on the exterior of the spacecraft.

Primary cosmic rays in space have very high energy levels on the order of 10^{19} electron volts per particle. At that energy level, no practical amount of shielding has any noticeable effect. These particles induce noise in analog circuits and upset the logic in digital circuits. They do not cause permanent circuit damage. The energy required to upset circuit logic is a function of the active area of the semiconductor devices used; smaller devices require less energy for upset. Current evaluations indicate that 10 micrometer and smaller device geometries are susceptible to cosmic ray upset. Consequently, high density memory circuits are particularly prone to upset. At the present time, the favored approach is to use dual redundant memories with error detection capability to enable detection and correction of cosmic ray induced upset. The probability of simultaneous cosmic ray damage to the same location in two different memories is exceedingly low.

Spacecraft requirements do not allow exterior use of any materials capable of dielectric charge storage. Materials used must have sufficient electrical conductivity to prevent charge buildup. Since fiber optic cables are normally fabricated using non-conductive materials, links to external cameras, etc., must use specially processed optical fiber. Use of either fibers with a metallized exterior or cables with metallized exterior jacketing should produce sufficient conductivity to satisfy the dielectric charging requirement. Evaluation to determine the best method should be accomplished as soon as definite requirements are established.

Active Device Reliability. One of the major contributors to lower confidence levels for fiber optic components is the absence of statistically significant failure rate data for its components. Among the reasons for this lack are the rapid evolution and relatively small production volumes of components to date. Because of this, few cmponents of any given type have been submitted for testing to produce failure rate data. Frequently, before testing of a particular device type has been completed, technology advances have made the part obsolete. In addition, fabrication volumes have been so low for many types of parts that laboratory and fabrication processes have been used. This results in potential for process and other variations which can have major impact on failure rate and performance among different samples of the same part type.

The technology has now advanced to the point where controlled process parts can be obtained and production volumes are increasing. This will enable submitting more units for test to provide a reasonable data base on most types of parts within a few years. In addition, the improvements in process and design should improve basic device reliability. Current reliability and performance data is based on small lot testing resulting from rapid evolution and other previously mentioned factors.

Currently, the best data is for light emitting diode (LED) optical sources. Based on data to date, failure rates for these devices range from one in 100,000 hours to one per 10,000,000 hours. Failure rates for solid state injection laser diode (ILD) sources are an order of magnitude worse, ranging from one per 10,000 hours to one per 1,000,000 hours.

The LED failure rate is based on a significantly larger number of test samples than the ILD rate; consequently, it has a higher confidence level in addition to the lower apparent failure rate. Optical detector failure rates are generally considered to be in the range of from one failure per million hours to one per hundred million hours. Electro-optic device failure rate data is generally based on testing of devices in windowed hermetic packages. Use of windowed packages in an actual application results in excessive device-to-fiber coupling losses. Use of devices with integral fiber pigtails to optimize device-to-fiber coupling currently results in a non-hermetic device. This results in degraded device reliability.

Connectors. Connectors have been one of the weakest areas in fiber optics technology and have been one of the slowest to develop. This has been due primarily to lack of standardization on fiber types and sizes and the proliferation of different types of both fibers and connectors. Fiber standards are now in place, and a number of different connector approaches have been developed that provide acceptable performance in most applications. Losses in the 1 to 2 dB range are typical when using the 50/125 micron-graded index all glass fiber typically used for data communications. Space qualified connectors are not currently available, chiefly because no program has defined detailed qualification requirements and tested connectors to meet them. Currently available connectors are predominantly based on epoxy fiber retention and grind and polish finishing techniques. Connectors designed for mechanical retention and cleve-and-break fiber preparation are also currently available. Both single fiber and multiple fiber connectors are now readily available.

Optical fiber. Optical fiber technology is the most advanced area related to fiber optics system application. Currently available fiber is more than adequate to meet advanced space platform data system requirements for bandwidth, loss, and reliability. Long-term life under radiation environment can still stand some improvement. However, technology advancements now underway to increase fiber performance in the 1300 to 1500 nanometer wavelength region, are expected to significantly improve radiation damage susceptibility as well as provide even lower losses and higher bandwidths than current fibers designed for use primarily in the 800 to 900 nanometer region. Present work in fiber development is in long distance, high bandwidth applications, and consequently is concentrating on the longer wavelengths. Extremely long distance, high bandwidth applications require use of single-mode fiber rather than multi-mode graded index most likely to be used in the advanced platform application. Multi-mode fibers are capable of bandwidths on the order of one gigahertz-kilometer. Since advanced platform cable lengths would be a small fraction of a kilometer in length, neither bandwidth nor cable loss would be significant to system operation under normal conditions. Consequently, use of single mode fiber with its higher device-to-fiber coupling losses and difficult and costly connectorization problems is not justified.

3.3.6 Technology Development Cost and Schedule Considerations

Several technology advancement programs that are expected to require NASA support were identified in section 3.3.5. The following paragraphs provide preliminary definition of these programs together with preliminary schedule and cost estimates.

3.3.6.1 Pigtailed Device Hermeticity

This paragraph identifies a preliminary task breakdown and schedule for the program required to complete the development of hermetic, pigtailed, optical sources and detectors. The first program task is the definition of specific performance, environmental, and test requirements for the devices. This will require more detailed definition of the data system network in order to determine permissible optical coupling loss, desired maximum data rate, and other system data such as maximum optical cable length, etc., required to meet the growth requirements of the advanced platform.

Following determination of applicable requirements, the next task is a review of ongoing work in the area to determine its current status compared to the established requirements. As a result of this review, one or more development contractors would be selected to conduct the development program.

After selection of the development contractor, a series of technical tasks required to develop suitable fabrication processes for production of hermetic pigtailed devices would follow. Normal design reviews and other developmental reviews would be included during this time period. Fabrication process development would include such items as development of die-bonding and other techniques compatible with the high temperatures typically required in sealing of hermetic packages. In addition, development of fiber-to-device alignment techniques to produce optimum optical coupling, and new approaches to fiber jacketing and strain relief would be required. The process development work should create alternative solutions to each identified problem in order to be able to select the one most suitable.

At the conclusion of process development, a number of prototype devices would be fabricated for performance and environmental testing. Test requirements and procedures would be designed to show compliance with established requirements. Successful completion of the tests would result in confirmation of fabrication processes which could then be used in production of space-qualified, pigtailed, hermetic optical sources and detectors for use in the advanced platform data networks.

The device hermeticity program is estimated to require about three years to complete. The first year is primarily a NASA internal effort to develop requirements, evaluate industry status, and select the development contractor(s). This is a worst case schedule and can be shortened significantly if work now under way for development of commercial hermetic pigtailed devices is found to be applicable, as will probably be the case. Based on discussions with several vendors, estimated costs for the development contractor work are in the range from $250K to $450K, depending on final requirements established during the first task in the program, and on the degree of commonality between those requirements and the ongoing commercial programs. Additional NASA work relating to selection of the development contractor would cost about $50K making total program cost range from $300 to $500K.

3.3.6.2 Integrated Circuit Transmitter-Receiver Development

A preliminary schedule for the development of integrated circuit fiber optic transmitters and receivers contains the same general tasks as the program for hermetic sources and detectors. The program starts with a definition of requirements with emphasis on space peculiar items. But first, factors such as configuration of the data network and a reasonable growth factor for bandwidth and data rate should be determined. Also, detailed environmental and other factors which can impact development direction should be considered to ensure that it will not be necessary to retrofit with enhanced units at a later date. The principal problems are in the design and development of the receiver portion. As mentioned briefly in section 3.3.5.2, it is a difficult state-of-the-art task to design and fabricate integrated circuits combining high gain, bandwidth analog circuitry and digital logic circuitry in the same package. Integrated circuit transmitters and hybrid circuit receivers have been produced, though not to the high data rate requirements expected in the advanced platform application. The most difficult problem in the transmitter circuit is providing adequate output stage power capacity with high reliability. In light of the receiver technical problems, it may be necessary to design a chip-set family rather than a single large integrated circuit in order to best serve the advanced platform program.

Cost and schedule estimates for the integrated circuit transmitter and receiver program were obtained by use of the RCA price hardware estimating model. Input parameters selected for the RCA program include size, weight, design and engineering complexity, similarity to previous work, required reliability, application type, etc. Best engineering estimates were made for all the required factors after consulting the Boeing cost estimating organization. Computer runs were then made to determine development cost and schedule for the task. The development cost estimate ranged from $6,665,000 to $8,026,000 with a median value of $7,272,000. The schedule was begun in January 1984 because the task was priced in constant 1984 dollars. The development schedule shows the first prototype being available in May 1986, and completion of the development program, including 10 prototype units, in February, 1988. Preparation for a production run of 2000 units would start in January, 1988 and run through April 1991. The results obtained from the cost model are judged to be both expensive and time consuming. However, they are the best available, since information necessary to refine input parameters does not exist at this time.

If the benefits, discussed in section 4 of this report are to be obtained, then an immediate start on this program is indicated.

3.4 LONG-LIFE THERMAL MANAGEMENT

A long-life thermal management system is necessary to economically meet the requirements set for an advanced manned platform. Thermal management is required for life support systems, power conditioning, communication and data processing systems, and experiment support. Consequently, any thermal management system failure may seriously affect space platform viability or impose unacceptable operational constraints. Technology advancement issues were addressed during this study to assess the long-term aspects of thermal management and recommend advancement tasks.

3.4.1 Issue

Potential failure mechanisms for the thermal management system include mechanical and electrical equipment failure, meteroid damage, fluid seal failure, fluid degradation, fatigue failure of flexed fluid lines, and degradation of thermal control coatings. Mechanical and electrical equipment (pumps, valves, sensors, controllers, etc.) failure generally requires use of redundant components. The possibility of meteroid damage (puncture of fluid line) requires redundant fluid loops or meteroid barriers. The possibility of fluid seal failure, fluid degradation and fatigue failure for flexed lines requires provision for on-orbit maintenance capabilities. Thermal coating degradation may result in failure of the thermal control system to maintain required temperature levels, and thus limit the thermal management system life.

The design of a fail-safe (high reliability) system with the use of current technology will result in large mass and cost penalties. Further technology advancement is required to reduce these penalties.

3.4.2 Requirements

The requirements for the thermal management system are summarized in figure 3.4-1. The 250 kW heat rejection requirement is a maximum for growth considerations. A value of 100 kW, representative of near term requirements (e.g. SOC), was used in the present study.

DOCUMENTED REQUIREMENTS	VALUE/DESCRIPTION
HEAT LOAD	UP TO 250 KW (1)
TRANSPORT DISTANCE	UP TO 150 FT (1)
ORBITAL ENVIRONMENT	LOW EARTH ORBIT (2)
GROWTH	MODULAR-EVOLUTIONARY (2)
FLEXIBILITY	MULTIPLE HEAT LOADS VARYING MAGNITUDES AND LOCATIONS (2)
LIFE	MINIMUM 20 TO 25 YEARS (2)
MAINTAINABILITY	ON ORBIT MAINTENANCE, REHABILITATION AND REPAIR CAPABILITIES AS REQUIRED TO MEET LIFE REQUIREMENTS (2)

(1) RFP NO. 9-BC73-19-2-378, DEVELOPMENT OF PROTOTYPE THERMAL BUS AND A HIGH EFFICIENCY AUTOMATED THERMAL CONTROL SYSTEM FOR LARGE SPACE PLATFORM AND NASA JSC, JUNE 1982

(2) HALLAWAY, PAUL F., SPACE STATION TECHNOLOGY, PAPER IAF-82-15, 33RD IAF CONGRESS, PARIS, FRANCE, SEPTEMBER 26 – OCTOBER 2, 1982

Figure 3.4-1. Thermal Requirements

The most severe requirement appears to be that of a long-life thermal management system. The projected life of a minimum of 10 and up to 20 to 25 years exceeds that of current thermal management technology. This is especially true for thermal control coatings and fluid pumps. This lifetime requirement will require on-orbit maintenance, rehabilitation, and repair capabilities to support the thermal management system.

The heat load and transport distances exceed the capabilities of current hardware. The growth and flexibility requirements cannot be met without further development of the state-of-art thermal management systems.

3.4.3 Characterization of Concepts

3.4.3.1 Thermal Management System Definition

The overall function of a space station thermal management system is to control temperatures and reject waste heat to space. Figure 3.4-2 shows a simple schematic diagram of a space station thermal management system. The major components (or subsystems) of this system are:

Module Thermal Control. Modules which are docked or berthed to the space station require a thermal management system which is autonomous, or one that is coupled to the space station thermal control system. Manned (pressurized) modules generally require an

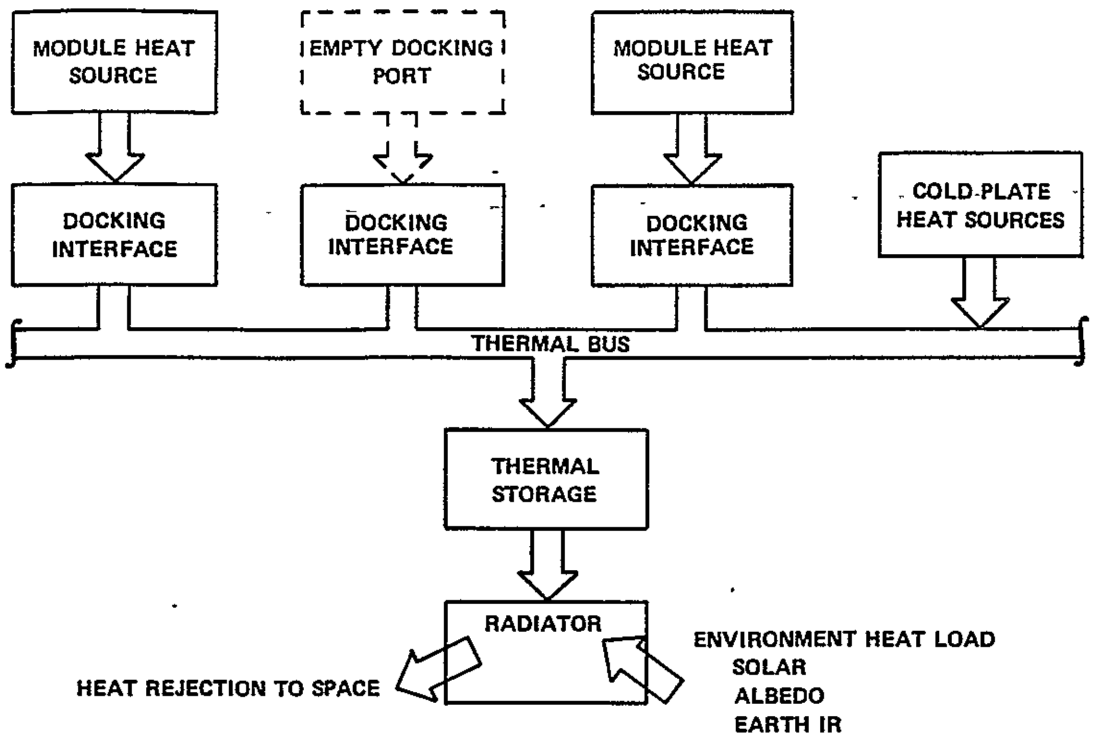


Figure 3.4-2. Thermal Management System

internal water coolant loop for crew safety. The heat transferred to the water must in turn be transferred to another fluid (e.g. Freon) which is suitable for use in a space radiator.

Docking Interface. Docking or berthing of modules or equipment which do not have autonomous thermal control systems will require an appropriate thermal interface. This interface provides thermal coupling to the space station thermal management system. Concepts for this interface include direct fluid coupling, fluid-to-fluid heat exchangers, and contact heat exchangers.

Cold Plates. Thermal control of equipment located on the space station (as opposed to docked or berthed modules) can be accomplished by using cold plates coupled to the thermal bus (or heat transport loop). For permanently positioned equipment (e.g. batteries) the cold plates may be integral with the heat transport loop. Equipment which may be located at various positions on the station require cold plates which can be coupled readily to the transport loop or else permanent cold plates at the various required locations.

Thermal Bus. A thermal bus or heat transport loop is required to transport heat from the heat sources to the space radiator(s). This thermal transport may be accomplished by using a pumped liquid loop, a pumped two-phase thermal bus, or a heat pipe thermal bus.

The pumped liquid loop represents current technology whereas the thermal bus concepts require further technology development.

Thermal Storage. Thermal storage provides thermal load averaging and takes advantage of the radiator heat rejection capability during the shadowed portion of the space station orbit.

Space Radiator. A space radiator is required for space station heat rejection. The heat rejection capability is determined by radiator location, orientation, surface coating and temperature; space station orbit; and environmental heat sources (solar, albedo, earth IR and other space station surfaces). The long-life thermal management system requirements for a space station and the large radiator area required to reject the heat load place stringent requirements on the space radiator. Radiator design concepts include pumped fluid radiator, integral manifold heat pipe and pumped fluid hybrid design, space constructable, and space deployable designs. These concepts provide lightweight radiators which minimize the effect of meteriod damage. A separate long-life problem is the degradation of thermal coatings.

Control System. The space station thermal management system requires automatic controls for various subsystems and components. These controls may require integration into an overall thermal management control system which in turn may require integration with other systems controls in an overall data management system.

3.4.3.2 Trade Study Approach

Identification of high leverage technology advancement areas for long-life thermal management requires trades between various concepts for each of the major components of the thermal management system. The trade results for each major component are generally interrelated and system level trades also have to be made. As an example, the trade between a pumped, liquid-heat, transport loop and a vapor transport thermal bus must include the effects of different radiator area required for the two systems. The system level trades need to include effects on other space station systems (e.g., attitude control, electrical power, life support, etc.).

Resources made necessary the focusing of this study on the most important problem area, since it was not possible to conduct a large number of detailed trade studies in diverse areas. The problem area selected was that of thermal coating degradation. Degradation of thermal coatings appears to be the primary factor limiting the useful life of a thermal management system. Techniques for alleviating the affects of coating degradation on the thermal system were studied.

Thermal coatings (e.g., white paints) are generally characterized by low solar absorptance and high infrared emittance. Space exposure results in increased solar absorptance. This degradation is caused by radiation (ultraviolet and charged particle) damage and surface contamination. Radiation damage can be assessed in laboratory tests and can be minimized by development of improved coatings. Contamination, however, depends primarily on the contaminant sources and proximity of the thermal coating. Consequently, while the radiation environment (and resulting degradation) is predictable, the contamination environment is much less certain. This is especially true for a space station with manned EVA's, shuttle arrivals and departures, etc. An estimate of coating degradation can be made from previous spacecraft experience. Figure 3.4-3 shows typical thermal coating degradation as a function of space exposure time. The estimated upper bound curve in this figure represents the degradation rate for Skylab.

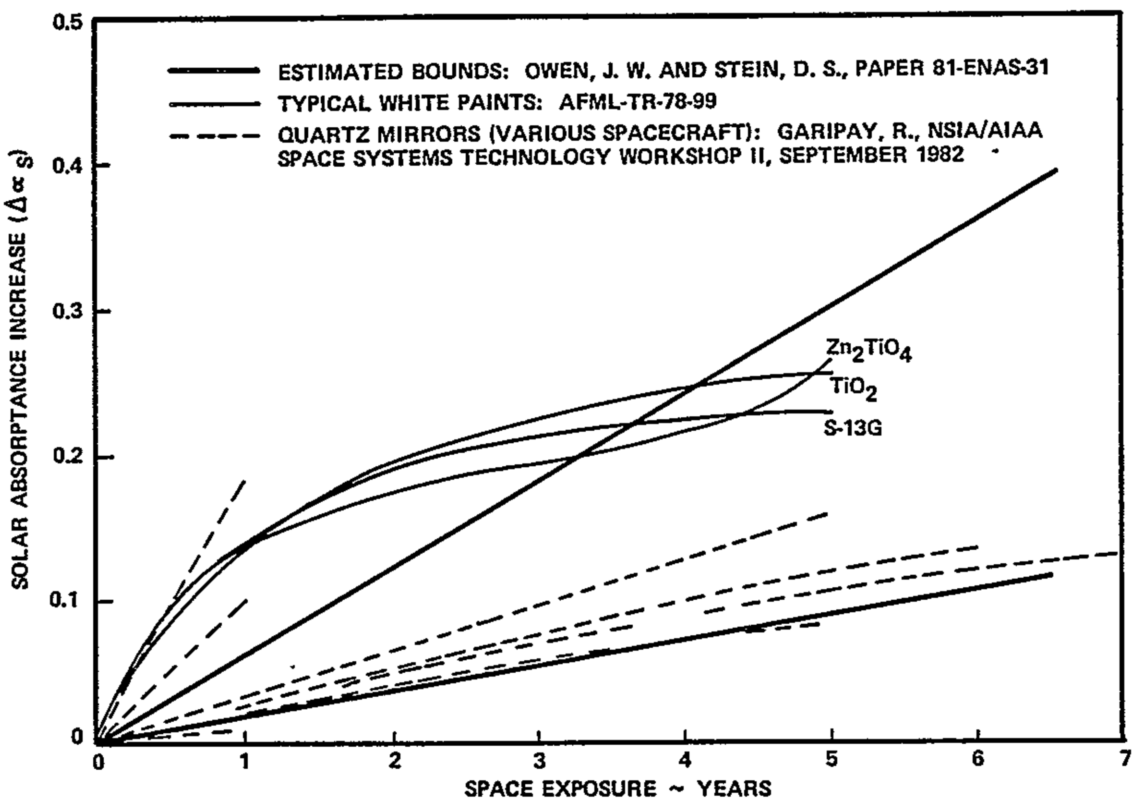


Figure 3.4-3. Thermal Coating Degradation

The degree of thermal coating degradation expected for a long-life thermal management system can result in large size and mass penalties and may result in an inoperable system at the required temperature levels. The approach of the present trade study was to compare various concepts which minimize (or reverse) the effects of coating degradation.

3.4.3.3 Trade Study Options and Analysis

The effects of thermal coating degradation or radiator performance depends on the orientation of the radiating surface to the sun and earth, space station altitude and magnitude of solar flux and earth albedo. For the present study it is assumed that the radiators are located such that their view of other space station components is negligible. This allows a generalized analysis in which the details of space station size and configuration do not need to be considered.

In order to determine radiator performance for a space station in low-Earth orbit the environmental heat fluxes (solar, albedo and earth IR) were calculated using the Boeing Orbital Payload Environmental Radiation Analyzer (OPERA) program for the following conditions:

a. 200 m.m. orbit.
b. Solar to orbit plane angles of 0,15,30,45 and 60°.
c. Orbit points every 15° around the orbit plus points just before and after the shadow crossings.
d. Earth-oriented space station.
e. Four radiator surface orientations:
    1. North (i.e., facing away from sun).
    2. South.
    3. East (i.e., facing along velocity vector).
    4. West.
f. Worst hot case conditions
    1. Solar flux = 440 BTU/ft^2-hr.
    2. Earth emission = 83 BTU/ft^2-hr.
    3. Albedo = 0.4.

Figure 3.4-4 shows a representation of the radiator surfaces and orbit parameters.

