NASA Conference Publication 10044

Beyond the Baseline

Proceedings of the Space Station Evolution Symposium

Volume 1: Space Station Freedom

Part 2

Proceedings of a conference held at
South Shore Harbour Resort
and Conference Center
League City, Texas
February 6-8, 1990

NASA

Preface

This publication is a compilation of papers presented at the First Annual Space Station Evolution Symposium: Beyond the Baseline on February 6-8, 1990. The symposium focused on the presentation of results by the personnel responsible for advanced system studies and advanced development tasks within the Space Station Freedom Program. The symposium provided an opportunity for dialogue between the users, designers, and advanced planners for Station regarding the long-term utilization of Space Station Freedom.

The papers describe efforts included within the Level I Transition Definition Program to define and incorporate baseline design accommodations which satisfy the requirements associated with potential evolutionary paths, and to develop advanced technology which will enhance Space Station capabilities and enable its evolution. The papers describe work accomplished during fiscal year 1989 and were presented by those in Government, industry, and academia who performed the tasks.

This publication consists of two volumes. Volume 1 contains the results of the advanced system studies with the emphasis on reference evolution configurations, system design requirements and accommodations, and long-range technology projections. Volume 2 reports on advanced development tasks within the Transition Definition Program. Products of these tasks include: engineering fidelity demonstrations and evaluations on Station development testbeds and Shuttle-based flight experiments; detailed requirements and performance specifications which address advanced technology implementation issues; and mature applications and the tools required for the development, implementation, and support of advanced technology within the Space Station Freedom Program.

Dr. Earle K. Huckins III
Director, Space Station Freedom Engineering
Office of Space Flight
NASA Headquarters

Listed below are the persons who made this symposium possible.

COMMITTEE MEMBERS

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- Earle Huckins III
  NASA Headquarters

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- Stephen Cook
  NASA Headquarters
  Evolution Systems Studies and Analysis

- Gregg Swietek
  NASA Headquarters
  Advanced Development Program

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  NASA Langley Research Center

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Time	Topic	Presenter
Monday February 5, 1990		
6:00 p.m. - 9:00 p.m.	Registration	
Tuesday February 6, 1990		
7:30 a.m.	Registration	
8:30	OPENING SESSION	
	Welcoming Remarks	Dr. Aaron Cohen *Director, NASA Johnson Space Center*
9:00	Keynote Address	Dr. William B. Lenoir *Associate Administrator for Space Flight and Acting Associate Administrator for Space Station*
9:30	Space Station Freedom Program Overview	Mr. Richard H. Kohrs *Director, Space Station Freedom*
10:00	Break	
10:30	Human Exploration Mission Planning	Dr. Franklin D. Martin *Associate Administrator for Exploration*
11:00	Mission to Planet Earth	Dr. Shelby G. Tilford *Manager, Geostationary Observations, Mission to Planet Earth*
11:30	Space Station Freedom Evolution	Dr. Earle K. Huckins III *Director, Strategic Plans and Programs Division Office of Space Station, NASA Headquarters*
12:00 - 1:30	Lunch - Harbour Club	
1:30 - 4:30	SESSION I — EVOLUTION MISSION AND PLANNING Session Chair: Mr. E. Brian Pritchard *NASA Langley Research Center*	
	Long-range Planning for Science Utilization on Space Station	Mr. Robert C. Rhome *NASA Headquarters*
	Space Station Accommodation of Lunar/Mars Exploration Program	Mr. Lewis Peach *NASA Headquarters*
	Advanced Transporation Systems	Mr. Darrell R. Branscome *NASA Headquarters*
	Future European Manned Space Infrastructure	Mr. Jacques Collet *European Space Agency*
	Break	
	Japan's Future Space Activities	Mr. Masatoshi Saito *National Space Development Agency of Japan*
	Canadian Space Activities in the 21st Century	Mr. R. Brian Erb *Canadian Liaison Office*
	Space Station as a Technology Testbed	Dr. Judith Ambrus *NASA Headquarters*
	Life Sciences Planning for Manned Missions	Dr. Arnauld E. Nicogossian *NASA Headquarters*
1:30 - 4:30	SESSION II — TECHNOLOGY AND ADVANCED DEVELOPMENT OVERVIEW Session Chair: Mr. Gregg Swietek *NASA Headquarters*	
	Office of Aeronautics and Space Technology (OAST) Programs	Dr. Judith Ambrus *NASA Headquarters*
	OAST Systems Autonomy and Telerobotics Programs	Dr. Mel Montemerlo *NASA Headquarters*
	Office of Space Flight Advanced Development Activities	Ms. Pat Connor *NASA Headquarters*
	Space Station Freedom (SSF) Flight Telerobotic Servicer	Dr. Harry McCain *NASA Goddard Space Flight Center*
	SSF Advanced Development Program Overview	Mr. Gregg Swietek *NASA Headquarters*
5:30	Reception	
6:30	Banquet with Speaker	