The calculated heat fluxes were used to determine radiator performance for the following configurations:

a. Fixed two-sided radiators.
b. Selectable one-sided radiators.
c. Steerable two-sided radiator.

A pictorial representation of the radiator options is shown in figure 3.4-5. The fixed two-sided radiators (N-S and E-W orientations) are considered representative of typical state-of-art radiator systems. In special cases more effective one-sided radiators could be used. For example if a space station had a fixed orientation with respect to the Earth, then a single sided radiator facing away from the sun (north-facing in present case) would minimize the degradation efforts. In general such a fixed orientation would, however,

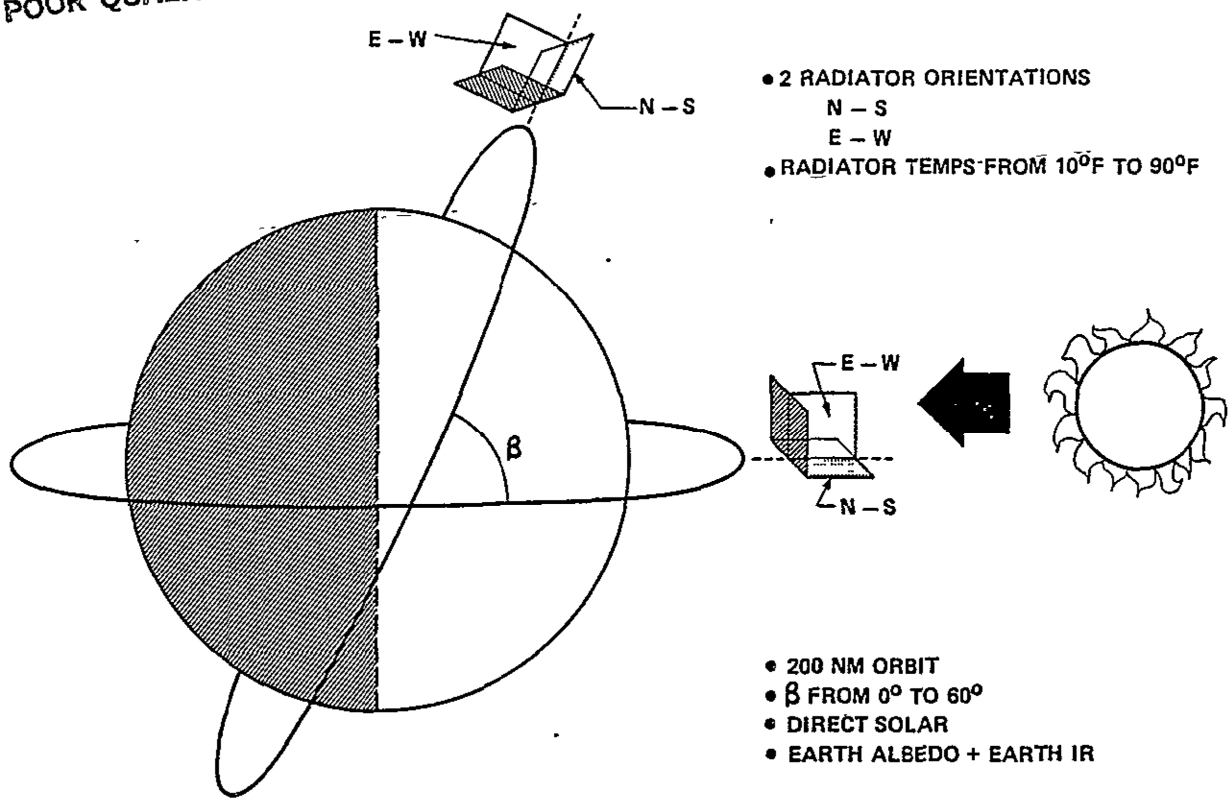


Figure 3.4-4. Radiator Analysis

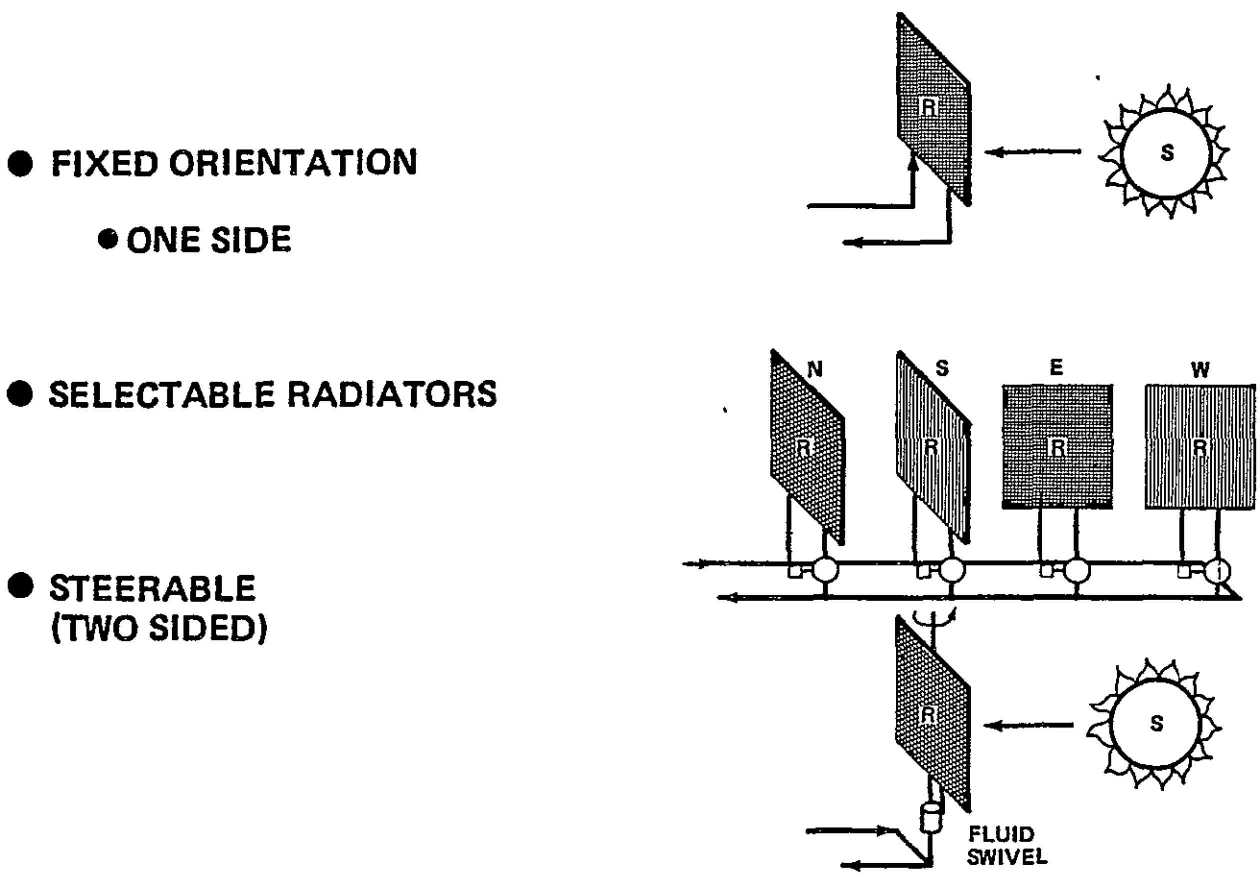


Figure 3.4-5. Radiator Options

result in unacceptable operational constraints and cost penalties for attitude control. The selectable single sided radiators (N, S, E and W orientations) allow the heat load to be distributed between the radiators in a manner which minimizes the degradation effects. The steerable, two-sided radiator minimizes degradation effect by keeping the surfaces oriented off sun.

Another concept to minimize the effects of coating degradation is to use thermal storage in conjunction with the radiator. Thermal storage allows a larger fraction of the heat load to be rejected during the shadowed portion of the orbit where coating degradation is irrelevant.

A FORTRAN computer program was written to perform parametric analyses for the selected radiator configurations using heat flux data from the OPERA program. The parameters used in the analyses were as follows:

a. Radiator emittance of 0.9.
b. Radiator weight of 1.2 lb/ft^2.
c. Thermal storage weight of 68 lbs/kWhr (50 BTU/lb).
d. Radiator (and storage) temperatures from 10 to 90°F.
e. Solar absorptance/IR emittance ratios from 0.1 to 1.0.

The program calculates the minimum and average heat rejection rates per unit area for each orbit at each temperature and each solar-absorptance-to-infrared-emission ratio. The amount of thermal storage (per unit radiator area) required to average the heat rejection over the orbit is also determined. This amount of storage (complete storage) results in full utilization of the radiator capability since the heat rejection temperature remains constant over the orbit. The program then calculates the radiator area (per kW of heat rejection) required with thermal storage values from zero to complete storage. The system (radiator plus thermal storage) weight is calculated and the optimum storage value is selected. (In most cases, the optimum corresponds to complete storage.)

3.4.3.4 Results of Radiator Analyses

The results of the analyses for a 50°F radiator temperature are shown in figures 3.4-6 and 3.4-7 for the various radiator concepts. Figure 3.4-6 shows the required radiator area per unit heat load (ft^2/kW) as a function of thermal coating degradation level (S/E). Also shown is the approximate space exposure time corresponding to coating degradation level. Figure 3.4-7 shows the corresponding system weight in a similar fashion. Without thermal storage, the fixed radiator system cannot be made large enough to be operable for more than about five (5) years. The selectable and steerable radiator system can be sized to

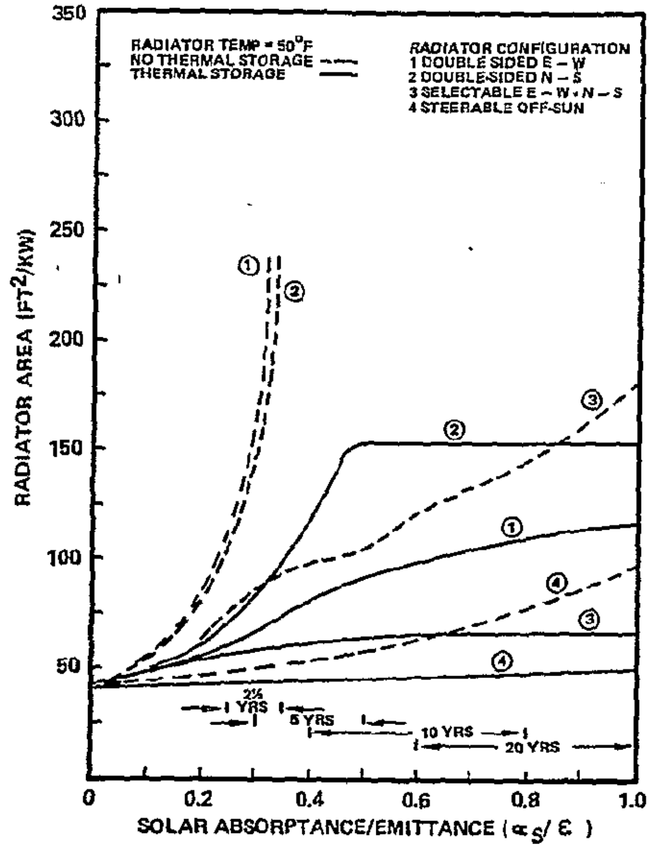


Figure 3.4-6. Effect of Coating Degredation on Radiator Sizing

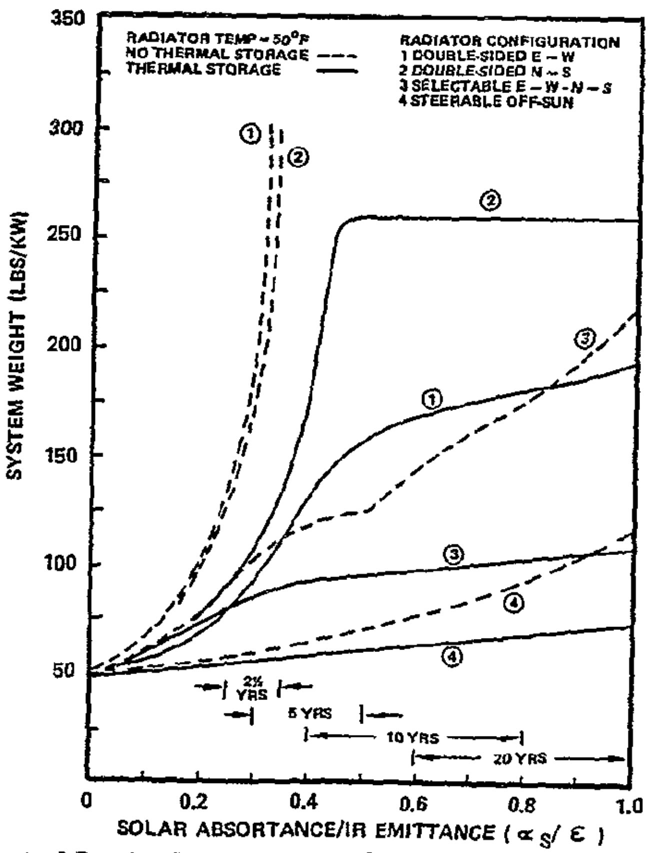


Figure 3.4-7. Effect of Coating Degredation on System (Radiator Plus Thermal Storage) Weight

last indefinitely (complete degradation) without thermal storage. However, large size and weight penalties are required for a long life system.

The use of thermal storage in conjunction with the space radiators allows all of the radiator systems to be designed for complete degradation of the thermal control coating. Even though thermal storage allows the fixed radiator system to be designed for complete coating degradation, this design results in large size and weight penalties. However, thermal storage, in conjunction with selectable or steerable radiators, offers a large savings in system size and weight.

The effect of heat rejection temperature on system weight is shown in figure 3.4-8 for systems designed for end-of-life (complete coating degradation) conditions. As indicated

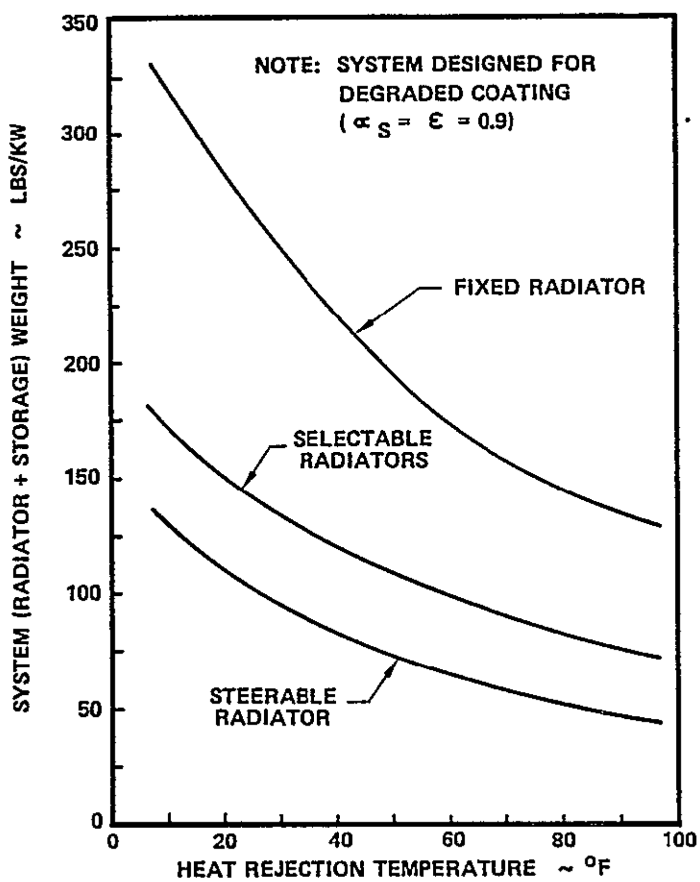


Figure 3.4-8. Effect of Heat Rejection Temperature on System Weight

by this figure, system weight (and size) are minimized by keeping the radiator temperature as high as possible. Table 3.4-1 summarized the parametric analysis results for radiator temperatures of 30, 50 and 70°F at a 100 kW heat rejection rate. Four levels of coating degradation are presented: (1) end of life (complete) degradation; (2) coating renewal at five (5) year intervals; (3) coating renewal at two and one-half (2-1/2) year

Table 3.4-1. Parametric Analysis Results

OPTION	FIXED TWO-SIDED RADIATOR			SELECTABLE ONE-SIDED RADIATORS			STEERABLE TWO-SIDED RADIATOR		
NO THERMAL STORAGE	30°F	50°F	70°F	30°F	50°F	70°F	30°F	50°F	70°F
COMPLETE DEGRADATION									
WEIGHT LBS	NA	NA	NA	36,370	21,580	14,810	20,960	11,710	7,830
AREA FT^2	NA	NA	NA	30,310	17,990	12,340	17,470	9,760	6,520
COATING RENEWAL									
5 YEAR CYCLE WEIGH									
WEIGHT LBS	NA	114,300	19,560	15,410	11,950	8,830	8,610	6,500	5,100
AREA FT^2	NA	95,300	16,300	12,850	9,960	7,360	7,170	5,420	4,250
2 1/2 YEAR CYCLE									
WEIGHT LBS	53,300	17,720	10,120	14,110	10,360	7,450	7,840	6,050	4,820
AREA FT^2	44,410	14,770	8,430	11,760	8,630	6,210	6,530	5,050	4,010
NO DEGRADATION									
WEIGHT LBS	15,050	8,600	6,830	11,110	7,830	5,880	7,200	5,660	4,570
AREA FT^2	12,540	8,000	5,690	9,260	6,530	4,900	6,000	4,720	3,800
THERMAL STORAGE	30°F	50°F	70°F	30°F	50°F	70°F	30°F	50°F	70°F
COMPLETE DEGRADATION									
WEIGHT LBS	25,400	19,480	15,580	13,340	10,760	8,940	9,560	7,360	5,840
AREA FT^2	16,050	11,960	9,100	8,960	7,000	5,600	6,610	5,090	4,040
STORAGE KWHR	90.3	75.1	68.2	37.9	34.6	32.5	23.8	18.3	14.6
COATING RENEWAL									
5 YEAR CYCLE									
WEIGHT LBS	18,090	13,400	8,760	11,270	9,250	17,550	7,340	5,840	4,750
AREA FT^2	11,540	8,320	5,840	7,850	6,220	14,950	5,650	4,500	3,660
STORAGE KWHR	62.1	50.0	25.6	27.2	26.1	23.5	8.13	6.48	5.27
2 1/2 YEAR CYCLE									
WEIGHT LBS	14,070	9,220	6,530	10,800	8,680	6,870	7,030	5,620	4,600
AREA FT^2	9,540	6,670	4,980	17,570	5,930	4,640	5,520	4,410	3,610
STORAGE KWHR	38.4	17.8	8.05	11,125.1	22.9	19 1	5.95	4.77	3.89
NO DEGRADATION									
WEIGHT LBS	9,460	6,930	5,360	9,620	7,400	5,740	6,730	5,410	4,430
AREA FT^2	7,430	5,560	4,340	7,110	5,780	4,500	5,390	4,330	3,550
STORAGE KWHR	7.94	8.84	2.16	15.9	6.92	4.91	3 88	3.12	2.56

intervals; and (4) no coating degradation. The system weight, for degradation levels other than complete degradation, does not include any weight required for restoring or maintaining coating properties.

The effect of heat rejection temperature on system weight suggests benefits for separating heat sources based on temperature requirements. Figure 3.4-9 shows options for rejecting heat from two sets of heat sources. One set (e.g., batteries and humidity control system) requiring a lower heat rejection temperature (e.g. 30°F) than the other set (e.g., electronics with a 70°F heat rejection temperature). The options shown are—

a. Reject entire heat load at lower temperature.
b. Reject entire load at higher temperature and use refrigeration system for lower temperature loads.
c. Reject heat with separate heat rejection systems.
d. Use shared radiator for rejecting heat at higher and lower temperatures at different orbit positions.

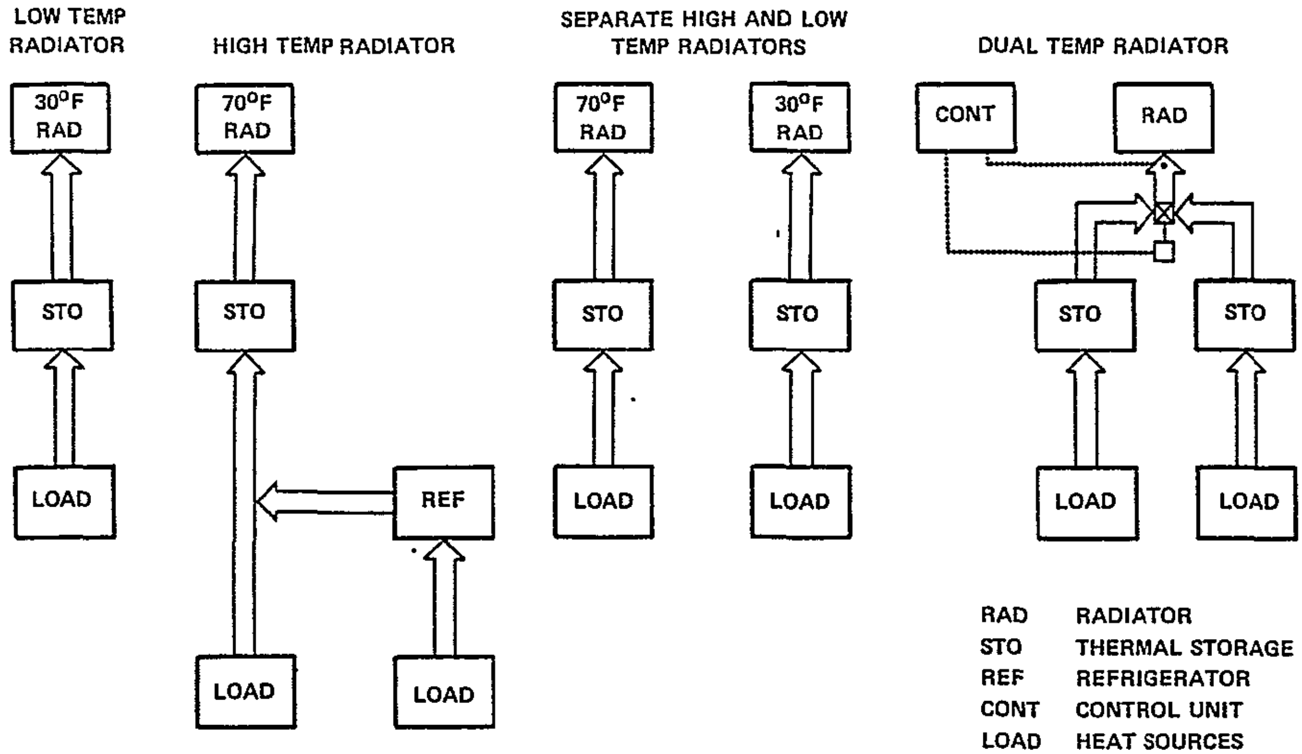


Figure 3.4-9. Heat Rejection Temperature Options

Table 3.4-2 gives an example of system weight (radiator, thermal storage and other penalties as noted) for the various heat rejection options. This example assumes 85

Table 3.4-2. System Weight (Pounds)

OPTION	FIXED TWO-SIDED RADIATOR	SELECTABLE ONE-SIDED RADIATORS	STEERABLE TWO-SIDED RADIATOR
HEAT REJECTION AT 30°F	25,400	13,340	9,560
(2) HEAT REJECTION AT 70°F	23,170	15,530	11,970
HEAT REJECTION AT 30 AND 70°F			
(3) TWO RADIATORS	17,400	9,950	6,750
(4) SHARED RADIATOR	——	——	——

(1) WEIGHT INCLUDES RADIATOR AND STORAGE FOR 100 KW DEGRADED COATING DESIGN – OTHER WEIGHT PENALTIES ADDED WHERE APPROPRIATE

(2) REFRIGERATION (COP = 1) FOR 15% OF LOAD. DESIGN LOAD INCREASED TO 115 KW AND WEIGHT PENALTY OF 350 LBS/KW ADDED FOR INCREASED POWER REQUIREMENT

(3) 85% OF LOAD REJECTED AT 70°F AND 15% AT 30°F. 350 LB WEIGHT PENALTY ADDED FOR ADDITIONAL TRANSPORT LOOP

(4) SINGLE RADIATOR REJECTS HEAT AT 70°F AND 30°F AT DIFFERENT ORBIT POSITIONS DETAILED ANALYSIS BEYOND SCOPE OF PRESENT EFFORT, HOWEVER, WEIGHT IS EXPECTED TO BE COMPETITIVE WITH TWO RADIATOR SYSTEM AND OFFERS GREATER FLEXIBILITY IN HANDLING VARIOUS MIXES OF HEAT LOADS

percent of the load rejected at 70°F and 15 percent at 30°F. For this case the two radiator system shows a clear benefit for all radiator options. The shared radiator concept is expected to be competitive with the two radiator systems and may deserve further consideration since it offers greater flexibility for handling various mixes of high and low temperature loads. With innovative design (e.g. diode heat pipe heat exchangers) the control system may be eliminated at a cost of additional radiator size and weight. Detailed analysis of the shared radiator concept was beyond the scope of the present effort. It should also be noted a detailed trade study of separation of heat sources will involve inclusion of high-temperature, experimental heat sources, alternate methods of humidity control, battery life versus temperature characteristics, etc.