Time	Topic	Presenter
Wednesday February 7, 1990		
8:30 - 12:00	SESSION III — CONFIGURATION EVOLUTION Session Chair: Mr. E. Brian Pritchard *NASA Langley Research Center*	
	Space Station Freedom Integrated Research and Development Growth	Mr. Rudy Saucillo *McDonnell Douglas, Washington, D.C.*
	Space Station Transportation Node Concepts and Analysis	Mr. William Cirillo *NASA Langley Reserach Center*
	Servicing Capability for the Evolutionary Space Station	Mr. Ted Grems *McDonnell Douglas Greenbelt, MD*
	Evolutionary Space Station Fluids Management	Mr. Steve Stevenson *NASA Lewis Research Center*
	Space Station Logistics Systems Evolution	Mr. Michael Tucker *NASA Marshall Space Flight Center*
	Space Transfer Vehicle Accommodations at Transportation Nodes	Mr. Uwe Hueter *NASA Marshall Space Flight Center*
	A Radiological Assessment of Space Nuclear Power Operations Near Space Station	Mr. Steve Stevenson *NASA Lewis Research Center*
	Platform Evolution Studies	Ms. Barbara Walton *NASA Goddard Space Flight Center*
8:30 - 12:00	SESSION IV — FLIGHT SYSTEMS AUTOMATION Session Chair: Mr. Paul Neumann *Space Station Freedom Program Office*	
	Autonomous Power Management and Distribution (PMAD)	Mr. Jim Dolce / Mr. Gale Sundberg / Mr. Jim Kish *NASA Lewis Research Center*
	Laboratory/Habitation Module PMAD Automation	Mr. Bryan Walls *NASA Marshall Space Flight Center*
	Environmental Control and Life Support System (ECLSS)	Mr. Brandon Dewberry *NASA Marshall Space Flight Center*
	PI-in-a-Box	Dr. Larry Young / Dr. Silvano Colombano *Massachussetts Institute of Technology /* *NASA Ames Research Center*
	RCS/RMS Automation using Procedural Reasoning	Mr. H. K. Hiers *NASA Johnson Space Center*
	Thermal Control Expert System	Dr. John Bull / Ms. Kathy Healey / Mr. Jeff Dominick *NASA Ames Research Center /* *NASA Johnson Space Center*
	Summary of Astronauts' Inputs Concerning Automation	Mr. Dave Weeks *NASA Marshall Space Flight Center*
12:00 - 1:00	Lunch - Harbour Club	
1:30 - 4:30	SESSION V — SYSTEM EVOLUTION Session Chair: Mr. Barry D. Meredith *NASA Langley Research Center*	
	Assuring Data Transparency Through Design Methodologies	Mr. Allen Williams *Harris Corporation*
	EVA Systems	Mr. Michael Rouen *NASA Johnson Space Center*
	Data Management Systems	Ms. Katherine Douglas *NASA Johnson Space Center*
	Active Thermal System	Mr. Richard L. Bullock *NASA Johnson Space Center*
	Break	
	Guidance Navigation and Control	Mr. Jerry Kennedy *TRW, Inc*
	Communications and Tracking	Mr. William Culpepper *NASA Johnson Space Center*
	Structural Analysis of Evolution Station Concepts	Mr. Paul Cooper *NASA Langley Research Center*
	Environmental Control and Life Support System	Mr. Paul Wieland *NASA Marshall Space Flight Center*