Further reduction in radiator weight and increases in thermal storage capacity will result in reduced weight for the radiator and thermal storage system. Figure 3.4-10 shows these benefits for the radiator system concepts designed for end-of-life (complete coating degradation) conditions with a 30°F heat rejection temperature and a 100 kW thermal load.

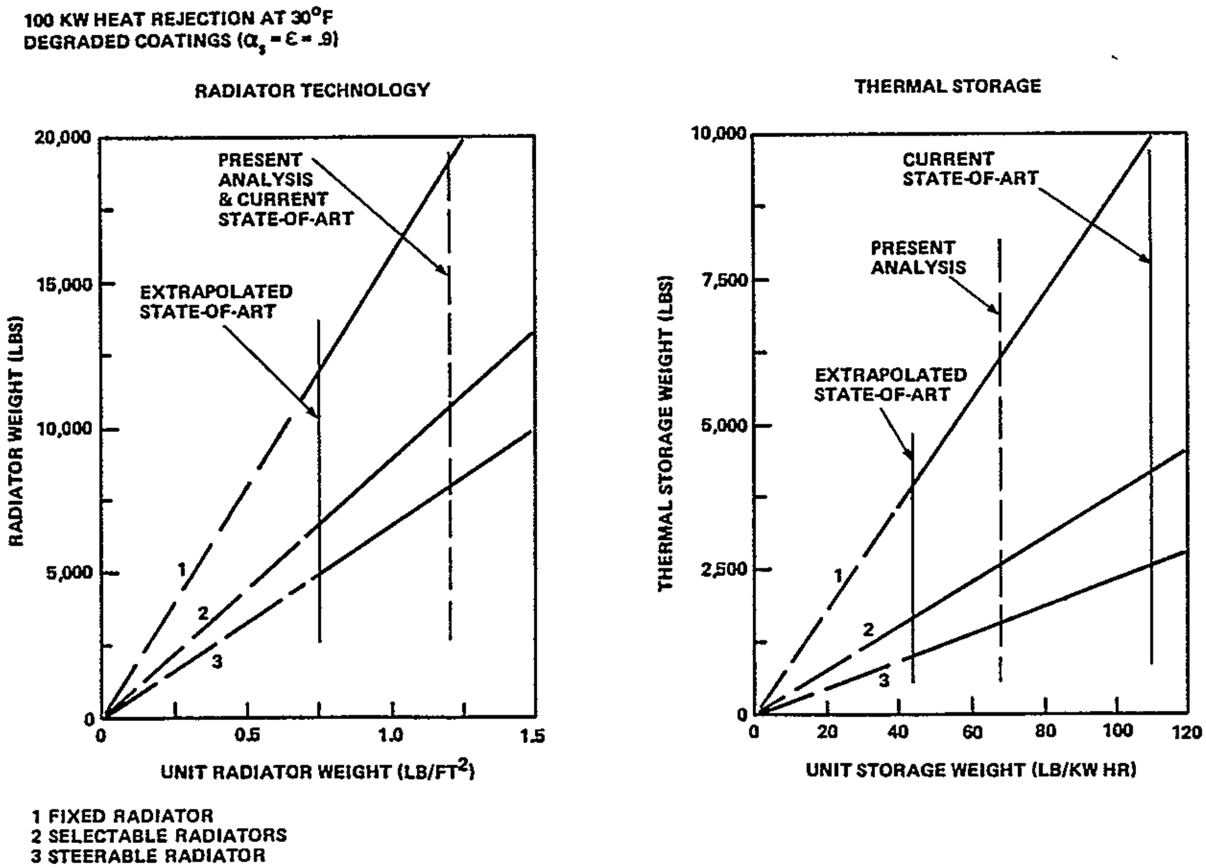


Figure 3.4-10. Benefits of Radiator and Thermal Storage Advances

3.4.4 Cost Benefit of Options

The benefits of thermal storage, steerable radiator, advanced radiator panels and advanced storage are compared with those of thermal coating renewal in figures 3.4-11, -12 and -13 for heat rejection temperatures of 30, 50 and 70°F respectively. The state-of-art values for radiator weight and thermal storage were taken to be 1.2 lb/ft^2 and 110 lb/KWhr. The advanced radiator panel and storage values were assumed to be 0.75 lb/ft^2 and 44 lb/KWHR. The weights shown in the figures correspond to a 100 kW heat rejection

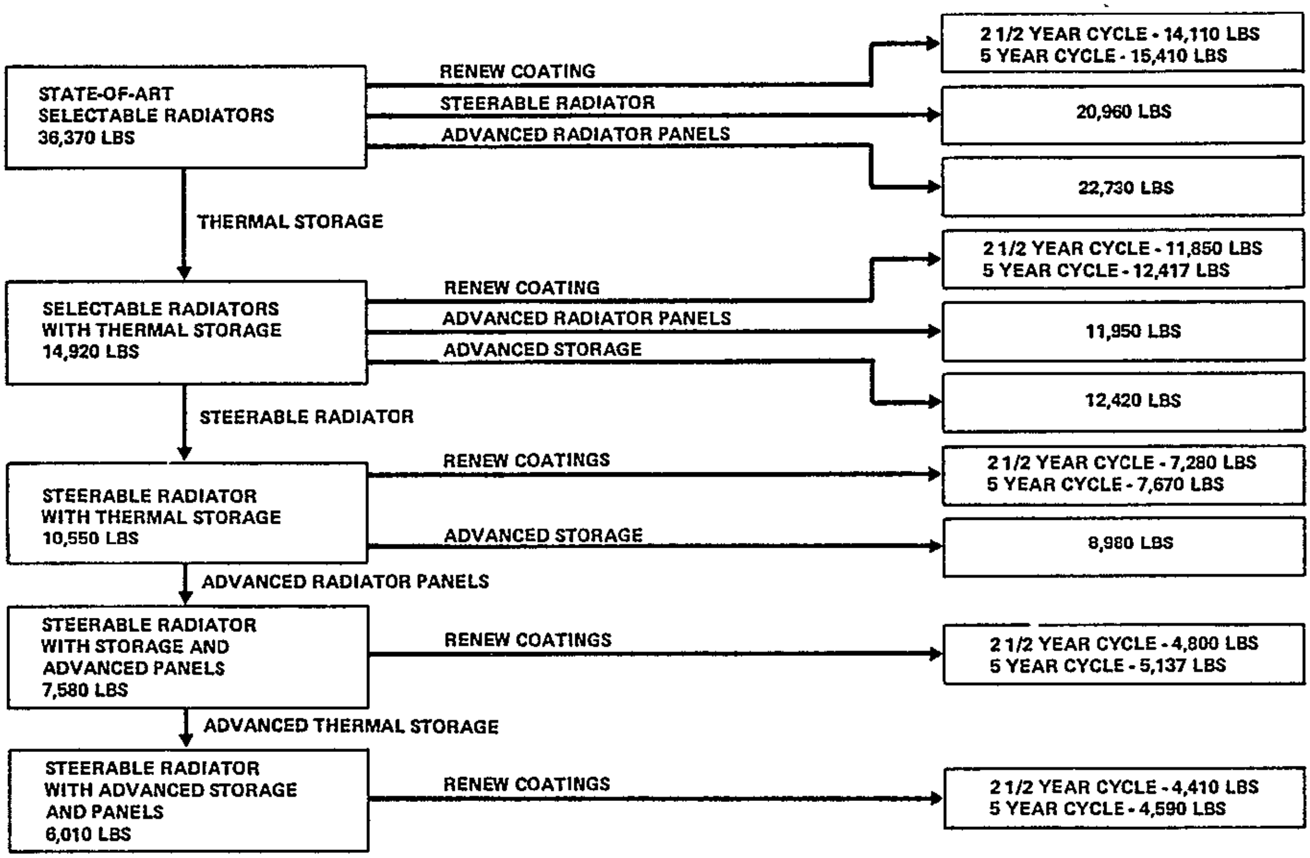


Figure 3.4-11. Technology Option Benefits (30°F Radiator)

rate and only include radiator and thermal storage weights (i.e., no weight penalties were assessed for coating renewal method, steering mechanisms, controls, valves, pumps, etc.).

The relative benefits of the various options depend on heat rejection temperatures. However, the combination of thermal storage and steerable radiator results in a lower system weight than does coating renewal for the baseline selectable radiator system. The benefits (system weight) are shown graphically in figure 3.4-14. This figure shows that the combination of thermal storage and steerable radiator results in about the same weight as that of a selectable radiator with non-degraded coating. Further benefits result from advanced radiator panels, advanced thermal storage, and thermal coating improvements. However, the largest benefits result from thermal storage and steerable radiator development.

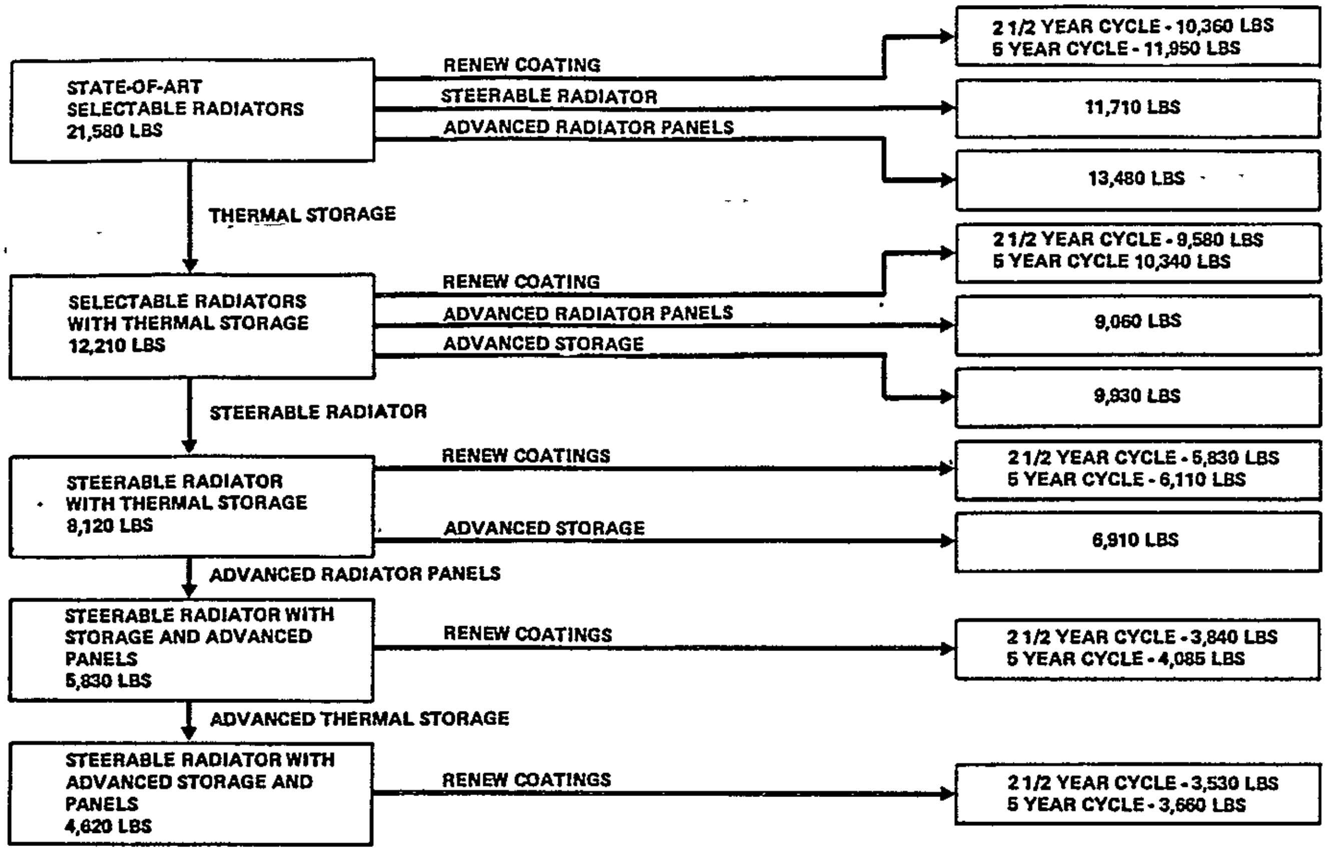


Figure 3.4-12. Technology Option Benefits (50° F Radiator)

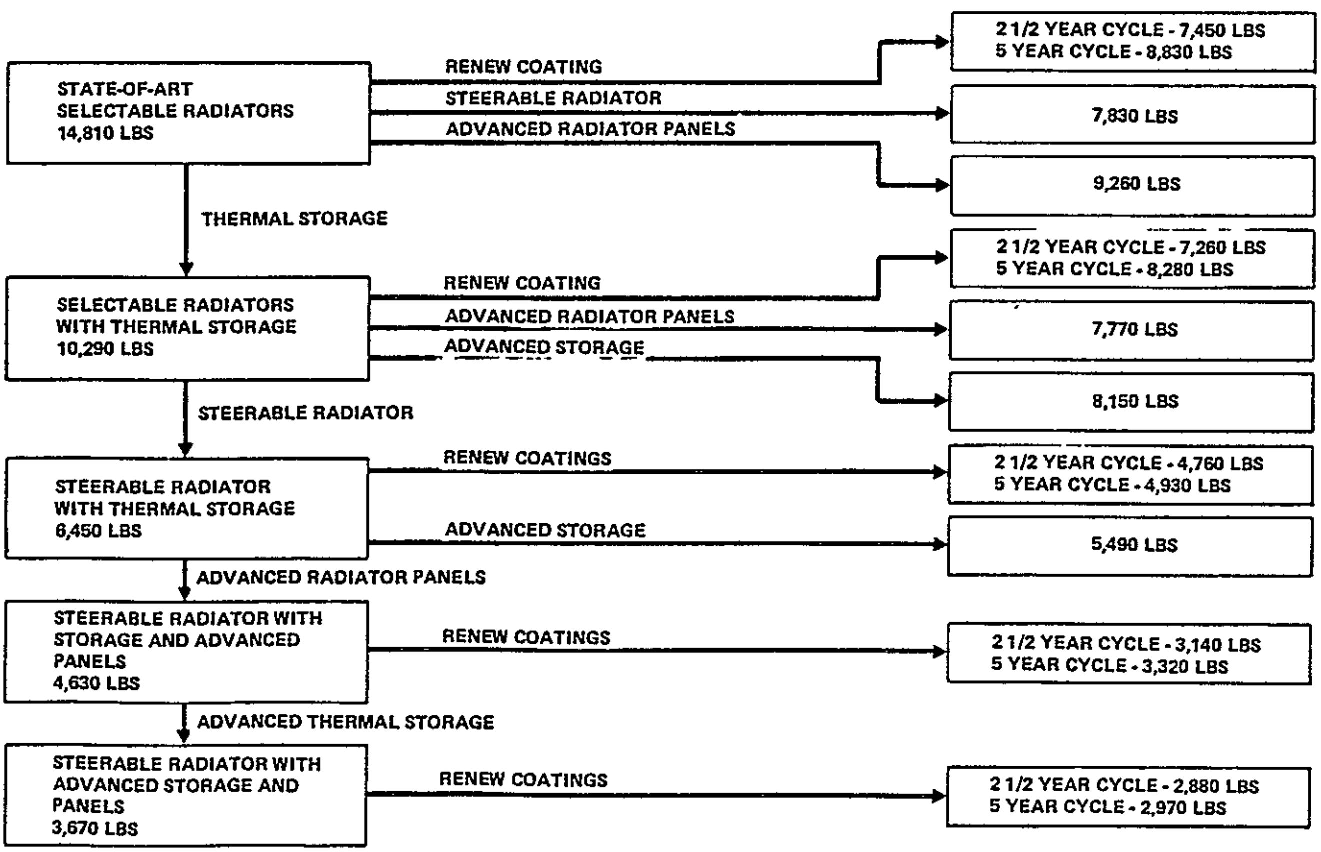


Figure 3.4-13. Technology Option Benefits (70° F Radiator)

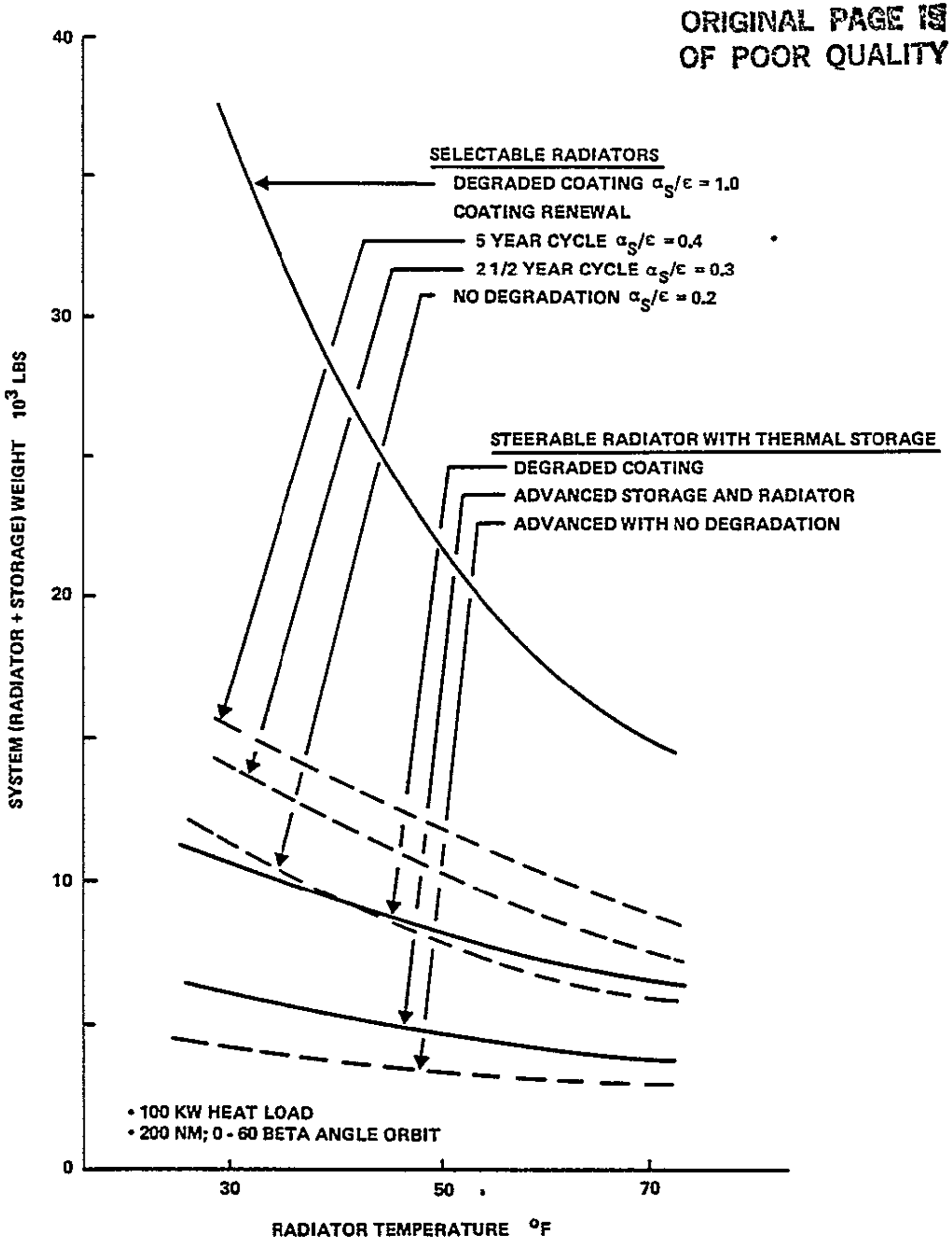


Figure 3.4-14. Thermal Management Technology Benefits

3.4.5 Technologies Needing Advancements

The analysis supports the advancement of thermal storage and steerable radiators. Advancement of these two technologies supplement the thermal coating improvement effort currently underway at NASA by providing additional design options. A test plan will not be prepared here for the thermal coating work since it is already underway. The work should be continued, probably at an increased funding level, since success with improved coatings will provide large dividends.

The development of thermal storage and steerable radiators requires further technology advancements. Thermal storage development involves advancements of—

a. Phase change material packaging.
b. Thermal interface with heat transport system.
   1. Pumped liquid loop.
   2. Two-phase fluid bus.

The primary technology advancement required for steerable radiators involves fluid coupling between the heat transport system and the radiator. Candidate concepts needing advancement include—
a. Flexible hose.
b. Fluid and heat pipe swivels.
c. Thermal slip rings.

In addition to these basic technology advancements, the concepts must be incorporated into the thermal management system. The thermal storage requires modularization and the steerable radiator requires sensors, drive mechanisms, and controls. These developments should require less advancement than that of the basic technologies.

3.4.6 Technology Development Cost and Schedule Considerations

The cost savings benefit for developing a steerable radiator and thermal storage module is estimated to be on the order of 9 to 25 million dollars, dependening on heat rejection temperature. For a 50°F radiator the savings is estimated to be 13 million dollars. This is based on a weight savings of 13,500 lbs and an area savings of 12,900 ft^2. Launch costs were taken to be \$718 per pound and manpower costs to be \$77,000 per man day (24 man-hours) with 8 manhours required to assemble 100 ft^2 of radiator panel.

The development cost is estimated at 2 million dollars each for steerable radiator and thermal storage. The cost savings is thus estimated to be three dollars for each dollar of development cost.

The development schedule is estimated to be 2-1/2 to 3-1/2 years for each program. This schedule requires an early start and possible schedule acceleration in order to complete the development by 1986. The schedule, together with the development program, is presented in volume IV of this report.

3.5 AUTOMATED INTEGRATION OF HOUSEKEEPING STUDY

This section covers the trade study conducted with respect to integrating the automation of three housekeeping functions on a manned space station in low-altitude Earth orbit. The housekeeping functions considered would be provided by the electrical power subsystem, the thermal control subsystem and the environmental control and life support subsystem (EC/LSS).

3.5.1 Issue

The issue considered in this trade study was that housekeeping functions on the space station are complex because of higher usage loads, larger variation in duty cycle, and longer duration of operations than any previous manned space system. The higher usage loads focus on a need for more efficient operations which could be obtained through integrated load management. The larger variations in duty cycle are due to modular growth of the station itself, variations in crew size and activity, as well as configuration changes due to variations in experimental tasks being conducted. These duty cycle variations could require the full-time attention of most of the on-board crew and a large number of ground controllers if automatic systems were not used. The integration of these automatic functions would provide for coordinated mode changes or transition through start-up or shut-down operations of the various housekeeping subsystem functions. Because the operating life of the space station requires on-board maintenance and refurbishment, integration of the control of the various housekeeping functions could be beneficial. This benefit could be provided by the integrated controller collecting data which would be useful in predicting any degradation of the subsystem functions. The integrated controller could also manage the mode shifts to take parts of the housekeeping system off-line during maintenance operations. At the present time, techniques for such integrated housekeeping control are not well understood and the availability of such a function for a space station in the 1990's will require an aggressive technology advancement effort.

3.5.2 Requirements

This section lists some top level requirements which have been identified or assumed for space station housekeeping functions. The requirements start with overall functional requirements on the housekeeping subsystems. These are defined unilaterally in order to define the housekeeping subsystems that we are considering in this study. Next we identify requirements on the functions to be performed by a partially regenerative EC/LSS. Again, these are very high level and defined unilaterally to define the concept. Likewise the functional requirements on automation of the housekeeping subsystems and integration of the automated subsystems are assumed to define the concepts. The design requirements of section 3.5.2.5 are extracted from JSC-17727, "Space Station Environmental Control and Life Support System Preliminary Conceptual Design" document, paragraph 1.1. These also are included to help characterize the options rather than to define limits on any specific subsystem.

The energy balance of figure 3.5-1 provides a constraint on the sizing of the electrical power and thermal control systems for a typical early space station.

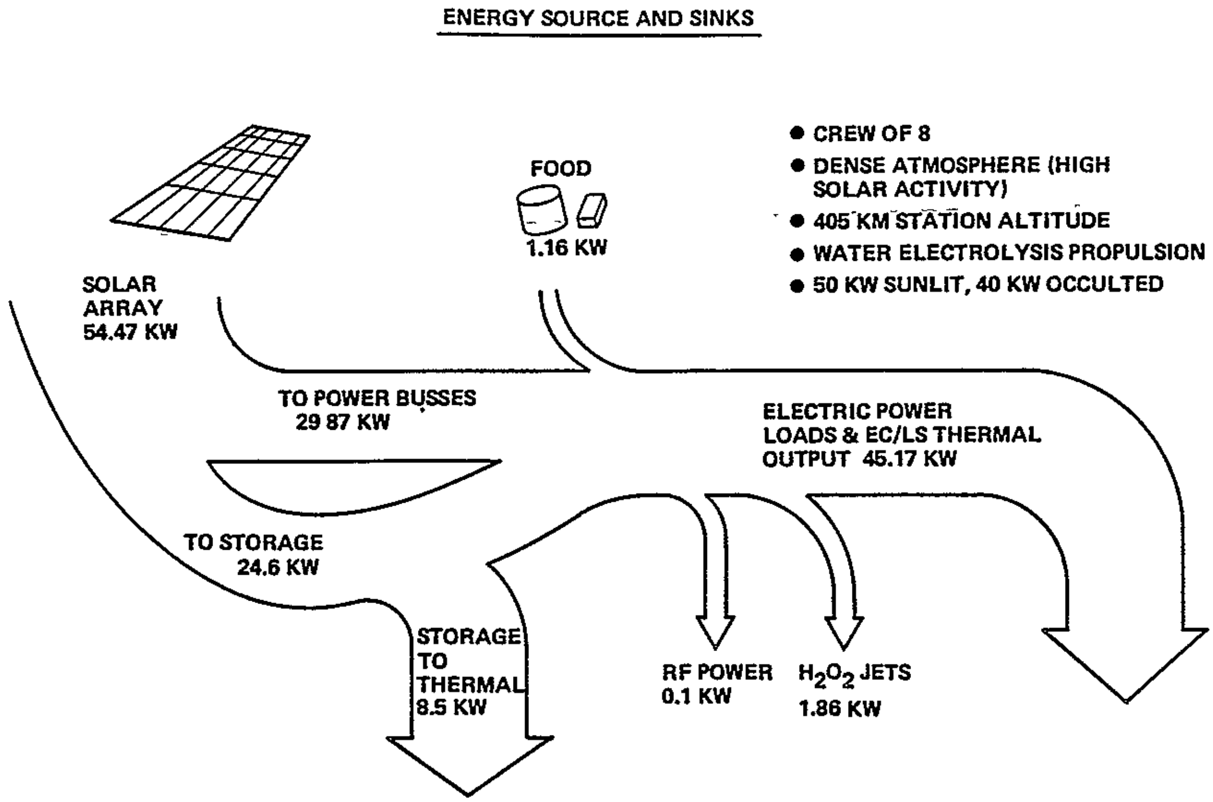


Figure 3.5-1. Energy Source and Skins

3.5.2.1 Housekeeping System Functional Requirements

The housekeeping systems shall perform the following functions as a minimum:

a. The supply of the specified quantity and quality of electrical power to the other systems on the space station.

b. The maintenance of specified thermal environments for the crew, for on-board equipment, and for experiments being conducted on the space station.

c. The control of the specified atmospheric composition and pressure.

d. The control of specified cabin humidity.

e. The provision of the specified quality of potable and wash water for the crew, equipment, and experiments.

3.5.2.2 Requirements on a Partiallly Regenerative Life Support System

If a partially regenerative environmental control and life support system is used, it shall perform the following functions as a minimum:

a. Revitalization of the atmosphere in the habitable parts of the space station.

b. Reclamation of water for the use of the crew and equipment.

c. Management of personal hygiene water.

3.5.2.3 Requirements on an Automated Housekeeping Function

If automatic control of housekeeping functions is used, it shall perform the following functions as a minimum:

a. Provide automatic parametric monitoring.
b. Adjust system operation to set point changes.
c. Provide for selected call-up of schematic diagrams for crew usage.
d. Maintain balances in operation of environmental control and life support system.

3.5.2.4 Requirements on an Integrated Automation of Housekeeping Functions

If integrated automation of housekeeping functions is used, it shall perform the following functions as a minimum:

a. Provide for integrated start-up and shut-down of housekeeping systems.
b. Provide for automatic emergency mode operation of housekeeping systems.
c. Provide for load management between the housekeeping systems.

3.5.2.5 Requirements for Design of Space Station Housekeeping System

The following requirements shall apply to the design of housekeeping functions for the space station:

a. Nominal total cabin pressure shall be one Earth atmosphere.
b. Emergency repressurization gases shall be provided for a one-time repressurization of each habitable module.
c. Any concept for reprocessing urine or hygiene water shall incorporate a phase change.
d. Any concept for reprocessing wash water must ensure adequate sterility and suitability for cleansing.
e. Emergency mode operation shall be provided to support the lives of the crew for at least 21 days.
f. The nominal shuttle resupply cycle shall be 90 days.
g. The overall design life time of the space station (including extensions through parts change out and refurbishment) shall be no shorter than 30 years in orbit.
h. Relative humidities shall not exceed the range of 25-75 percent.
i. Partial pressure of 0_2 shall be greater than 2.3 psia.
j. The energy balances and load parameters of the space station for design purposes are shown by figure 3.5-1.

3.5.3 Characterization of Concepts

The trade studies were conducted cover the following options:

Option 1 Resupply EC/LSS. This option uses manual monitoring and control of the EC/LSS as well as independent regulation of power and thermal control systems—like skylab.

Option 2 Partially Regenerative EC/LSS. This option uses a partially regenerative EC/LSS (air and water recycling only) with manual monitoring and control and independent regulation of power and thermal systems (see figure 3.5-2 for a description of a

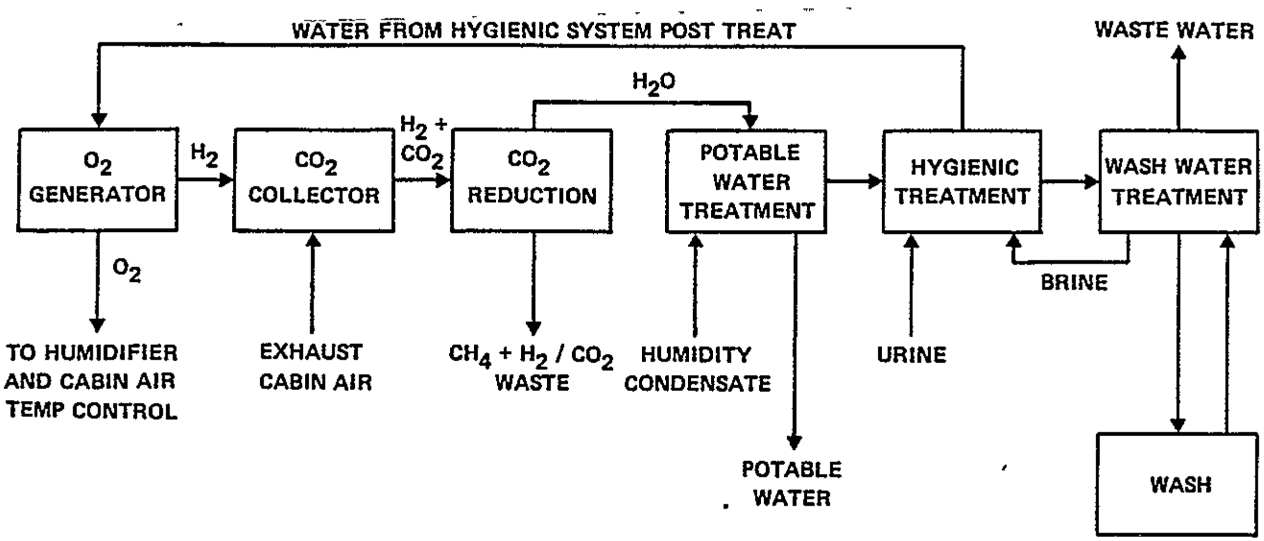


Figure 3.5-2. Partially Regenerative Environmental Control (EC/LSS) Subsystem

typical partially regenerative EC/LSS). The block diagram of figure 3.5-2 shows the primary functions and interconnections which make up the partially regenerative environmental control and life support subsystem (EC/LSS) considered here. The subsystem produces oxygen for the cabin atmosphere and potable water and wash water for use by the crew. It collects and recycles exhaust cabin air, humidifier condensate, urine and wash water. The waste from the subsystem is a minimal amount of methane, carbon dioxide and hydrogen gas, and waste wash water. The subsystem is conceptual at the present time but a simulator is being developed with partial loop closures. Significant effort is being expended at this time to develop a partially regenerative EC/LSS, but unreliable or temperamental sensors and complex support systems which require extensive human monitoring indicate that much progress is required to achieve space qualification of the subsystem.

Option 3 Independent Automatic Housekeeping Control. This option uses independent automatic controllers for the EC/LSS, power subsystem, and thermal control subsystems (see figures 3.5-3 and 3.5-4 for description of typical automated power and thermal control). Figures 3.5-3 and 3.5-4 show conceptual block diagrams for a space station electrical power subsystem and thermal control subsystem respectively. These diagrams show interactive lines between the automatic controllers and subsystem function blocks. The control functions are not specified but they are more sophisticated than simple voltage or current regulation for power or heater on-offs for thermal. The functions

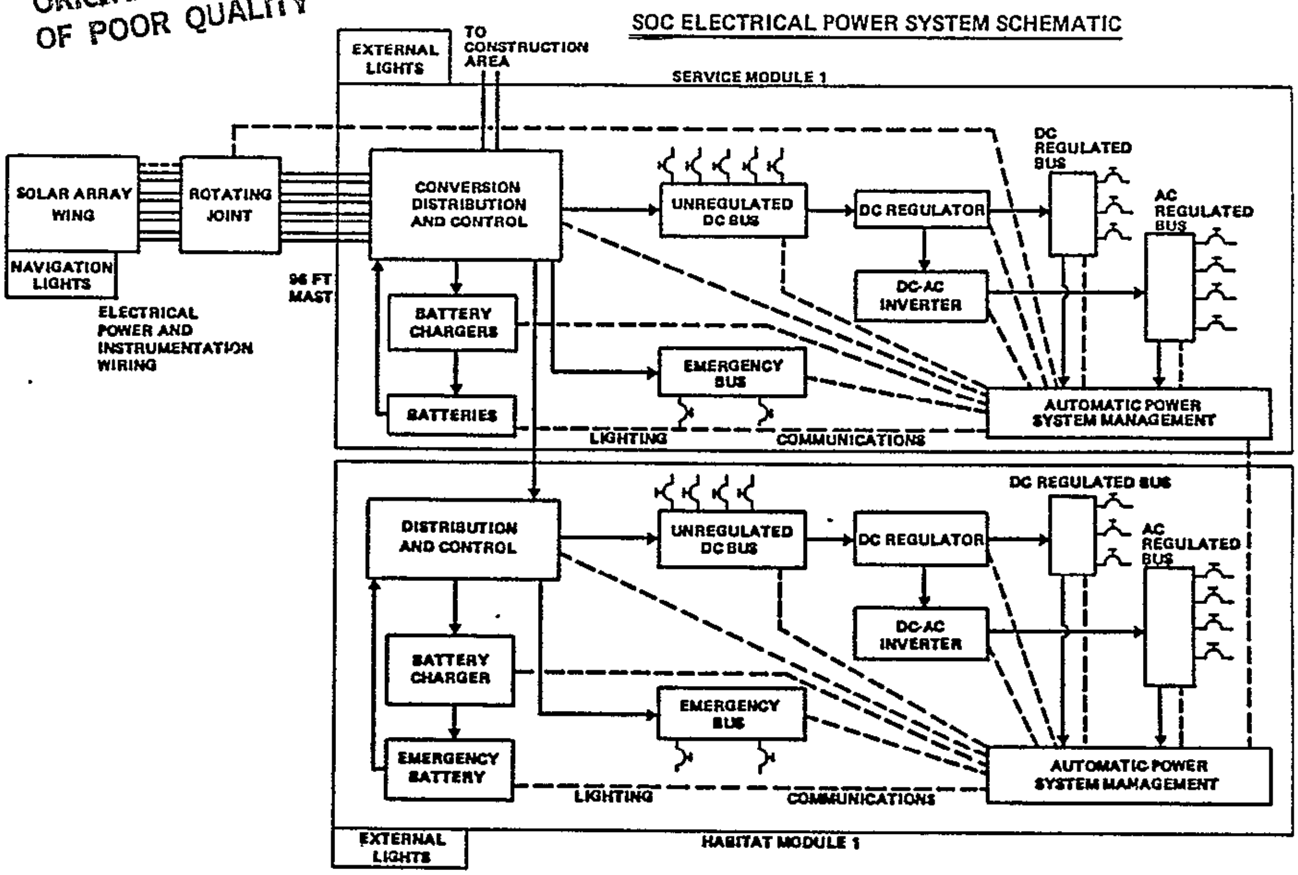


Figure 3.5-3. SOC Electrical Power System Schematic

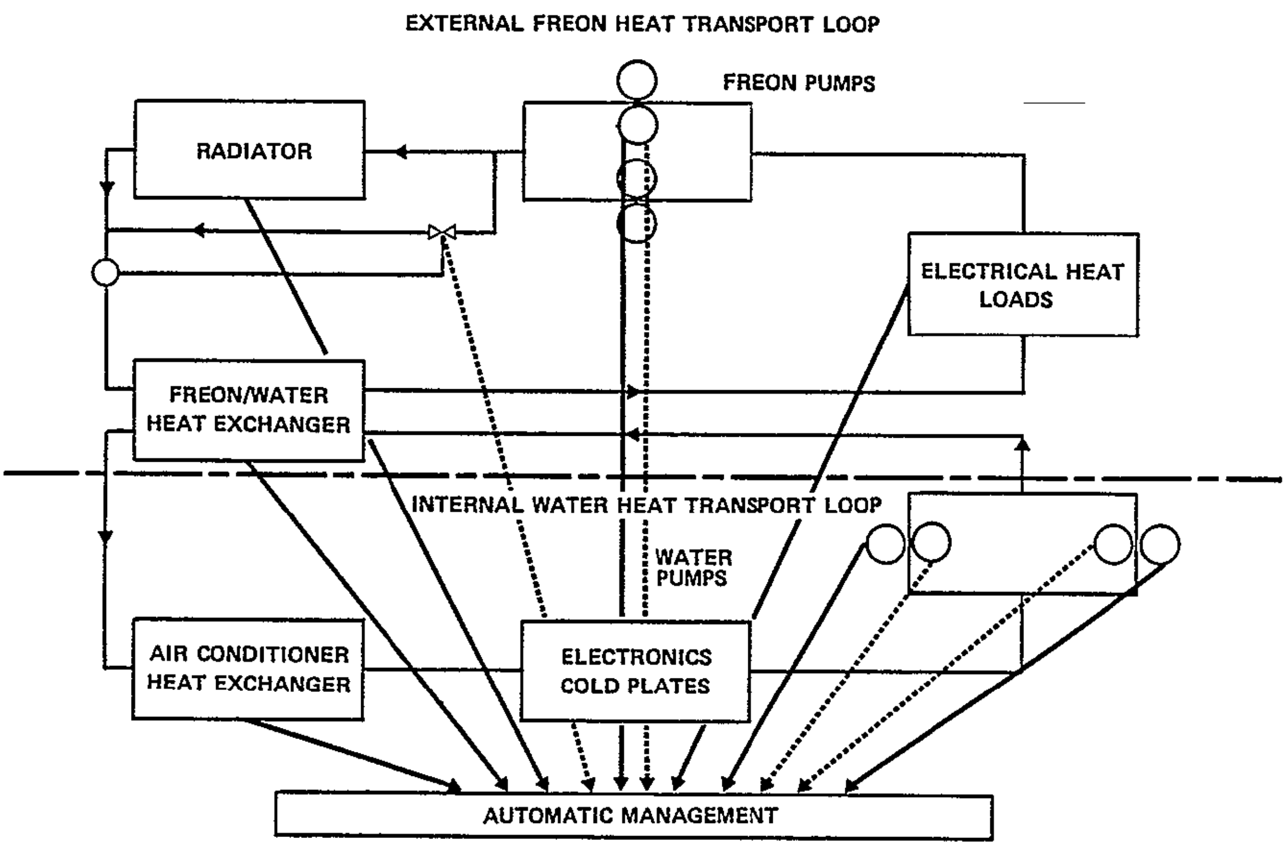


Figure 3.5-4. Basic Thermal Control Schematic Diagram

indicated are integration functions that are discussed later for expert systems. Several NASA studies are currently underway toward automating electrical power and thermal subsystems independent of other housekeeping.

Option-4 Integrated Automatic Housekeeping Control. This option uses integrated control of the automation of partially regenerative EC/LSS, power subsystem and thermal control subsystem (see figure 3.5-5 for block diagram of concept). Figure 3.5-5 shows a conceptual block diagram of an integrated controller for automated housekeeping functions. As indicated, the interactions are mode selection and monitoring, except for the continuous balancing control shown between the controller and the partially regenerative EC/LSS. Such balancing functions would also be present in a more predictable manner for electrical power and thermal if the sophisticated automation shown on figures 3.5-3 and 3.5-4 were used. Such an integrated control system is not being developed at this time and any move toward it would require large software and sensor development efforts.

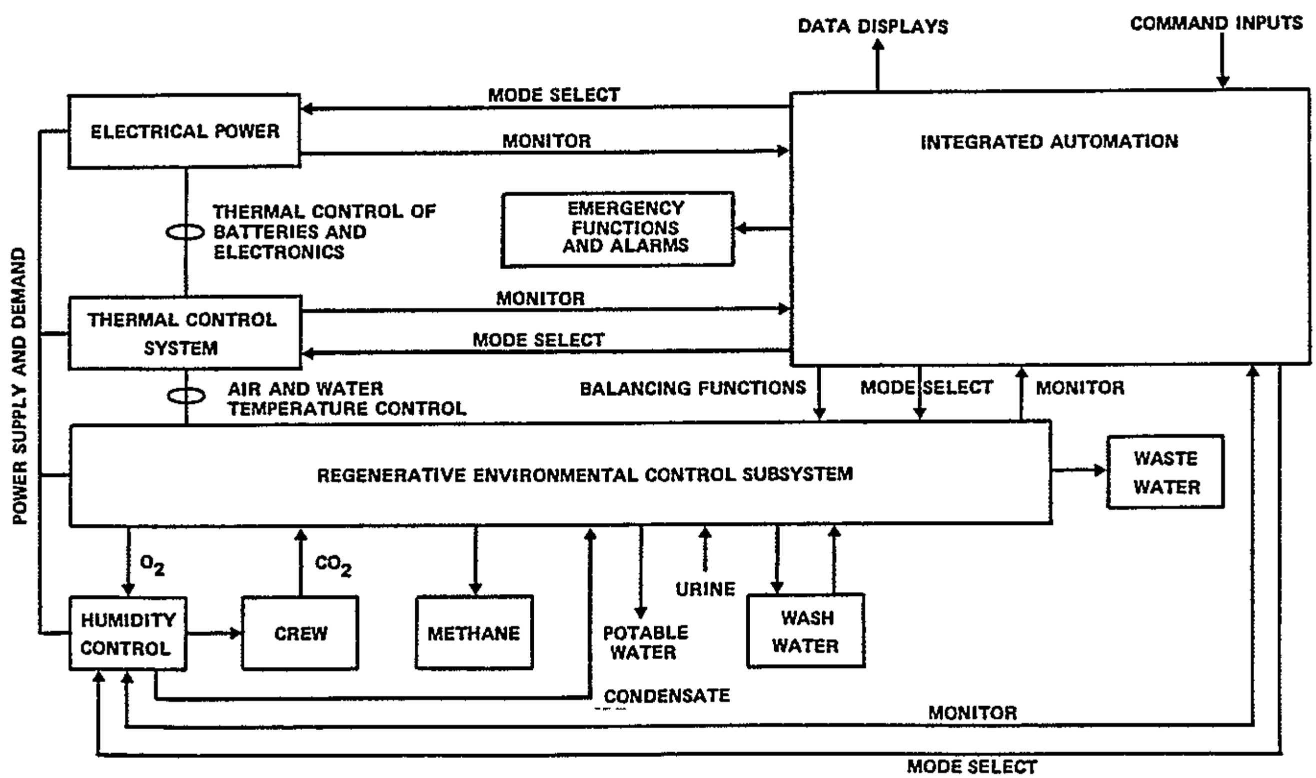


Figure 3.5-5. Integration of Automated Housekeeping Subsystems — Block Diagram

3.5.3.1 Expert Systems Concept

A technique which has been advanced recently and which appears to be applicable to integration of automated housekeeping system on the space station is the expert system concept. This concept is basically one which uses a natural programming language input to a large data processing capability. The natural language allows a human expert to program their knowledge or expertise into the data processing system. Use of that expertise by other interactors with the expert system is accomplished by processing input data through decision-making rules. These rules are typically more flexible and adaptable than the "if" statements of conventional higher-order languages. The rules are programmed as part of the expert systems software development and may be updated along with the expert data as a result of experience gained while using the system. Annunciation of outputs from the expert system is also a characterization of this concept.