Time	Topic	Presenter

Wednesday February 7, 1990 *(continued)*

1:00 - 4:30

SESSION VI — GROUND OPERATIONS AUTOMATION
Session Chair: Mr. John Muratore
NASA Johnson Space Center

Time	Topic	Presenter
	Real Time Data Systems for Mission Control	Mr. John Muratore / Mr. Troy Heindel *NASA Johnson Space Center*
	Transition Flight Control Room Automation	Mr. Al Brewer *NASA Johnson Space Center*
	Intelligent Computer-Aided Training Environment	Mr. Bob Savely *NASA Johnson Space Center*
	Platform Management System (PMS) Evolution	Mr. John Hartley / Mr. Mike Tilley *NASA Goddard Space Flight Center*
	Automated PMS Scheduler	Dr. Larry Hull *NASA Goddard Space Flight Center*
	Concepts in Distributed Planning and Control	Dr. Elaine Hansen / Dr. Larry Hull *NASA Goddard Space Flight Center*

Thursday February 8, 1990

8:30 - 11:00

SESSION VII — OPERATIONS EVOLUTION
Session Chair: Ms. Karen Brender
NASA Langley Research Center

Time	Topic	Presenter
	Operations Analysis for Evolution Station Concepts	Ms. Karen Brender *NASA Langley Research Center*
	Vehicle Processing Operations Database (VPOD)	Mr. George Ganoe *NASA Langley Research Center*
	On-orbit Assembly and Servicing Task Definition	Mr. Rick Vargo *McDonnell Douglas, Kennedy Space Center*
	Advanced Robotics for In-Space Vehicle Processing	Dr. Jeffrey Smith *NASA Jet Propulsion Laboratory*
	Advanced Automation for In-Space Vehicle Processing	Dr. Michael Sklar *McDonnell Douglas, Kennedy Space Center*
	Space Vehicle Deployment form Space Station	Mr. Paul Henry *NASA Jet Propulsion Laboratory*
	Graphical Analysis of Mars Vehicle Assembly	Mr. Kevin Lewis *NASA Johnson Space Center*

8:30 - 11:00

SESSION VIII — SPACE STATION INFORMATION SYSTEMS
Session Chair: Mr. Del Weathers
Space Station Freedom Program Office

Time	Topic	Presenter
	Data Management System Advanced Automation	Ms. Katherine Douglas / Mr. Terry Humphrey *NASA Johnson Space Center*
	Operations Management System (OMS) Global Fault Detection / Isolation	Mr. Matt Hanson
	OMS Event Evaluator and Scheduler	Mr. Rick Eckelkamp *NASA Johnson Space Center*
	Automated Software Development Workstation	Mr. Ernie Fridge *NASA Johnson Space Center*
	Technical and Management Information System Design Knowledge Capture	Dr. John Boose / Dr. Jeff Bradshaw / Dr. David Sheema / Dr. Stanley Covington *Boeing Advanced Technology Center*
	Evolution Paths for Advanced Automation	Ms. Kathy Healey *NASA Johnson Space Center*
11:00 - 12:00	Lunch - Harbour Club	

12:00 - 4:00

SESSION IX — ADVANCED AUTOMATION ENVIRONMENTS
Session Chair: Dr. Henry Lum
Ames Research Center