Functions which might be performed by using the expert system concept to integrate space station housekeeping include:

a. Electrical power load management between subsystems.
b. Integrated system balancing between thermal control and EC/LSS functions.
c. Integrated start-up and shut-down including effects on all housekeeping systems.
d. Integrated selection of nonstandard operational modes.

3.5.4 Cost and Benefits of Options

The cost benefits comparisons for each of the four options are displayed by tables 3.5-1 through 3.5-4 and a cross plot of the trends for the options is given by figure 3.5-6.

3.5.4.1 Trade Study Conclusions

a. The partially regenerative EC/LSS is necessary to reduce resupply costs. If none of the air or water used by the astronauts is recycled then all that is used must be transported from earth to orbit. Based on data from the Bioastronautics Data Book 1973, an eight-person crew would require 149,270 lbs of water per year and 5,373 lbs of oxygen per year. This would require the total payload of one shuttle flight every 90 days just for resupply. In addition because the waste products are not recycled, they would either be dumped into space or stored onboard and returned to earth by the shuttle. At $718 per pound for shuttle transportation costs, the annual resupply would be over 111 million dollars and the return cost would be a substantial fraction of that, in addition, depending upon how much was dumped or vented. Clearly resupply is a very expensive way to go with long-term missions and crews as large as eight people.

   For the partially regenerative EC/LSS, a substantial amount of development is required and without automation of the on-board processes, a crew of 6 to 7 people would be required continuously to monitor all of the functions. This is based on experience currently being gathered with the partially regenerative EC/LSS simulator

Table 3.5-1
Automated Integration of Housekeeping Subsystems
Option 1
Resupply EC/LSS with Manual Control

Cost	Benefit
o Additional shuttle flights required for resupply. o Total payload of one flight every 3 months for air and water resupply for a crew of 8. o Large number of manhours monitoring and regulating housekeeping functions. o 22,000 man hours/year (based on 1/2 time attention of one astronaut and two controllers on the ground full time). o Greater contamination from venting CO2 and water, or, conversely, storage and transport of waste back to earth.	o Simple concept which has been used.

Table 3.5-2
Automated Integration of Housekeeping Subsystems
Option 2
Regenerative EC/LSS with Manual Controls

Cost	Benefit
o Increase in number of controllers required. o 56,950 man hours/year (6 controllers plus 1/2 astronaut attention full time). o Dependence on the reliability of complex equipment. o 30 to 50 actuated valves per system for each inhabited module (4 modules = 120 to 200 valves). o On-board power usage approximately 4 times that of resupplied system (at 8500 watts per system x 2 modules = 17,000 watts).	o Avoidance of shuttle resupply missions for O_2 and water. o Reduced production of excess CO2 and used water. o Contamination from venting reduced. o Transport of excess waste to earth reduced o More consistent supply of life support substances. o Regenerated water would not go stale because of storage time. o O_2 supply would not be constrained by the amount remaining in storage.

Table 3.5-3
Automated Integration of Housekeeping Subsystems
Option 3
Partially Regenerative EC/LSS with Independent Automation

Cost	Benefit
o Dependence on reliability of complex control functions and sensors. o Dependence on reliability of an automatic failure detection and redundant path selection functions. o Weight of on-board automation equipment increased 300 pounds. o Power required for on-board automation equipment increased 250 watts.	o Reduction in number of controllers to 1 full time for normal operations (8,760 man hours/year plus four for start-ups, shut-downs and emergency mode periods 1/10 time x 4 = 3,500 man hours/year) Total = 12,260 man hours/year.

TABLE 3.5-4
Automated Integration of Housekeeping Subsystems
Option 4
Automated Partially Regenerative EC/LSS Integrated with
Electrical Power Control and Thermal Control

Cost	Benefit
o Very complex control system algorithms which require significant data processing capacity and speed. o Interactions between the control of the separate subsystems could result in migration of failures from one to another. o Additional weight and power for on-board integration equipment of 120 pounds and 80 watts.	o Allows trend prediction and prevention of anomolies. o Allows load management. o Allows integrated system balancing. o Allows integrated emergency modes. o Allows integrated start-up and shutdown. o Reduces need for separate thermal control, power and EC/LSS controllers (at 1 full time = 8,760 man hours/year).

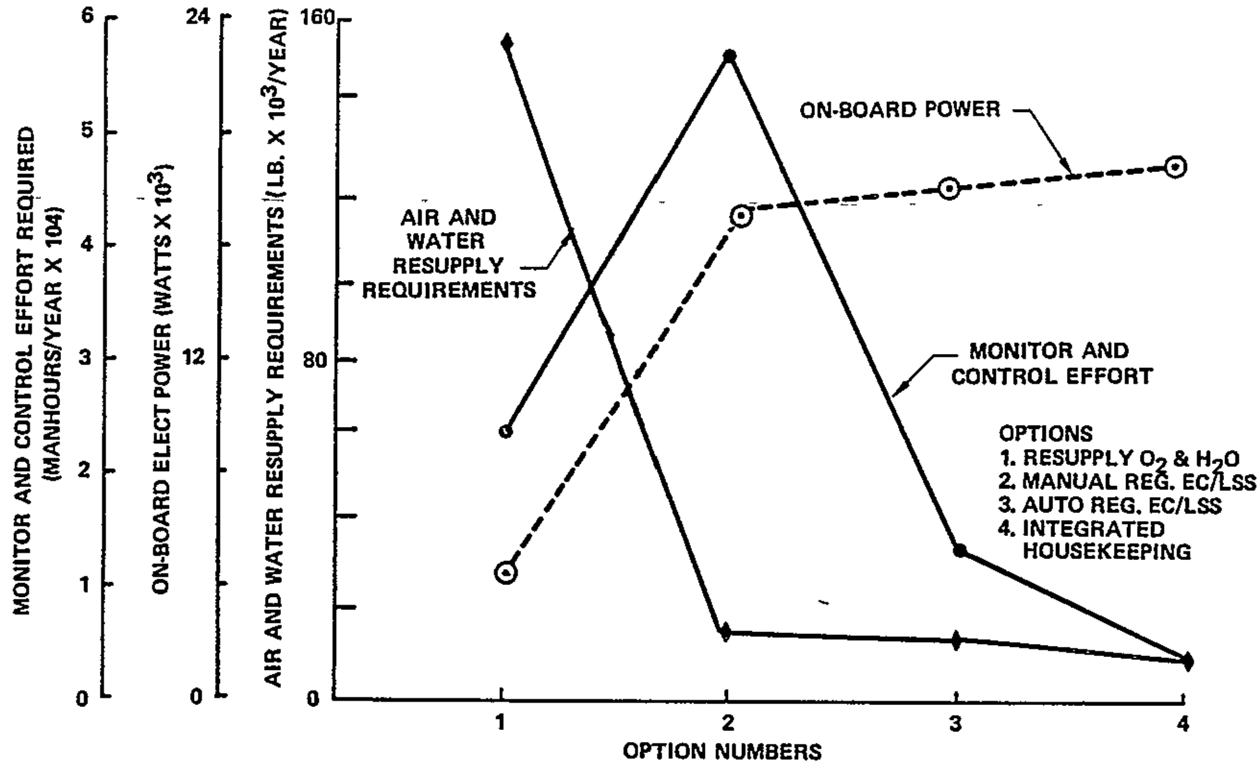


Figure 3.5-6. Comparison of Housekeeping Options

at JSC. Based on \$2000 per man day for ground controllers and \$77,000 per man day of astronaut time, the monitoring cost for 6 controllers and 1/2 astronaut is \$18,800,000 per year. For comparison, the resupply system would use four fewer ground controllers and the monitoring cost on the same basis would be \$3,000,000 per year less. The partially regenerative EC/LSS will require a substantial increase in the needs for onboard electrical power from approximately 4000 watts for resupply to about 17,000 watts for a partially regenerative system for a crew of eight. The acquisition of and launch costs for the additional 13 kW of power is estimated at \$100,000,000. Based on a 10-year mission it appears that a partially regenerative EC/LSS would save over a billion dollars in operational cost of an eight-person station. This clearly indicates a need to advance the technologies needed. The only apparent disadvantage of using the partially regenerative EC/LSS would be the significant increase in complexity of the EC/LSS equipment.

b. Automation of the independent housekeeping subsystems accomplishes limited reduction in cost when compared with manual monitoring and control. The six full-time ground controllers identified for the manually controlled partially regenerative EC/LSS could be reduced by an estimated five persons. The involvement of astronauts is not significantly reduced, however, because the start-ups and shutdowns of the subsystem are estimated to require the support of half of the eight astronauts and that is estimated to occur 1/10 of the time. These combined effects reduce the monitoring cost back to $12,000,000 per year which represents a savings of about $70,000,000 over a 10-year mission when compared to the manually monitored partially regenerative EC/LSS.

The increase of on-board weight and power requirements would be modest with independent automation but the complexity of the system and the needs for maintenance and repair could be even greater than they would be for the manually monitored regenerative EC/LSS.

At the midterm, the conclusion was that automation of the partially regenerative EC/LSS was necessary for the space station. At this point with further consideration of the costs and benefits, it is not as clear that significant monitoring costs would be saved. This is because the largest monetary cost is for astronaut time and that wouldn't be reduced significantly by independent automation without mode shift coverage. It must be noted, however, that development of the technology for independent automation of the housekeeping subsystems is a necessary step in the development of the integrated automation capability which characterizes option 4.

c. In integrating the automation of the separate housekeeping functions, it is assumed that human monitoring can be reduced to one full-time ground controller. Astronaut involvement is essentially nil since the system would be designed to handle start-up, shut-down and emergency mode changes in a hands-off manner. The ground controller would monitor global data, would have access to advisory expert system data on the ground, and would activate alarms for the astronauts as necessary. Thus the monitoring cost would be $750,000 on the same basis as was used above.

The system would have built into it a means of providing maintenance prediction data so that some reduction in the substantial maintenance and repair cost for the partially regenerative EC/LSS could be expected. The integration of electrical power management with EC/LSS and thermal would allow optimal reaction to set-point changes and mode shifts, so that the systems could operate more efficiently and could provide a more predictable environment for the crew.

<u>It is apparent that the integrated approach is a key element in developing practical automation of the partially regenerative EC/LSS and in achieving cost effective and trouble-free housekeeping functions.</u> It is also apparent that such a management-type integration controller with the large number of variables involved is a real

technology advancement, and one that may prove to have a very large development price tag.

3.5.5 Technologies Needing Advancement

Three areas of technology advancement have been identified to support integration of automated housekeeping functions on the space station. These are:

a. Sensor advancements to support automatic control of housekeeping systems. They include:
    1. A more reliable total organic carbon sensor for a partially regenerative EC/LSS.
    2. An ammonia sensor for a partially regenerative EC/LSS.
    3. A self-cleaning pH sensor for a partially regenerative EC/LSS.
    4. A liquid level detector for EC/LSS.
    5. A liquid flow detector for thermal control or EC/LSS.
    6. An iodine detector for partially regenerative EC/LSS.
    7. A reliable humidity sensor.
    8. A conductivity sensor.

    The first two on the list are the most critical from the point view of need and development effort needed to reach the level of technology required. An outline for a development plan focusing on those two is included as section 3.5.5.1 of this report.
b. Algorithm development and control system conceptual design for automating the electrical power system, thermal control system, and EC/LSS independently. These technologies are already being pursued through contracted efforts already underway in NASA, and therefore we will not outline a plan here for them.
c. Algorithms and concept development for "expert systems" to manage the integration of the automated housekeeping functions. While some attention is being paid to this area in efforts underway through NASA, it is believed that the technology is in need of aggressive advancement if such a system is to be available for space station use in the 1990's. We are, therefore, including an outline development plan in section 3.5.5.2 for that technology.

3.5.5.1 Steps in Advancing Sensor Technology for EC/LSS (Ammonia Sensor or TOC Sensor)

See figure 3.5-7 for flow diagram.

a. Research available technology and existing concepts (college and university studies).
b. Develop sensor concepts (college and university or industry effort):
    1. Electrodes.
    2. Materials.
    3. Process concepts.

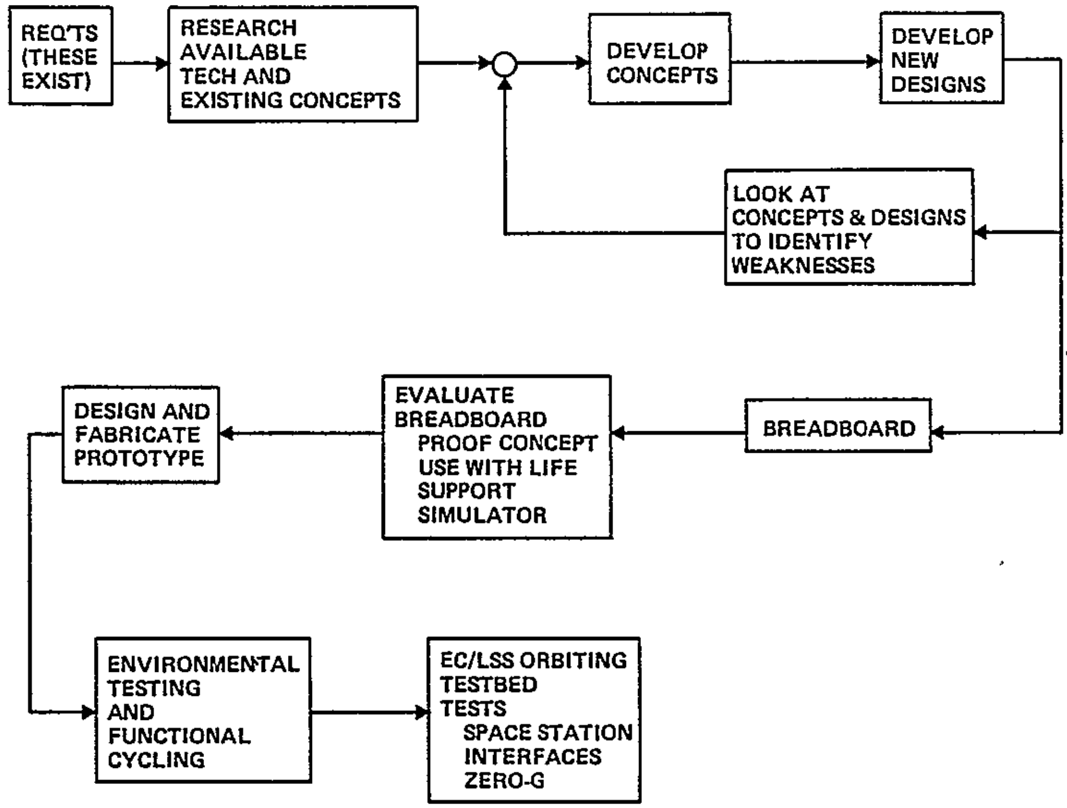


Figure 3.5-7. Technology Advancement Plan Flow Ammonia Sensor and Total Organic Carbon (TOC) Sensor Development for EC/LSS

4. Automatic calibration concepts.
   (a) Solutions in conjunction with electrodes
   (b) Electrical calibration.
   (c) Generate calibration gas.

c. Develop designs (industry and college-university):
   1. Membrane development.
      (a) Durability.
      (b) Compatibility with fluids.
   2. System or subsystem elements needed to achieve readout.

d. Look at concepts and designs to establish or define weaknesses and to develop means to eliminate weaknesses (industry and college-university).
   1. Calibration.
   2. Replenish fill solutions.
   3. Cleaning.

e. Breadboard (proof of concept, exposure to environment, pre-proto use with life support simulator) (industry or college and university).

f. Design prototype (industry).

g. Prototype test and evaluation (industry/NASA)
   1. Extend testing in environmental range.

2. Autocycling—autocalibration checks.
3. Functional test in environmental simulator.
4. More testing with astronauts in life support simulator.

h. EC/LSS flight test bed testing to determine zero-g effects and space station interface problems (industry/NASA).

Figure 3.5-8 shows a schematic of a pre-prototype water quality monitor which uses the two sensors identified for advancement. The sensors currently being used cost about

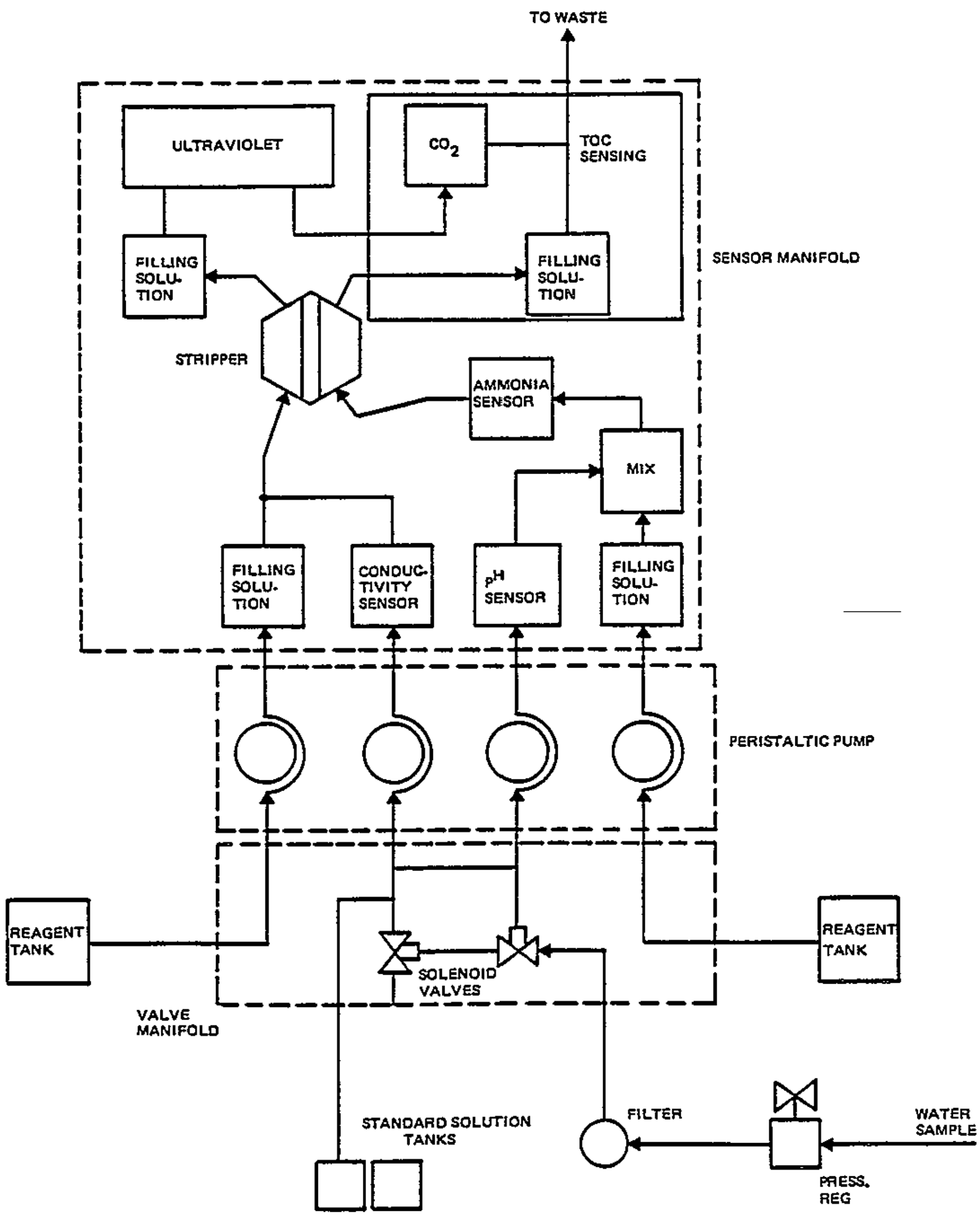


Figure 3.5-8. Water Quality Monitor System

$1,000 each but their reliability is marginal. The ammonia sensors typically have a useful life of 2 to 3 hours and the total organic carbon (TOC) sensor does a little better, giving up to 3 or 4 days before it has to be changed out. New materials for the electrodes and for the membranes need to be developed, and the concept involving balancing and calibration should be reviewed. These sensors are essential to a partially regenerative EC/LSS in that trace levels of toxic or undesirable substances need to be detected in the recovered water so that removal can be completed. The advancement of this technology is very high in priority to support the early manned space station.

3.5.5.2 Overall Expert Systems Advancement Plan

The integration of automated housekeeping functions, or even automation of the partially regenerative EC/LSS by itself, would involve a wide variety of inputs from different parts of the space station that need to be considered against a variety of operating conditions or modes. Selection of rules for evaluating all of these interactions may require the use of expertise which is developed as experience is gained through operation of the space station or simulators. In order for interaction of the management level controller with an evolving human expertise to be implemented, the use of the expert systems branch of artificial intelligence is indicated.

Expert systems to date has been implemented only on a small scale or for systems where real time reaction is not critical. The R1 system developed for Digital Equipment Corporation uses about 850 rules but is used in a non-real time mode to provide configuration information to support the sale of VAX data processing equipment. The system we are suggesting would use the "fuzzy" decision making and human interactives which are characteristic of the expert systems, but the system management control loop would be closed through the expert systems function. Successful development, checkout, and verification of such a concept would be a technology advancement that would indeed benefit the manned space station.

Development of an expert system concept for integration of the automation of housekeeping on the space station is envisioned as involving three steps:

a. Define requirements for such a system:
    1. Identify modes of operation.
    2. Identify controller interactions with the subsystems.
    3. Identify controller interaction with human operators and crew members.
    4. Identify constraints imposed by hardware and by software configuration control.
b. Perform controller development (see section 3.5.5.2.1).
c. Development of a more efficient programming language than LISP.

3.5.5.2.1 An Example of Expert Systems Development

The following discussion assumes that those portions of the overall system for which Expert Systems controllers are suitable have been identified. (In fact defining the requirements for an expert system in housekeeping control is a major effort.) It is further assumed that expert systems controllers are not suitable for the entire system, because we are dealing with a new type of system which is not well understood and for which no analytic model exists. The final assumption is that it would be possible for a sufficient number of human operators to control the system manually.

The first step is to develop a simulator and set of manual controls for the system. For our purposes here, it is not important whether this is done in hardware or software.

The second step is to create a suite of scenarios of various conditions to which the system would be subjected. Ideally, the suite should cover all conditions including normal conditions and crisis conditions.

The third step is to train the operator(s) to respond to the suite in an acceptable manner. The goal should be to satisfy rather than optimize. The expert systems approach is particularly well suited to subsequent modification as experience is gained; thus, it is easy to observe the dictum that "premature optimization is the root of all evil."

The fourth step is, once the operator(s) is performing satisfactorily, to identify those operator functions not well suited for closed loop automation. These functions should be incorporated into the expert systems level of controller. The remaining functions should be analyzed to determine what type of closed loop controller is best for each function.

The fifth step is to exercise the controllers using the suite of scenarios. If the controllers are satisfactory, the development process is complete.

The sixth step is to debug the rules in conjunction with the operator. This step will almost certainly occur several times because picking the brain of the operator is an erroneous process. Expert system architectures are generally designed to facilitate iterative development. Repeat step six after debugging the rules. (Figure 3.5-9 illustrates this process.)

Finally, the software for the rules and the data base needs to be prepared, verified and validated, and integrated with the data processor hardware and interactive equipment which will be used in the space station.

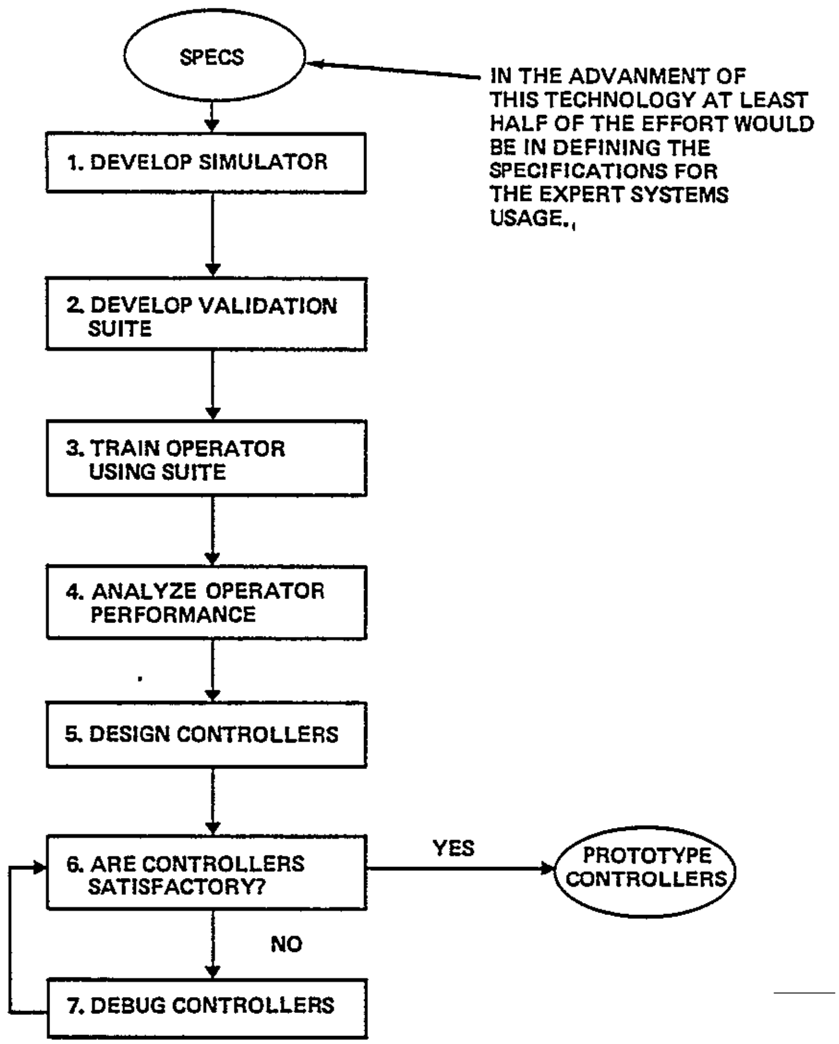


Figure 3.5-9. Technology Advancement Flow Plan Expert System Application for Integration Management of Automated Housekeeping

3.5.6 Technology Development Cost and Schedule Considerations

This section gives general consideration to the elements of cost and the schedule factors which are related to advancing the technologies suggested for integration of the automated housekeeping functions. See section 4.1 for a quantitative calculation of the cost and benefits ratios for these technology advancements.

3.5.6.1 Cost and Schedule Considerations for Advancement of Ammonia and TOC Sensors

At present, the partially regenerative EC/LSS simulator uses a pre-prototype water quality monitor in an adjacent laboratory for measurement of pH, conductivity, ammonia, and TOC. This equipment is bulky and requires frequent maintenance and adjustment. The TOC sensor is an essential component in the urine recovery system. The TOC must be detected at trace levels in order to protect the crew and ensure NASA water quality standards are met. The ammonia sensor is also necessary to meet these standards. These sensors become a necessity when automation of the partially regenerative EC/LSS is considered.

A partially regenerative EC/LSS controller on board the space station would require sensing of these substances by compact, reliable and easily maintained devices which are space qualified. The development task then is to advance a sensing process from laboratory equipment to small sensor units which are space qualified. This rather substantial task needs to be initiated immediately with a target of providing at least flight type prototype sensors by 1987-1988. Development studies are being considered at the level of $100,000. Carrying the study of requirements and concepts through breadboards to prototype models will require several times that level of expenditure for each sensor over a period of two to three years beyond those studies.

3.5.6.2 Cost and Schedule Considerations for Advancement of an Expert System Controller
At present, the partially regenerative EC/LSS simulator is operated in separated modes, i.e., regeneration of air or reclamation of water, with human monitors and controllers at each of six process control panels. To progress from this rather cumbersome, but still advanced situation, to one with compact, self managing automatic controllers of a complete regenerative EC/LSS on a space station seems a revolutionary step. If we add to that the integrated management of all housekeeping functions, the advancement seems well beyond the realm of being available for an early 1990's space station. It is not too soon to start if we want such a capability for an early evolution of the space station. Since the major parts of the advancement task are to define requirements and concepts and to develop operational, and hierarchial interactions with respect to programmed rules and data, a major part of the effort will be in software development. By comparison, software development efforts of 100 to 300 man years are common for major aerospace programs.

3.6 ATTITUDE CONTROL STUDY

Two attitude control technology advancement areas were placed on the top priority trade study list as a result of the final trade study candidate screening by the Boeing technical evaluators and the management advisory committee. These areas were the: (1) development of a control system which is robust with respect to changing control and structural interactions, and (2) development of techniques for precision instrument pointing to minimize space disturbances. After initial review with MSFC, the area of precision instrument pointing was selected for study. This selection was not only based on the importance of the area but also took into account the resources available for detailed trade studies.

It was decided at a subsequent review at NASA Headquarters that a start on the much broader topic of changing control and structural interactions would be of more benefit to the total space station study; as a result, the control and structural interaction effort was initiated. It was acknowledged at the time of the headquarter's meeting that a top level approach to the subject would have to be taken due to the wide variety of issues to be addressed and the study resources available. It was also acknowledged that the study would probably not have time to accomplish detailed trade studies of technology advancement options. The study was therefore limited to accomplishing the following:

a. Identify space station attitude control requirements giving reasonable numerical values where possible.
b. Identify disturbance sources of significance for space station attitude control.
c. Calculate magnitude of disturbance sources for a specific space station configuration.
d. Calculate (i.e., predict where possible) the pointing accuracy and the effectiveness against disturbances to be expected from a low bandwidth controller.
e. Identify control technology options and recommend the next steps required for their development.

3.6.1 Issues

The following issues have been identified as being of prime importance for control of a large manned space platform.

3.6.1.1 Flexible Mode Stability Versus Pointing Accuracy Requirements

Tight pointing accuracy requirements produce a derived requirement for increased control system bandwidth. As controller bandwidth increases, many structural mode frequencies will be included within the controller passband. Stabilization of these modes without sacrificing pointing accuracy will be a complex task. The task is made more challenging by the variations in mode shapes and frequencies caused by space station configuration changes (e.g., solar array articulation, docking and undocking of shuttle orbiter, station growth and construction activities).

3.6.1.2 Structural Design Impact on Control System Performance and Sizing

Structural stiffness and damping characteristics are crucial to control system design. Early attention must be given to configuration options (e.g., nonrotating cruciform solar array, increased integral damping design of structural members) that increase modal frequencies and damping. External environment torques depend on mass and area distributions and, in turn, drive control system momentum storage and propellant requirements. These control requirements are equally sensitive to space station commanded attitude and must be considered in the earliest trades of structural configurations and operational attitude.

3.6.1.3 Sensor and Actuator Sizing, Location, Adaptability to Growth

Actuator sizing requires predictions of disturbance source magnitudes and trades of levels of redundancy versus feasibility of replacement. Actuator size is further affected by strategies selected to accommodate maximum station growth (centralized versus distributed, full size at start versus incremental additions). Distributed sensors and actuators should also be evaluated in techniques for improved modal sensing and compensation.

3.6.2 Requirements

While it is too early to specify precise values for space station stabilization and orientation requirements, the functions required of the space station ACS (attitude control system) may be qualitatively described as follows:

The ACS shall ensure stability of space station attitude control in the presence of—

a. External and internal disturbances.
b. Large changes in magnitude and distribution of mass and inertias.
c. Low frequence structural modes which may be densely packed and whose shapes and frequencies are variable and imperfectly defined.

The ACS shall support precision pointing and rate stabilization requirements of—

a. Earth observation instruments.
b. Solar and astronomical observations.
c. Scientific experiments.
d. Industrial processes.

The pointing requirements of these potential space station payloads were reviewed and found to vary from the arc minute level to subarcsecond level. Some representative values are listed in table 3.6-1. The 20 microradian (4 arcsecond) resolution for Earth observation instruments corresponds to 10-meter resolution at 500 km altitude. Finer resolutions are considered in the military range and are out of scope for this study. It seems reasonable to assume that this several (4) arcsecond level represents the tightest pointing requirements that will be assigned to the space station itself. That the requirement may be difficult to satisfy is indicated in the discussion which follows on disturbance sources and their probable impact. An additional assumption regarding space

Table 3.6-1. Payload Pointing Requirements

Instrument	Angular Resolutions	
	Microradians	Arcseconds
Very Long Base Interferometry	—	150
Synthetic Aperture Radar	—	70
Multi-Spectral Scanner	150 to 20	30 to 4
Earth Observation Cameras	to 20	to 4
Planetary and Stellar Observation	5	1

station pointing requirements should be noted. The requirements apply in the presence of some (but not all) external and internal sources. Large disturbances (orbiter docking, module transfers, construction, and assembly activities) occur relatively infrequently, therefore, precision pointing is not appropriate during such periods. Moderate to small disturbances arise from crew and other activities, which should not normally be constrained for the sake of assisting the ACS to perform its pointing and stabilization function. Pointing requirements should be met in the presence of these moderate disturbances.

3.6.3 Disturbance Sources, Their Magnitude and Impact, and the Effectiveness of a Low Bandwidth Controller in Counteracting Them

Sources of space station attitude disturbance have been identified and the magnitude of their impacts have been computed (see the equivalent momentum disturbance values listed in column 3 of table 3.6-2). For most of the sources listed, the torque disturbance acts over a short period compared to the controller response time so that the disturbance appears as a torque impulse (or momentum disturbance) resulting in a step change in momentum. The environmental torques conversely vary quite slowly. Their associated momentum values represent the maximum impulse to be stored during one half orbit period due to cyclic environmental torques.

Calculation and analysis of disturbance impact was prepared relative to a specific reference space station, namely, Operational SOC (and derivative configurations). Operational SOC (configuration 1) is shown in figures 3.6-1 and 3.6-2. It has a mass of 145,000 kg and a pitch moment of inertia of 20,000,000 kg-m^2. Configuration 2 is the operational SOC with a docked orbiter (figure 3.6-3). Configuration 3 (figure 3.6-4) illustrates a

Table 3.6-2

Disturbance Source	Characteristics (and Assumed) Values	Corresponding Disturbance Momentum
External Disturbances		
Orbiter Docking	Orbiter nominal approach: Linear velocity - 0.015 m/s Angular rate - 0.2 deg/s Space Station C.G. offset 1.0 m Orbiter Mass 84,000 kg	1,260 N m s 34,900 N m s
Environmental Torques Aerodynamic, Gravity Gradient, Solar Pressure	Generic Space Station: Values of torque disturbances are extremely dependent on Space Station configuration and orientation requirements. Operational SOC Combined environmental disturbance torques for earth oriented SOC at 400 km altitude: Roll - 4.1 N m (cyclic) Pitch - 10.4 N m (secular) Yaw - 0.5 N m (cyclic)	7,250 N m s 880 N m s
Internal Disturbances		
Module Transfer from Orbiter payload bay to Space Station berthing port	Habitat module transfer Mass 20,000 kg Transfer rate 0.1 m/s Transfer path offset 10 m from C.G.	20,000 N m s

Table 3.6-2 (Continued)

Disturbance Source	Characteristics (and Assumed) Values	Corresponding Disturbance Momentum
Liquid Transfer	OTV fuel transfer Mass 30,000 kg Transfer time 4 hr Transfer distance 10 m Transfer path offset 10 m from C.G.	200 N ms
	Pumped cooling loop Mass 200 kg Flow rate 1 m/s Supply/return 0.5 m pipe separation	100 N m s
Rotating Equipment	CELSS Centrifuge 4 ft long by 8 ft diameter drum: operating at 1/2 g operating at 1 g	 330 N m s 470 N m s
Rotating Equipment	Medical Centrifuge 25 lb, 20,000 rpm wheel	800 N m s
Crew Activity	Push off and free flight inside work space or habitat module: Crew member mass 100 kg Free flight velocity 0.4 m/s Flight path offset 10 m from station C.G.	400 N m s

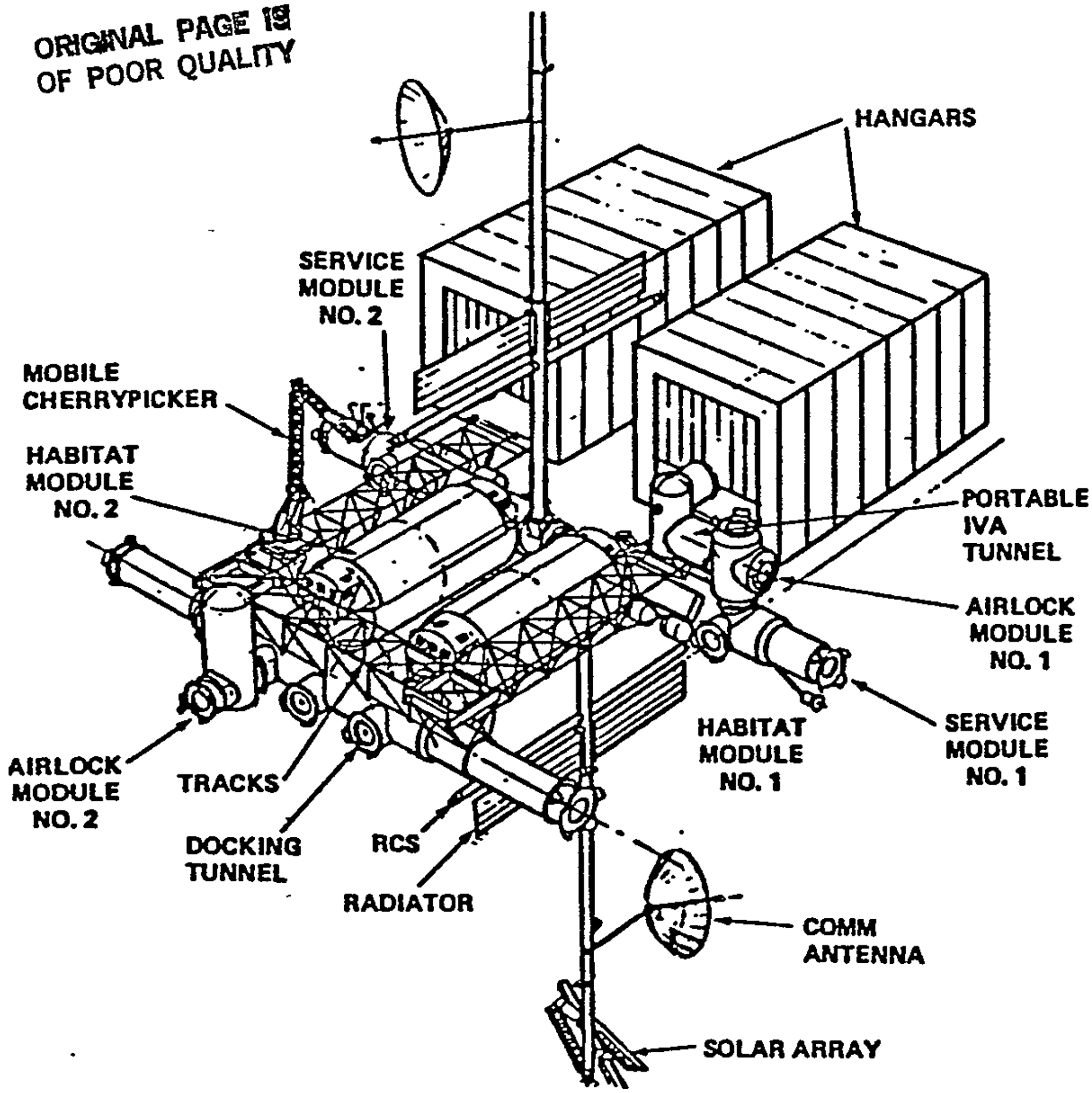


Figure 3.6-1. Operational SOC Configuration

possible extension of operational SOC that would have very low frequency structural modes. The modes for all three configurations have been computed and are indicated in figure 3.6-5. In configurations 1 and 2, the twelve modes below 1 Hz are associated with the solar array and its supporting mast, the lowest frequency being 0.04 Hz. A low bandwidth controller for this SOC configuration might have a passband limited to 0.01 Hz.

3.6.3.1 Discussion of Assumptions and Disturbance Magnitude Calculations

Orbiter Docking. The nominal rate control capability for the orbiter during docking approach is 0.015 m/s and 0.2 deg/sec. At its nominal angular rate, the orbiter angular momentum would be approximately 35,000 Newton meter seconds. This momentum disturbance is large compared to the storage capacity (3,100 N m s) of current large CMG's and shows that the RCS (reaction control system) should be used to re-establish

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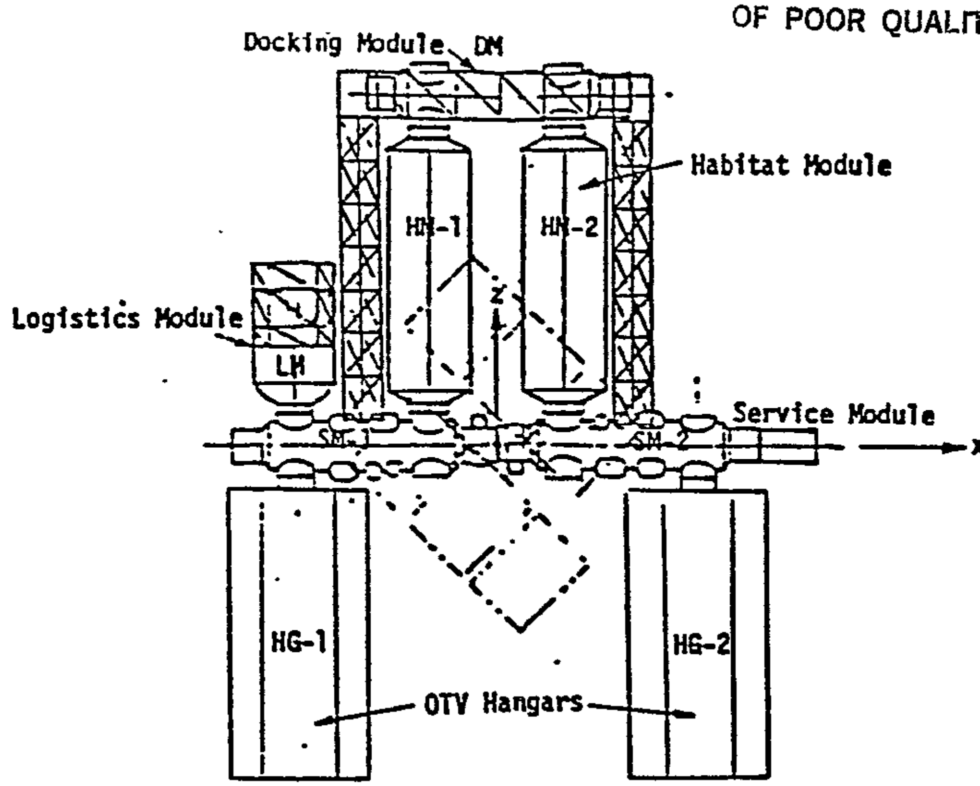