Time	Topic	Presenter
	CLIPS/Ada Programming Tool	Mr. Chris Culbert *NASA Johnson Space Center*
	ART/Ada Programming Tool	Mr. Chris Culbert *NASA Johnson Space Center*

Time	Topic	Presenter
Thursday February 8, 1990 *(continued)*		
	Knowledge-Based System Verification and Validation	Ms. Sally Johnson *NASA Langley Research Center*
	Intelligent Systems Engineering Methodology	Dr. Bruce Bullock *ISX, Inc.*
	Software Support Environment Design Knowledge Capture	Mr. Tom Dollman *NASA Marshall Space Flight Center*
	Advanced DMS Architectures Testbed	Mr. Terry Grant *NASA Ames Research Center*
	Spaceborne Autonomous Multiprocessor System	Mr. Alan Fernquist *NASA Ames Research Center*
	Information Sciences Experiment System Architecture	Mr. Nick Murray / Mr Steve Katzberg *NASA Langley Research Center*
12:00 - 3:00	SESSION X — TELEROBOTICS TECHNOLOGY AND APPLICATIONS Session Chair: Mr. Wayne Zimmerman *NASA Headquarters*	
	JPL Shared Control Architecture	Dr. Paul Backes / Dr. Samad Hayati *NASA Jet Propulsion Laboratory*
	JPL/KSC Robotic Inspection	Mr. Brian Wilcox / Mr. Leon Davis *NASA Jet Propulsion Laboratory /* *NASA Kennedy Space Center*
	Robotic Assembly of Large Space Structures	Mr. Ralph Will / Mr. Marvin Rhodes *NASA Langley Research Center*
	Space Station IVA Payload Robot	Mr. E. C. Smith *NASA Marshall Space Flight Center*
	Advanced Human-System Interface	Dr. Mike McGreevey *NASA Ames Research Center*

SESSION V
SYSTEM EVOLUTION

Session Chair:
Mr. Barry D. Meredith
NASA Langley Research Center

FREEDOM

SESSION V - SYSTEM EVOLUTION

INTRODUCTORY REMARKS

Mr. Barry Meredith
Deputy Director,
Evolutionary Definition Office
NASA Langley Research Center

SPACE STATION EVOLUTION "BEYOND THE BASELINE"

SYSTEM EVOLUTION - STUDY PRODUCTS

PRINCIPAL PRODUCTS OF THE FY89 DISTRIBUTED SYSTEMS EVOLUTION ANALYSES ARE:

- o BASELINE DESIGN FEATURES ("HOOKS & SCARS")
- o EVOLUTION DESIGN REQUIREMENTS (PRD & PDRD)
- o TECHNOLOGY NEEDS

SPACE STATION EVOLUTION "BEYOND THE BASELINE"

SESSION V - SYSTEM EVOLUTION

- DATA MANAGEMENT SYSTEM (DMS)
- EXTRAVEHICULAR ACTIVITY SYSTEMS (EVAS)
- ACTIVE THERMAL CONTROL SYSTEM (ATCS)
- GUIDANCE NAVIGATION AND CONTROL SYSTEM (GN&CS)
- COMMUNICATIONS AND TRACKING SYSTEMS (C&TS)
- STRUCTURES
- ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS)
- ELECTRICAL POWER SYSTEM (EPS)

Assuring Data Transparency Through Design Methodologies

ABSTRACT

This paper addresses the role of design methodologies and practices in the assurance of technology transparency. The development of several major subsystems on large, long life cycle government programs was analyzed to glean those characteristics in the design, development, test and evaluation that precluded or enabled the insertion of new technology. The programs examined were Minuteman, DSP, B1–B, and space shuttle. All these were long life cycle, technology–intensive programs. The design methodologies (or lack thereof) and design practices for each were analyzed in terms of the success or failure in incorporating evolving technology. Common elements contributing to the success or failure were extracted and compared to current methodologies being proposed by the Department of Defense and NASA. The relevance of these practices to the design and deployment of Space Station Freedom were evaluated.

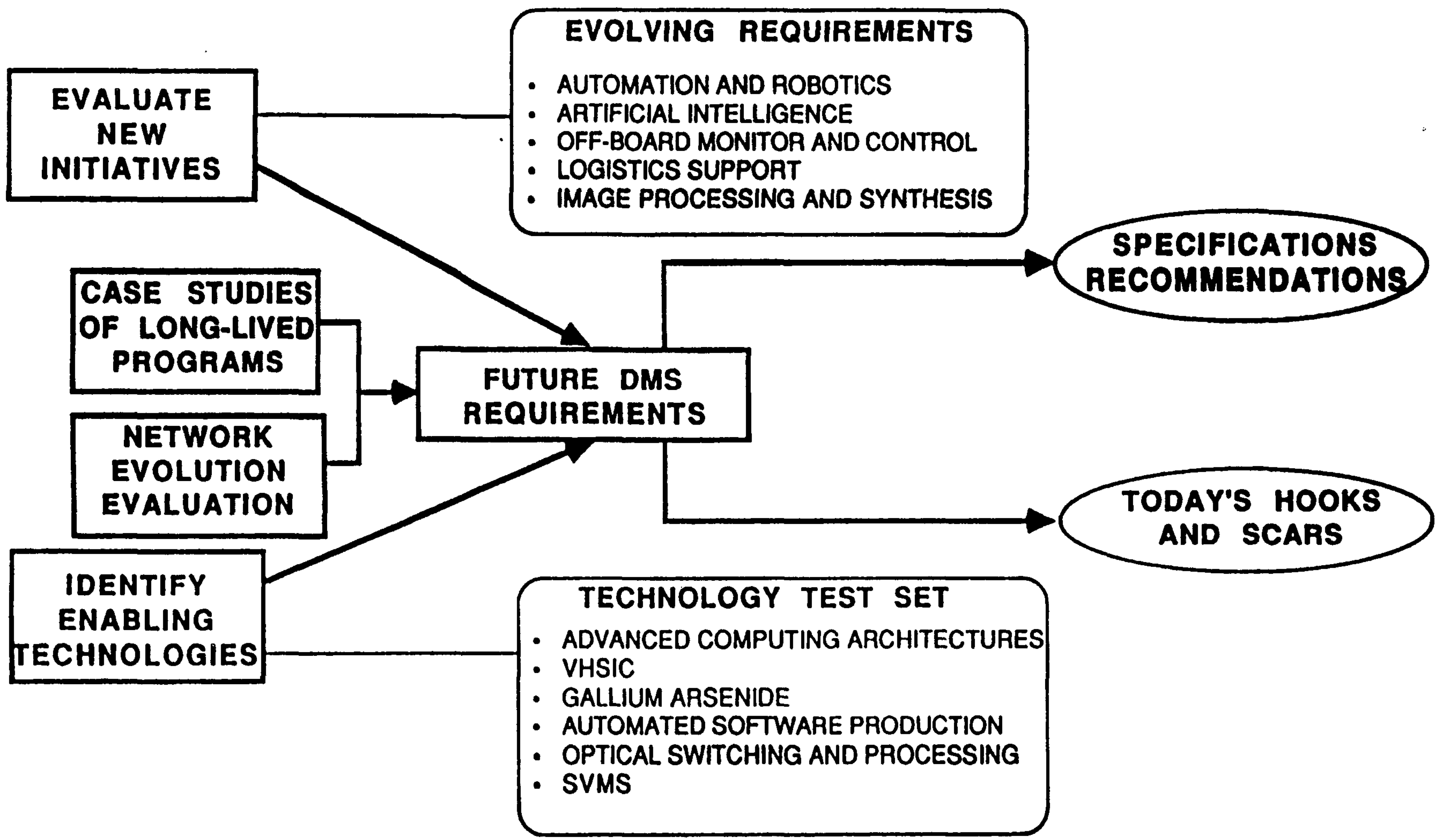
DMS Evolution Study

PURPOSE: The objective of this study was to provide the space station program with those hooks and scars necessary for evolution to support NASA's new initiatives (permanently manned lunar colony and manned Mars mission).