Figure 3.6-2. SOC Configuration 1

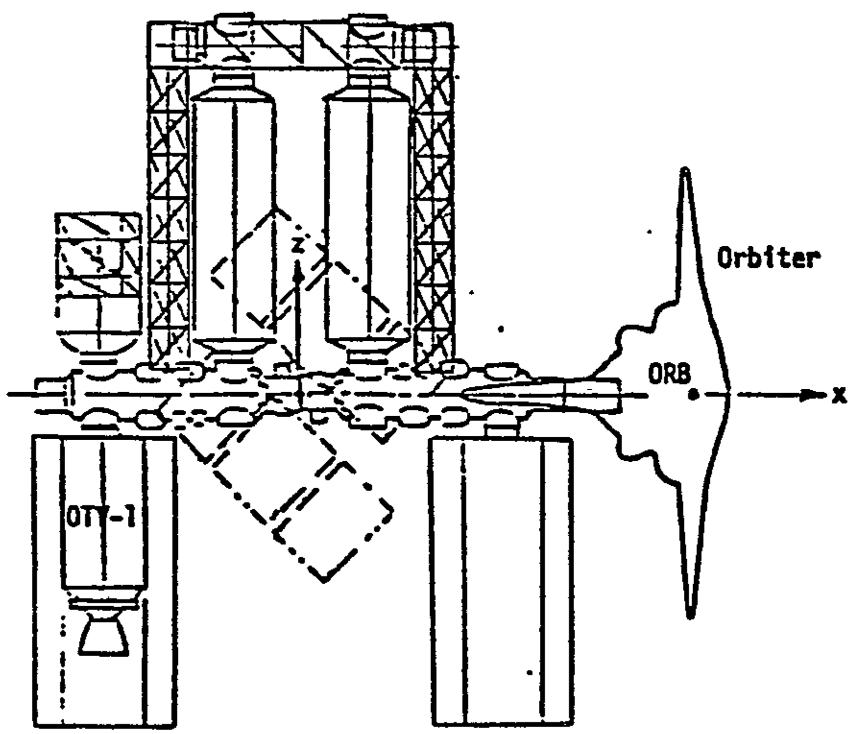

Figure 3.6-3. SOC Configuration 2

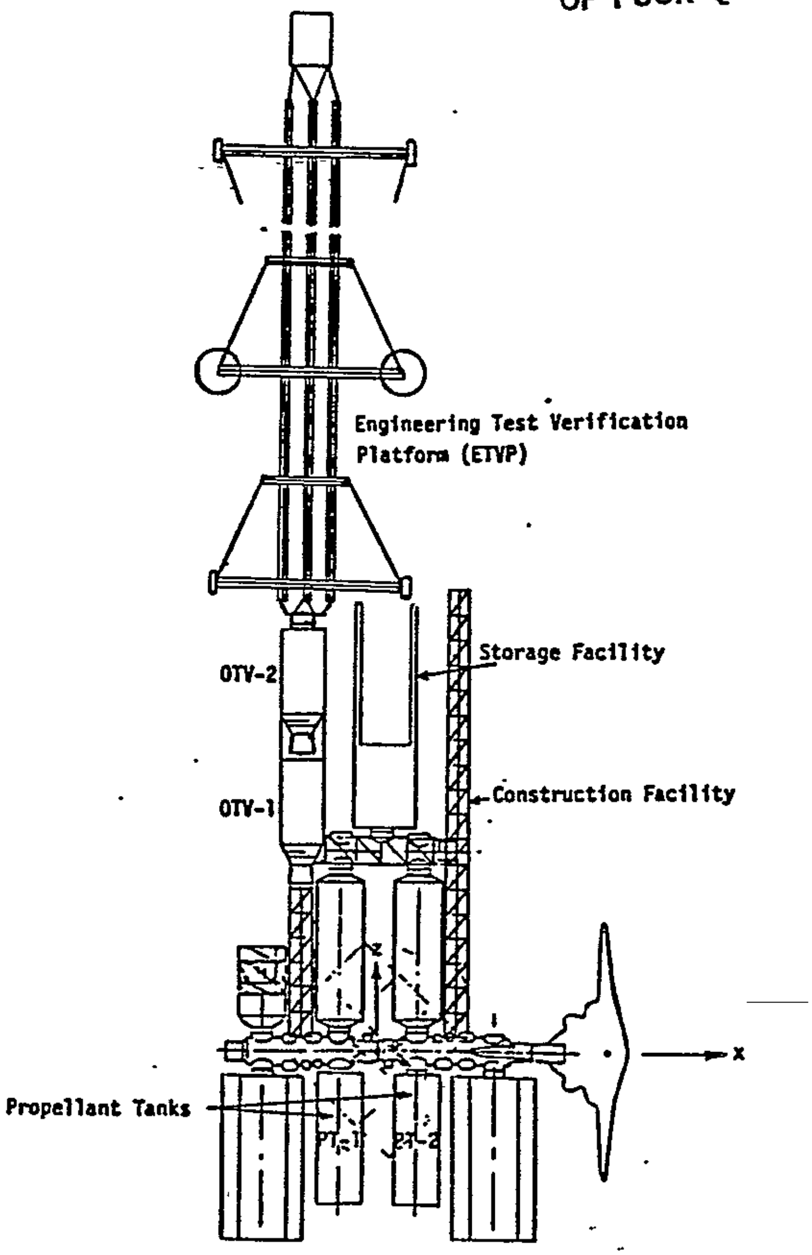

Figure 3.6-4. SOC Configuration 3

space station attitude following docking disturbances. The momentum disturbance due to the linear approach velocities is relatively small so long as the docking port and approach velocity are aligned within a few meters of the space station center of mass.

Environmental Torques. The torques due to solar pressure, gravity gradient, and aerodynamic effects depend directly on configuration (area distribution, inertia ratios). Examples of torque values for a specific configuration are listed in tables 3.6-3 and 3.6-4. At one point in a 400 km orbit, the net roll torque for Operational SOC (table 3.6-3) was 17.4 Newton meters at the attitude that maximized torque disturbance in that axis.

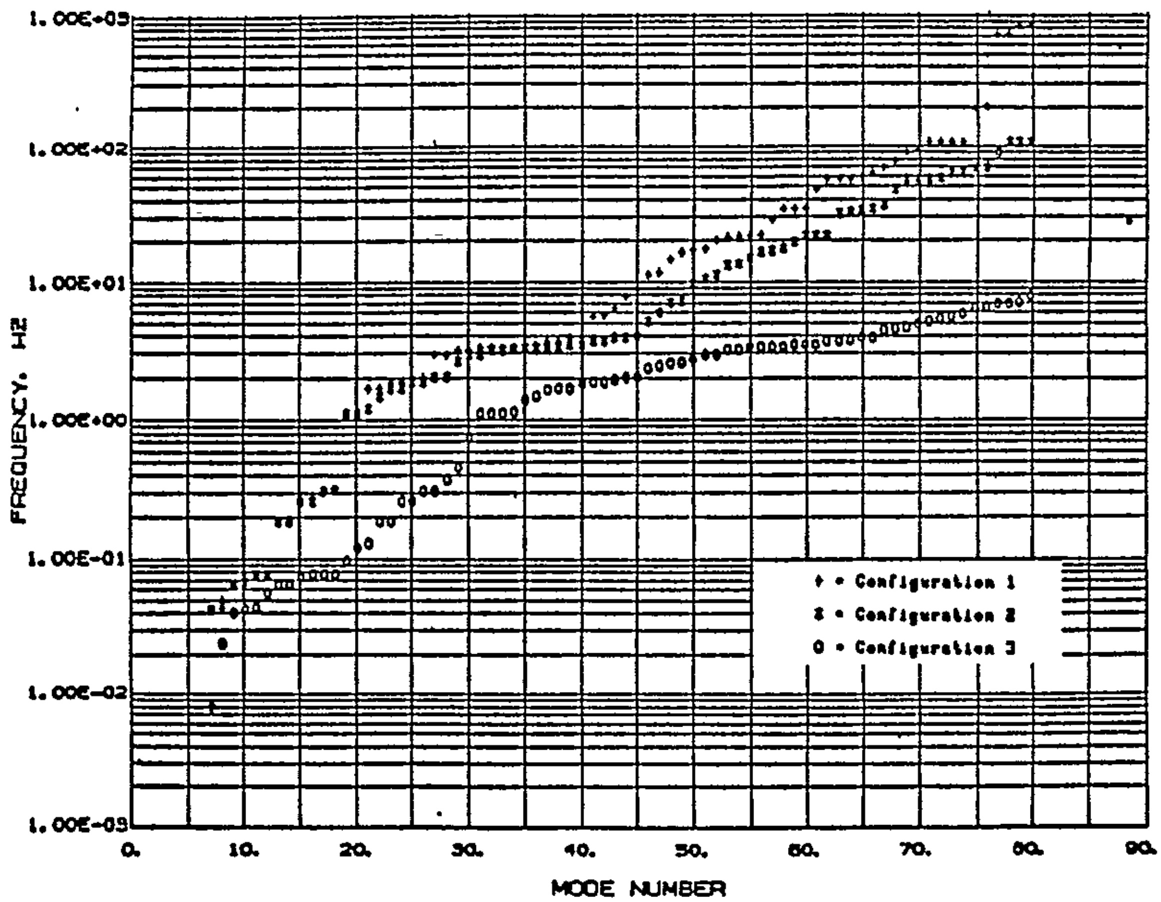

Figure 3.6-5. Modal Frequency — Configurations 1 — 3

Table 3.6-3. Operational SOC — Torque, Momentum and Propellant Requirements

ALTITUDE, KM	AXIS	DISTURBANCE TORQUES		CMG IMPULSE REQUIREMENT IN ORBITAL ATTITUDE HOLD, N – M – SEC	90 DAY PROPELLANT CONSUMPTION	
		WORST CASE ATTITUDE, N – M	ORBITAL ATTITUDE, N – M		ORBITAL ATTITUDE HOLD, KG	ALTITUDE MAINTENANCE, KG
300	ROLL	59.7	10.2			
	PITCH	47.3	40.7			
	YAW	10.0	0.6			
400	ROLL	17.4	4.1	7,250		
	PITCH	12.0	10.4		3,740	1,890
	YAW	8.1	0.5	880		
500	ROLL	9.2	2.8	4,950		
	PITCH	4.1	3.6		1,300	1,010
	YAW	7.4	0.5	880		

Table 3.6-4. Initial SOC — Disturbance Torques and Propellant Consumption

ALTITUDE, KM	ANS	DISTURBANCE TORQUES		90 DAY PROPELLANT CONSUMPTION	
		WORST CAST ATTITUDE, N – M	ORBITAL ATTITUDE, N – M	ORBITAL ATTITUDE HOLD, KG	ALTITUDE MAINTENANCE (± 10 KM), KG
300	ROLL	-76.8	30.6		
	PITCH	-28.1	14 5		
	YAW	152.5	151.9		
400	ROLL	-19.0	7.6		
	PITCH	-7.6	3.9	1,400	950
	YAW	37.6	37.0		
500	ROLL	-6.1	2.6		
	PITCH	-3.0	0.9	320	560
	YAW	11.9	11.3		

Aligning the SOC axes with orbit coordinates (LV/LH - local vertical/local horizontal) reduced the roll torque to 4.1 Newton meters. If this value remained constant around the orbit, the net momentum accumulated (by a CMG controller) would be zero, but the peak accumulated value would be 7,250 Newton meter seconds at the end of one-half orbit. Unlike the roll and yaw axis, the pitch axis torque (10.4 N m) is secular rather than cyclic, and the accumulated momentum must be countered by RCS thrusters. Assuming thrusters on 10-meter arms and specific impulse of 220 sec, a constant disturbance of 10.4 Newton meters would require expulsion of 3,740 kg of propellant in a 90-day period, an amount in excess of the altitude maintenance requirement. This pitch attitude is not the minimum disturbance attitude, nor does the SOC configuration represent any attempt to minimize torque disturbances. This is particularly evident in the case of Initial SOC (table 3.6-4), where a single (unbalanced) solar array produces very large yaw moments (see figure 3.6-6).

Module Transfer. An example of a potentially large internal disturbance source is the transfer of a module from the docked orbiter across the space station towards its berthing location. If a 20,000 kg habitat module is moved at 10 cm/sec along a path offset 10 meters from the station center of mass, its angular momentum of 20,000 Newton meter seconds exceeds probable CMG storage capacity and would have to be supplied by RCS propellant expulsion. Slower transfer rates wold reduce the momentum requirements, but for most module transfer and space station construction activities, use of the reaction control system would probably be required.

Liquid Transfer. If an OTV (orbit transfer vehicle) fuel tank is filled in four hours by pumping 30,000 kg of fuel a distance of 10 meters along a path offset from the station

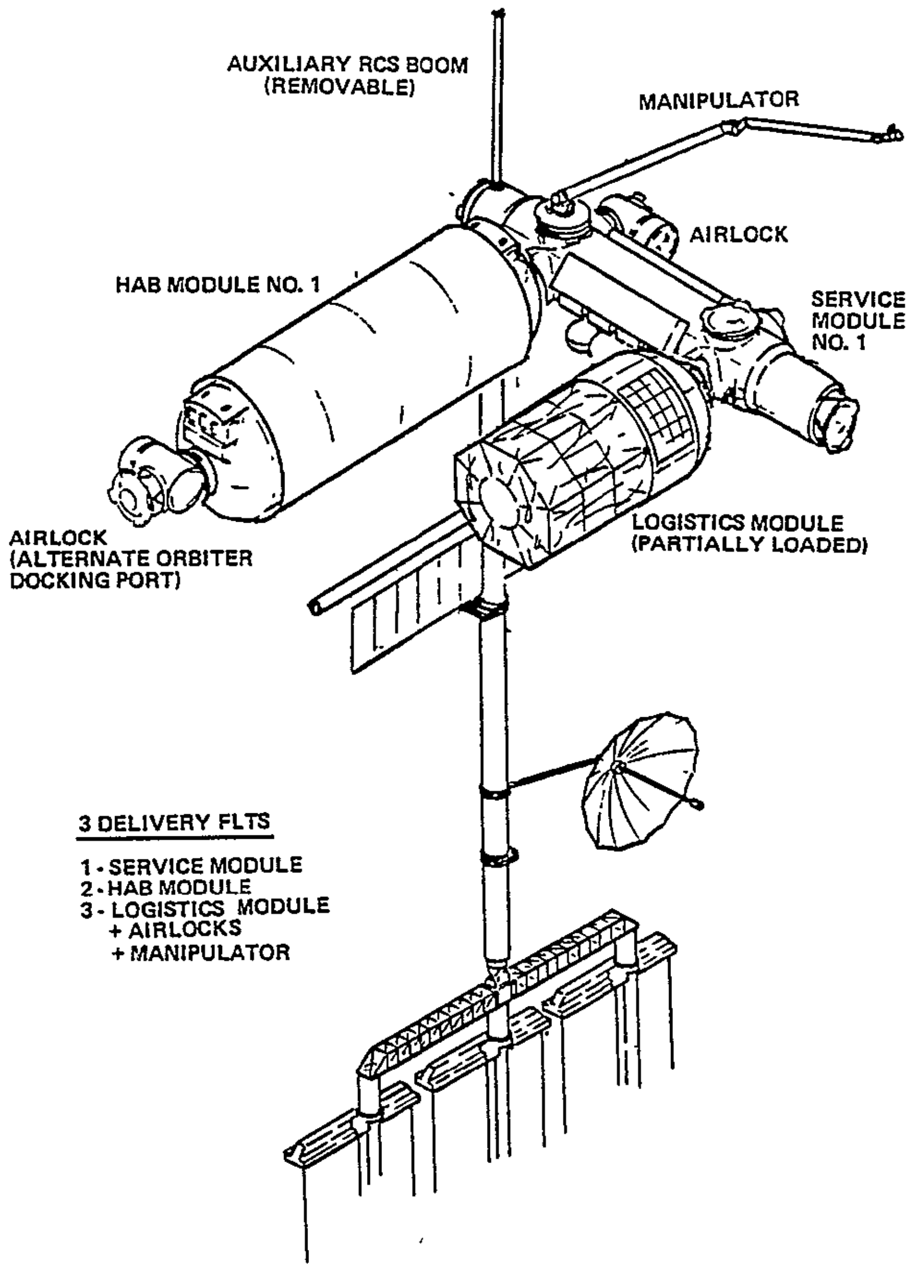

Figure 3.6-6. Initial SOC Configuration

center of mass by 10 meters, the resulting momentum disturbance is approximately 200 Newton meter seconds. At any practical pumping rate, the corresponding momentum would be within the storage capacity of a single CMG. Similarly a pumped cooling loop for a 100 kW power system will store only a relatively small angular momentum. Assuming the supply and return pipes can be mounted no more than 50 cm apart, the stored momentum would be 100 Newton meter seconds.

Rotating Equipment. A set of CELSS (Controlled Ecological Life Support System) centrifuges can be arranged with equal numbers rotating in opposite directions, so that the net stored momentum need be no greater than that associated with the starting and stopping of a single centrifuge. In the design example cited in table 3.6-2, a centrifuge operating up to 1 g would produce a momentum disturbance of less than 500 Newton meter seconds. A medical centrifuge, while small, can create a significant momentum disturbance (800 Newton meter seconds) because of its high angular velocity.

Crew Activity. A crew member moving from one location to another will acquire momentum from the space station by pushing off from the module wall, and at the end of a free flight distance will exert a decelerating force which returns the borrowed momentum. For simulation purposes, the time history of a typical push-off force is modeled (by P. Nicaise of MSFC) as a force ramp rising from zero to 100 Newtons in 0.8 sec and then dropping to zero immediately as contact is lost and free flight begins. Similarly the landing force is represented as rising immediately on contact to a peak of 100 Newtons and then decreasing linearly to zero in 0.8 sec. It is interesting to examine the effect this 40 Newton second impulse would produce on a space station assuming no control system intervention. Again, assuming the forces and flight path are offset from the station center of mass by 10 meters, the 40 Newton second impulse would produce a momentum exchange of 400 Newton meter seconds between crew member and space station. Assuming station inertia of 20 million Newton meter seconds square, the station would acquire an angular velocity of 20 microradians per second (approximately 4 arc-seconds per second). The total angular deflection of the space station would depend on the available free-flight path length as indicated in figure 3.6-7. The 40 Newton second impulse would produce free-flight velocities inversely proportional to the crew member's mass. A 100 kg crew member would traverse the entire length of a 10-meter module in 25 seconds and the total station deflection would reach 100 arcseconds. It should be noted that if the attitude control system bandwidth were as low as 0.01 Hz, the control system response would be too slow to arrest the space station's angular velocity. In general the disturbances due to crew activity will be at frequencies extending from near to well beyond the effective bandwidth of a low bandwidth controller; the resulting space station pointing error would be as shown in figure 3.6-7.

3.6.3.2 Prediction of Low Bandwidth Controller Effectiveness

Space Station Pointing Error as a Function of Controller Bandwidth. Computation of the pointing errors resulting from environmental torques requires a fairly detailed simulation. It can be noted that these torques vary slowly along the orbit path (periods of several hundred seconds), and, therefore, a controller bandwidth of 0.01 Hz or lower may be effective in maintaining pointing accuracy in the presence of environmental disturbance torques.

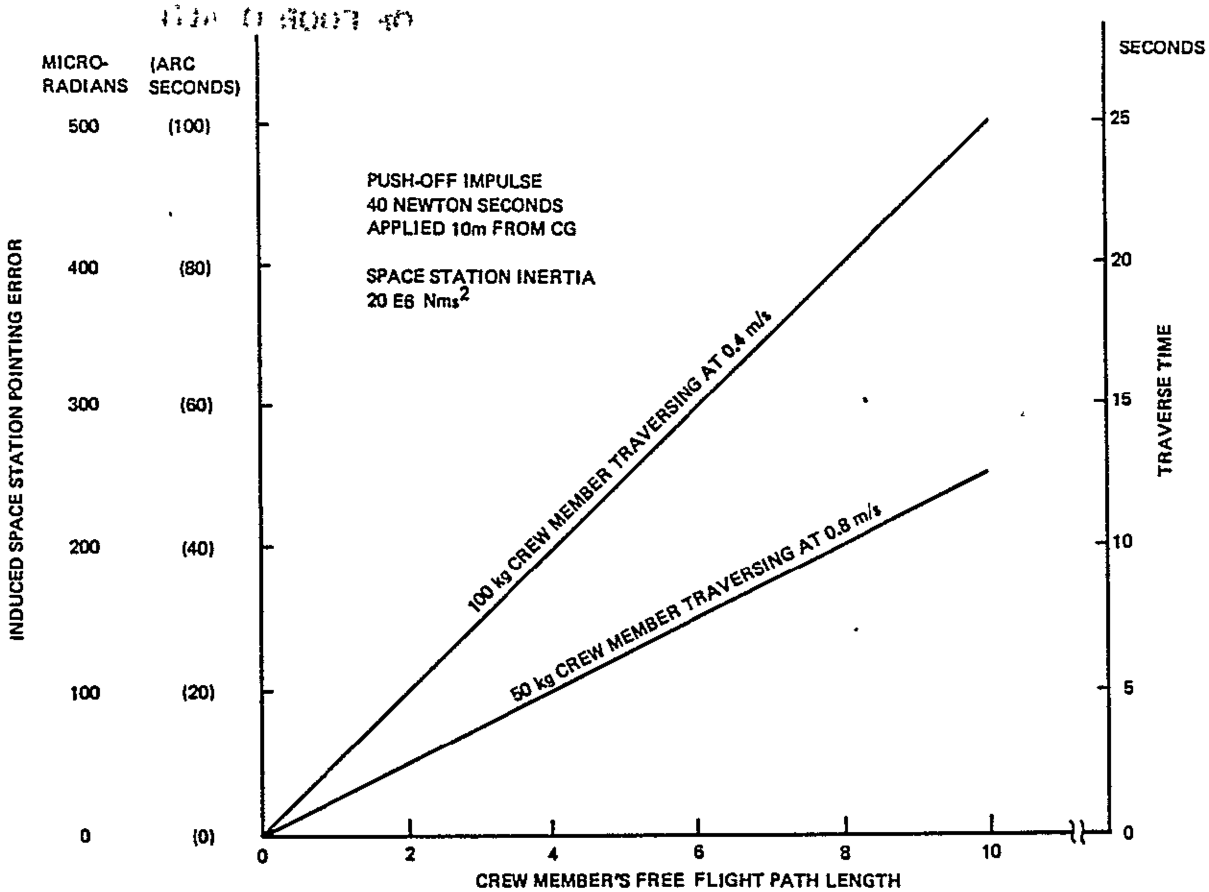

Figure 3.6-7. Space Station (Uncontrolled) Pointing Error in Response to Crew Member Pushing Off and Traversing Module Interior

The impact of the remaining moderate disturbance (impulses of 1000 N ms or less) sources listed in table 3.6-2 can be predicted by analysis. The space station response to torque impulses (step disturbance in momentum) was computed by representing the controller as a simple second order angular position controller with a bandwidth of W. Figure 3.6-8 shows the peak attitude error as a function of momentum disturbance magnitude and was computed for the case of W = 0.01 Hz. A disturbance of 400 N m s for example would produce a deflection of 36 arcseconds before the 0.01 Hz controller could bring the angular error rate to zero. The same disturbance would have greater effect on a smaller space station and lesser effect on a station with greater inertia (W = 0.01 Hz in each case). The effect of increasing the controller bandwidth was computed (for the case of spacecraft inertia equal to 20E6 kg m^2) and results for two levels of disturbance (400 N m s and 1000 N m s) are plotted in figure 3.6-9. Also indicated in figure 3.6-9 are the values of the first six modal frequencies for the operational SOC configuration. The significant result shown is that in order to limit errors produced by moderate disturbances to less than 10 arcseconds, controller bandwidths of 0.1 Hz or higher may be required, and such a passband will likely include many structural mode frequencies. This illustrates the issue of conflicting requirements on controller bandwidth (pointing accuracy vs. stability of structural modes).