METHODOLOGY: The study consisted of four interrelated tasks: identification of the requirements imposed by the new initiatives, identification of emerging technologies that enable or enhance those requirements, identification of hooks and scars necessary to incorporate those technologies into the space station, and development of a design methodology that provides maximum support for the life– cycle of the station. There was also demonstrated an extremely high– fidelity simulation of an FDDI network that could be used as a foundation for the subsystem models (discovered to be crucial during the investigation of design methodologies) necessary to space station evolution.

This paper addresses the design methodology task, describing the approach taken and the results. The primary outcome of this effort was an identification of relevant programs in the Department of Defense and NASA that have specifically addressed the issue of support for long– life– cycle systems and how those methodologies may be utilized by the Space Station Freedom Program. Although initially planned to develop an appropriate methodology based on lessons learned from our own long– lived programs, it was soon discovered that the DoD has invested hundreds of millions of dollars in the development of not only the design methodologies but also the tools to implement them. These tools and techniques are readily available to NASA and SSFP to maximize the utility of Freedom over its thirty year life.

STUDY PRODUCTS



PROGRAMS CHOSEN

- DEFENSE SUPPORT PROGRAM
- MINUTEMAN
- B1 BOMBER
- NATIONAL SPACE TRANSPORTATION SYSTEM

LESSONS LEARNED: SUMMARY

- SPECIFICATIONS SHOULD BE BEHAVIORAL, AT THE ORU LEVEL
- SIMULATION SHOULD BE A KEY DRIVER IN DESIGN DECISIONS
- MARGIN IS FOR DESIGN UNCERTAINTY, NOT GROWTH
- STANDARDS USED SHOULD BE APPLICABLE AND BEHAVIORAL
- DESIGNS SHOULD BE CAPTURED IN STANDARD, TECHNOLOGY- INDEPENDENT FORMAT
- FORGET LIFE- CYCLE SPARING

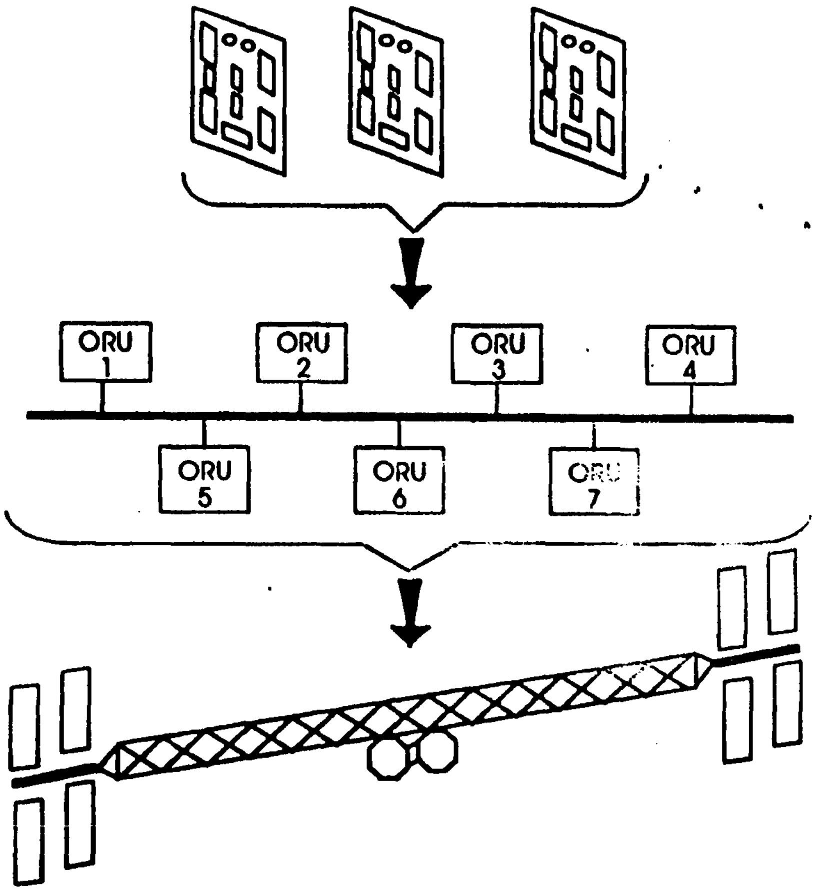
CASE STUDY SUMMARY

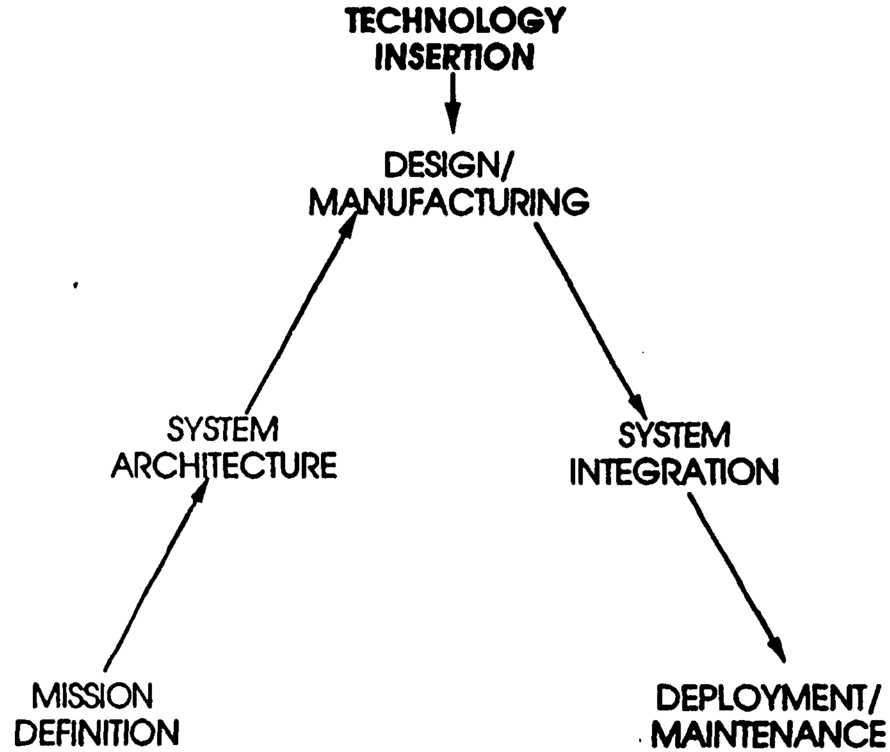
	NSTS	DSP	MM	B1
SPECIFICATIONS	X		X	X
GROWTH MARGINS	X	X	X	
SIMULATION	X	X		
DESIGN CAPTURE		X		X
STANDARDIZATION	X		X	X