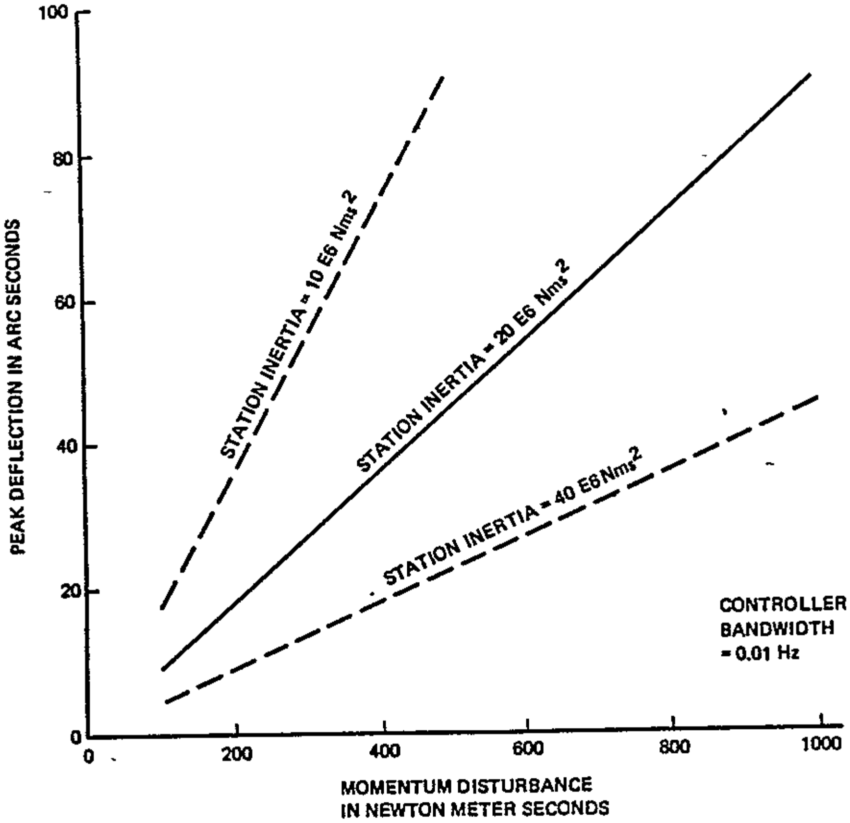

Figure 3.6-8. Space Station Deflection Versus Momentum Disturbance Magnitude

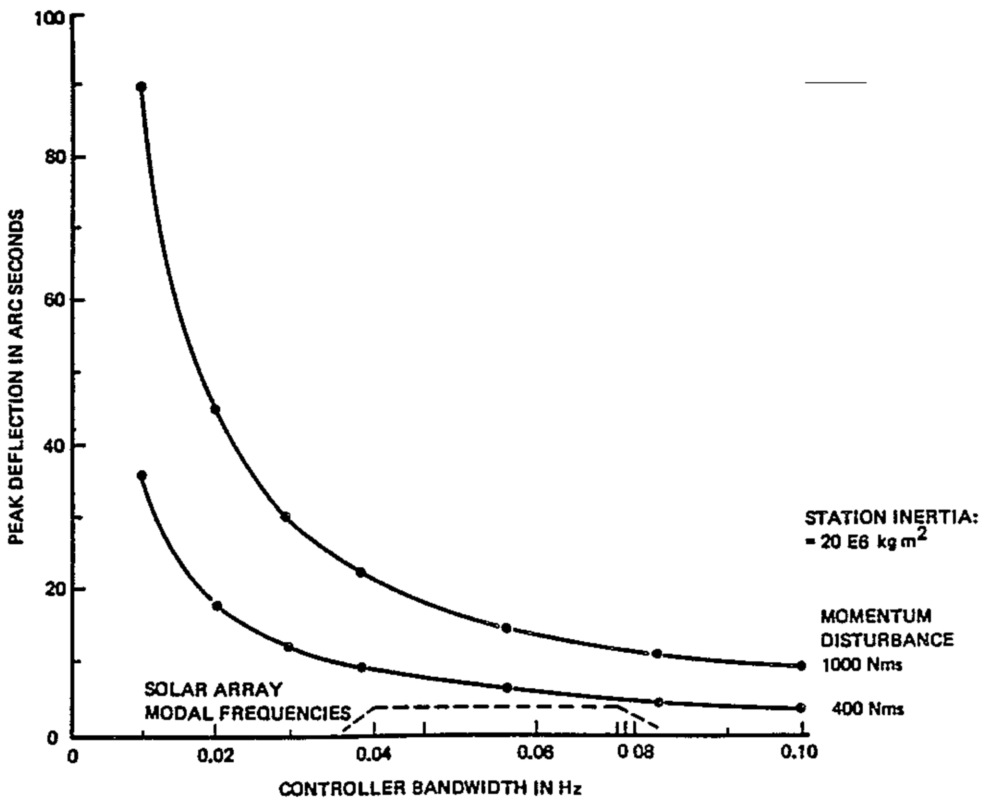

Figure 3.6-9. Space Station Deflection (In Response to Momentum Disturbance)

In summary, depending on developments in space station structural stiffness and damping, a low bandwidth controller will be one with passband limited to 0.1 Hz, and more likely, as low as 0.01 Hz. Such a controller is well suited to control of slowly varying environmental torques but cannot by itself maintain space station pointing to 10 arcseconds or better in the presence of the kinds of moderate disturbances that must be anticipated in a manned station.

3.6.4 Characterization of Technology Options

The space station controller design challenge is to provide effectively rapid controller response to disturbances (high bandwidth) and still maintain stable, well-damped control of low-frequency structural modes. To accomplish this will require the development of one or more of the following technology options:

a. Develop structural design approaches to increase stiffness (raise modal frequencies) and damping; develop module interconnections that attenuate modal deflections.

b. Active control of structural modes via centralized or distributed effectors and sensors, and adaptive control techniques to provide robustness with respect to knowledge and variability of modal characteristics.

c. Isolation of payload modules from main space station rigid modes and low-frequency structural modes by mechanical isolation and by separation of controllers' functions:
   1. Apply low bandwidth controller to main station.
   2. locate payloads on an isolating mount separately stabilized with a higher bandwidth controller.

A three-axes mount for an individual instrument is one example of option 3, but consideration should be given to locating many instruments and experiments in a single isolated module.

3.6.5 Technology Advancement Recommendations

Each of the technology options listed above should be pursued. Option 3 would benefit from mechanical isolation techniques developed in option 1. Detailed study will be required before relative merits of the different options can be identified. Because advanced techniques for payload pointing and stabilization may include the application of a low bandwidth controller for the main station structure, it is recommended that an early start on a study of the low bandwidth controller application be given high priority.

4.0 TECHNOLOGY SELECTION

This section presents the rank ordering of the eight technologies suggested for advancement as a result of this study and provides the compilation of cost benefits ratios along with supporting discussion. Table 4.0-1 lists the eight technology items according to the technology areas.

4.1 COST BENEFITS

This section discusses the ratio of estimated cost of advancing each technology for use on the manned space station against the estimated value of the benefits to be obtained from the technology. Each of the eight technology items will be discussed from the cost benefits point of view in sections 4.1.1 through 4.1.8. A ranking comparison of the cost benefits ratios of all eight will be made in section 4.1.9.

4.1.1 Cost Benefits of Local Area Network Architecture Development

The cost of developing a local area network architecture has been estimated using the RCA price model. This estimate is reported in section 3.2.4 of this volume as $64M.

The benefit value for this technology is based on the difference between the cost of developing the interconnecting network architecture versus the cost of developing the same function using nonstandard subsystems. This cost of developing the function using nonstandard subsystems is also reported in section 3.2.4 as $240M. The difference then is $176M giving a cost benefit ratio of 64/176 or 0.36. Other significant benefits of using the local area network architecture have been identified in section 3.2, but quantification of these has not been estimated for this study, and the interaction with other subsystems makes accounting of those benefits unclear.

4.1.2 Cost Benefits, Pigtailed Hermetic Sources and Detectors

The estimated cost of the Pigtailed Hermetic Sources and Detectors development program ranges between $300K and $500K as stated in section 3.3.6.1. The principal benefits from this program result from improved reliability of the hermetic pigtailed devices compared to nonhermetic units. Since optical sources have about an order of magnitude higher failure rate than detectors, the source failure rate predominates. Consequently, the following benefits example is based on LED optical sources only.

Table 4.0-1. Technology Advancement Items

DATA ARCHITECTURE

- o Local area network architecture development.

DATA BUS

- o Hermetic pigtail device development for fiber optics.
- o Integrated circuit development for fiber optic transmitters and receivers.

LONG-LIFE THERMAL MANAGEMENT

- o Thermal storage for a pumped liquid heat transport system.
- o Thermal storage for a two-phased heat transport system.
- o Fluid coupling concept for steerable radiators.

AUTOMATED HOUSEKEEPING SUBSYSTEMS

- o Ammonia and TOC sensor development for EC/LSS.
- o Expert system application for integration management of automated housekeeping.

In section 3.3, the graph data network was identified as the most suitable approach to meet the advanced platform data communications requirements. Table 3.3.4-1 shows that the station configuration used for comparative purposes required 2050 fiber optic transmitter-receiver units. Based on continuous operation of the data network, the 2050 optical sources would accumulate a total of almost 18 million operating hours in a year. Assuming hermetic device, spontaneous light-emitting diode failure rate to be one failure per million hours, this would result in 18 failures per year. Nonhermetic devices would have a failure rate ranging from about one failure per 100,000 hours to one per 500,000 hours. This would result in from 36 to 180 failures per year for nonhermetic LED's. Using the lowest failure rate to be conservative would result in a cost differential of about $62,000 per year in system repair cost alone. This assumes that each failure would require about one hour to restore operation of the failed link, $77,000 per man day for man in space, and replacement cost for the LED of $250. This assumes reducing the failure rate from 36 per year to the hermetic device rate of 18 per year. At the 180 failures per year rate, the reduced cost would be more than $560,000 per year.

Based on a $500K development program cost, and on the most conservative failure rate, program costs would be recovered in slightly over 8 years as a result of reduced maintenance alone. At the 180 failures per year rate, program costs would be recovered in less than a year. Based on a midrange benefit figure, the cost benefits ratio for a ten year mission would be 500K/3110K = 0.160.

Nonpigtailed hermetic devices could be used to achieve the improvements in reliability cited for the pigtailed units. However, this results in compromise of system optical power margin since optical coupling losses for the windowed hermetic packages are typically 6 to 10 dB worse than pigtailed devices. This results in the need to increase transmitter power or receiver sensitivity to maintain the desired optical signal margin. If this is not done, then allowances for radiation damage must be decreased.

These benefits are subjective and difficult to quantify until detailed system definition work is completed. However, assuming that LED ratings would allow, increasing device optical output power to compensate for increased coupling loss would increase the electrical power requirements of the system. It is estimated that increasing transmitter output by 6 dB would increase required electrical power by about one watt per transmitter. Thus, the increase would be over 2000 watts for the station. Launch costs for electrical power are estimated to be 100 pounds per kilowatt and $718 per pound. This translates to a launch cost of $143,600 in order to maintain optical link margins using nonpigtailed devices.

4.1.3 Cost Benefits, Integrated Circuit Transmitter-Receiver Development Program

The estimated development program costs for the Integrated Circuit Transmitter-Receiver development program were estimated by the RCA price hardware development model to be $7,272,000. Nominal development cost range is $6,665,000 to $8,026,000.

Benefits to the program accrue as a result of a number of factors. The most significant are the development and production costs of the required units themselves and the launch weight saving for the integrated version compared to a discrete version. Improved reliability and reduced power consumption are also of importance but difficult to quantify at this time.

The RCA price hardware cost model was used to develop pricing for both discrete component and integrated versions of the transmitter-receiver units required for the fiber optic data networks for the advanced platform. It was assumed that the links will be point-to-point links making up a graph structured data network. As before, a total of 2050 transmitter-receiver units are assumed to be required. Based on the development and production costs obtained from the RCA model, for the two versions, a cost saving of

$17,748,000 would result from use of the integrated circuit version. This is the result of combining development and production costs for both versions and taking the difference in the totals. Thus, the saving to the advanced platform program would be about almost 2-1/2 times the development cost without considering other benefits that will result or a cost-benefits ratio of 0.4.

The integrated circuit version of the transmitter-receiver was assumed to weigh 0.6 pounds each when packaged for use. The discrete version was assumed to weigh three pounds. The launch weight saving would amount to $3,500,000 based on use of 2050 units and the $718 per pound launch cost.

Combined cost savings to the program from application of the integrated circuit version would be about $21,250,000 as a result of the development, production, and launch weight alone. Increased production quantity for spares, ground laboratories, etc., would increase the savings. Subsequent launch cost saving for in-orbit replacement of failed units would also result.

It is estimated that the integrated circuit version would have less than one-fourth the parts count of the discrete/LSI/MSI version. Reliability would be significantly improved by this reduction. Projection of expected failure rate for either version of the transmitter-receiver is beyond the scope of the current effort. Consequently, determination of a quantitative dollar benefit is not possible at this time. However, assuming a failure rate proportional to parts count of two failures per year for the discrete/LSI/MSI and one manhour to isolate and repair the failure, the savings would amount to about $29,000 per year. At the low failure rates assumed, the cost savings are not significant.

4.1.4 Cost Benefits of Developing Thermal Storage for a Pumped Liquid Heat Transport System

Based on comparison with similar development efforts the cost of advancing the thermal storage concepts for a pumped liquid heat transport system is estimated at $.8M.

The value of the benefits obtained from such an advancement is determined by the reduction in the size for a fixed radiator when a thermal storage system is used. Based on the data presented on table 3.4-1 of this report, the radiator could be reduced by 10,800 lb or in area by 10790 ft^2 if thermal storage is used. This results in a $7.75M savings in launch cost and a $2.77M saving in astronaut assembly time. These numbers are based on $718 per pound of shuttle weight and 80 astronaut hours to assemble 1000 square feet of radiator at $3208 per hour. The cost benefits ratio then is 0.8/10.52 = 0.076.

4.1.5 Cost Benefits of Developing Thermal Storage for a Two-Phased Heat Transport System

Again, based on comparison data for similar developments, the cost of advancing the thermal storage concept for a two-phased heat transport system is estimated at $1.2M.

The benefit value is the same as that calculated above for the pumped liquid heat transport thermal storage or $10.52M. The cost benefits ratio then is 1.2/10.52 = 0.114.

4.1.6 Cost Benefits of Developing a Fluid Coupling Concept for Steerable Radiators

The fluid coupling development constitutes an estimated 80 percent of the $2M estimated for development of steerable radiators under section 3.4.6 of this report. This gives a development cost of $1.6M.

The benefits values again are calculated based on saving of radiator size when the steerable concept is used. Based on data in table 3.4-1, the area of the radiator can be reduced by 8230 ft^2 and the weight by 9870 lb using the $718 per pound of shuttle payload and $275K for astronaut time to assemble 1000 square feet of radiator panels. These calculations give a savings of $7.09M in shuttle cost and $2.11M savings in astronaut costs for a total benefit of $2.9M. The cost benefits ratio is then 1.6/(9.2x.8) = 0.22.

4.1.7 Cost Benefits of Ammonia and TOC Sensor Development for EC/LSS

Two aspects of development are considered in costing the advancement of the ammonia and TOC sensor technologies. First, the materials and concept development of the sensors themselves, and second, the refinement of the water quality monitor system which uses the sensors. Based on rather loosely defined models input to the RCA price hardware modeling programs, the cost estimate for advancing the technology for both sensors is $500K to $1M. This development would produce qualified ammonia and TOC sensors and would not be sufficient to produce an entire redesign and flight qualification of the water quality monitor system.

The benefits of the sensor development can be assessed by assuming the three-hour change-out cycle for current ammonia sensors and three-day change-out cycle of current TOC sensors versus an improvement to 10-day change-out cycle for both by the advancement.

	Current	Advanced
Cost of astronaut time for change outs*	750 changes in 90 days $2.4M/year	18 changes in 90 days $58K/year
Cost of sensors at $2K each	$6M/year	144K/year
TOTAL	$8.4M/year	$0.2M/year

* Each change assumed to require 1/4 hour for one astronaut at $800 labor cost per change.

The savings by using the advanced sensors would be $8.2M/year or $82M of a 10-year life. The cost benefit ratio then is 1/82 or 0.0122.

4.1.8 Cost Benefits of Developing an Expert System for Integration of Automated Housekeeping Functions

In order to cost the development of an expert system, it is necessary to define the size. Expert systems are usually sized in terms of the size of the knowledge base. If expert system rules are used to represent the knowledge, then, the number of rules is used as a measure of size. As an indication of the size of currently used expert systems, the R1 system, used by Digital Equipment Corporation for configuring VAX Systems, has 850 rules. Because of current limitations of computing hardware as well as the experience level of development teams in managing the complex interactions, systems with more than 2000 rules are considered impractical.

Based on an improvement in capability by the mid 1990's, at least a doubling in maximum rule size is assumed. Based on information in the following sources for maximum project team size for rule development today is five persons and the minimum rule development rate is one per day.

Sources:

Duda and Gasching	"Knowledge Based Expert Systems Come of Age," Byte, Sept. 1981, pp. 238.
Davis	"Expert Systems: Where Are We? Where Do We Go From Here?" AI Magazine, Spring 1982, pp. 34.
Anon	Teknowledge, Teknowledge, Inc., n.d.

With these factors in mind, the production of an expert system with 4000 rules would take 20,000 man/days at an estimated cost of \$4.4M. Assuming a doubling of that number to cover verification, validation and systems integration gives \$9M for the system cost.

To assess the benefits of advancing the expert systems concept to implement automation of the regenerative EC/LSS and to integrate automation of the space station housekeeping refer to the form 3A on integration of housekeeping functions in section 5 of volume III. On that form it is estimated that use of a regenerative EC/LSS on the space station, without automation, would cost \$45.9M per year, but by automating the regenerative EC/LSS and integrating the automation of the housekeeping, the operating cost could be reduced to \$27.5M per year. The savings then would be \$18.4M per year. The portion of this that could be attributed to the expert system would be substantial, but, assuming 50 percent, a 10-year savings of \$92M from the advancement is possible.

The cost benefits ratio for advancing expert systems to be used for integrating automated housekeeping on the space station then is 9/92 or 0.098.

4.2 RANKING OF SUGGESTED TECHNOLOGY ADVANCEMENTS BY COST BENEFIT RATIOS

Table 4.2-1 gives the ranking of the technology advancements considered above according to the computed ratios of estimated advancement costs over estimated values of the benefits expected from the advancements.

These rankings form a portion of the rationale for selecting top priority technology advancement candidates because they will establish rank positions that will be changed only by schedule, total development cost, or unquantified considerations.

Table 4.2-1. Cost Benefits Ranking

1.	Ammonia and TOC Sensor Development	0.012
2.	Development of Thermal Storage for Pumped Fluid System	0.076
3.	Development of Expert Systems for Integrating Auto H/K	0.098
4.	Thermal Storage Development for Two-Phased System	0.110
5.	Development of Pigtailed Hermetic Sources and Detectors	0.160
6.	Fluid Coupling Development for Steerable Radiators	0.220
7.	Local Area Network Development for Data Architecture	0.360
8.	Development of Integrated Circuit Transmitter-Receivers	0.400

5.0 TECHNOLOGY RECOMMENDATIONS

The eight technologies suggested for advancement are the survivors of an elimination process which started with 106 technology areas. In order to provide a basis for discussion of the technologies in any planning process, a ranking of recommendations within the eight will be given here. The elements of this ranking are (1) the cost benefits ratios listed in section 4.2, (2) schedule urgency for the technologies to be available for a 1990's space station, (3) nonquantified benefits, and (4) those technology advancement programs with the highest price tags will be considered for lower ranking. Table 5.0-1 shows the ranking according to schedule urgency, table 5.0-2 shows a listing of nonquantified benefits, and table 5.0-3 shows a ranking according to development price tags. Cost benefits ratios are ranked in table 4.2-1.

Table 5.0-4 gives a final ranking of the eight technologies suggested for advancement. This ranking is based on a uniform weighting of each of the four elements. The selection of candidates within the group which is all recommended for advancement would be on the order shown in table 5.0-4.

Table 5.0-1. Schedule Urgency Ranking of Technology Candidates

1. Integrated Circuit Development for Fiber Optic Transmitter-Receivers —
   7 years to complete Qual testing

2. Expert System Application for Integration Management of Automated Housekeeping —
   6 years to verified software

3. Local Area Network Architecture Development —
   3 years for development to brassboard level

4 Ammonia or TOC Sensor Development for EC/LSS —
   3½ years to complete Qual testing

5 Thermal Storage for a Pumped Liquid Heat Transport System —
   3¼ years to complete module Qual testing

5 Thermal Storage for a Two-Phased Heat Transport System —
   3¼ years to complete module Qual testing

5 Fluid Coupling Concept for Steerable Radiators —
   3¼ years to complete Qual testing

6 Hermetic Pigtailed Device Development for Fiber Optics —
   3 years to complete Qual testing

Table 5.0-2. Non-Qualified Benefits of Technology Candidates

RANKING	ADVANCEMENT ITEM DEVELOPMENT	ENHANCES SAFETY	ENHANCES RELIABILITY	INCREASES LIFETIME	IMPROVES MAINTAIN-ABILITY	IMPROVES OPERATIONS	INCREASES CREW COMFORT
1	EXPERT SYSTEM FOR INTEGRATED AUTOMATED HOUSEKEEPING	X	–	–	X	X	X
2	DATA ARCHITECTURE LOCAL AREA NETWORK	–	X	–	X	X	–
3	AMMONIA AND TOC SENSOR	X	QUANTIFIED	–	–	–	X
3	PIGTAILED HERMETIC OPTICAL SOURCE AND DETECTOR	–	X	–	X	–	–
3	INTEGRATED CIRCUIT TRANSMITTER/ RECEIVER	–	X	–	X	–	–
4	THERMAL STORAGE FOR PUMPED FLUID SYSTEM	–	–	X	–	–	–
4	THERMAL STORAGE FOR TWO-PHASED SYSTEM	–	–	X	–	–	–
4	STEERABLE RADIATOR FLUID COUPLING	–	–	X	–	–	–

Table 5.0-3. Development Price Ranking of Technology Candidates

	Technology Candidate	Price $ x 10^6
1	Hermetic Pigtailed Device Development for Fiber Optics —	0.5
2	Thermal Storage for a Pumped Liquid Heat Transport System —	0.8
3	Ammonia and TOC Sensor Development for EC/LSS —	1.0
4	Thermal Storage for a Two-Phased Heat Transport System —	1.2
5	Fluid Coupling Concept for Steerable Radiators —	1.6
6	Integrated Circuit Development for Fiber Optic — Transmitter-Receivers	7.3
7	Expert System Application for Integation Management of — Automated Housekeeping	9.0
8	Local Area Network Architecture Development —	64.0

Table 5.0-4. Compilation of Rankings of Technology Candidates

Technology Candidate	Cost/ Benefits	Schedule	Non-Quantified	Price	Total
Ammonia and TOC Sensor Development	1	4	3	3	11
Development of Thermal Storage for a Pumped Fluid System	2	5	4	2	13
Development of Expert Systems for Integration Automated Housekeeping	3	2	1	7	13
Development of Hermetic Pigtailed Sources and Detectors for Fiber Optics	5	6	3	1	15
Thermal Storage Development for Two-Phased System	4	5	4	4	17
Development of Integrated Circuit for Fiber Optic Transmitter-Receivers	8	1	3	6	18
Fluid Coupling Development for Steerable Radiators	6	5	4	5	20
Local Area Network Development for Data Architecture	7	3	2	8	20