CHARACTERISTICS OF FUTURE PROGRAMS

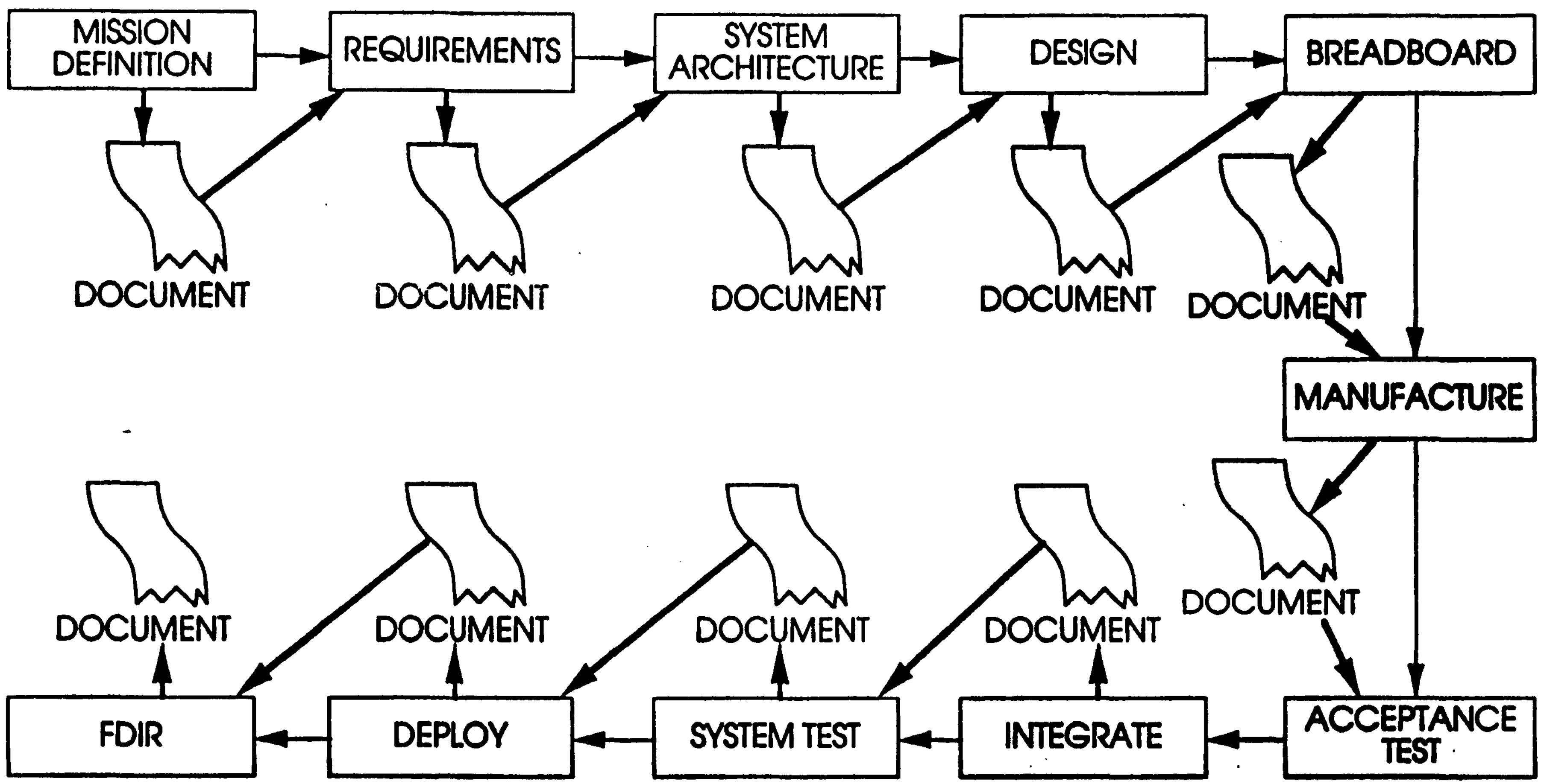
- ANTICIPATE TECHNOLOGY TURN-OVER EVERY 3-4 YEARS
- ASIC AFFORDABILITY INCREASED BY RAPIDLY DECREASING TURN-AROUND TIME AND NRE
- SIMULATION, NOT PROTOTYPE, SUPPORTS ASIC DEVELOPMENT IN TERMS OF SCHEDULE AND COST
- SIMULATABLE ASIC MODELS ARE THE STANDARD PARTS OF TOMORROW

TECHNOLOGY TRANSPARENCY PROBLEM

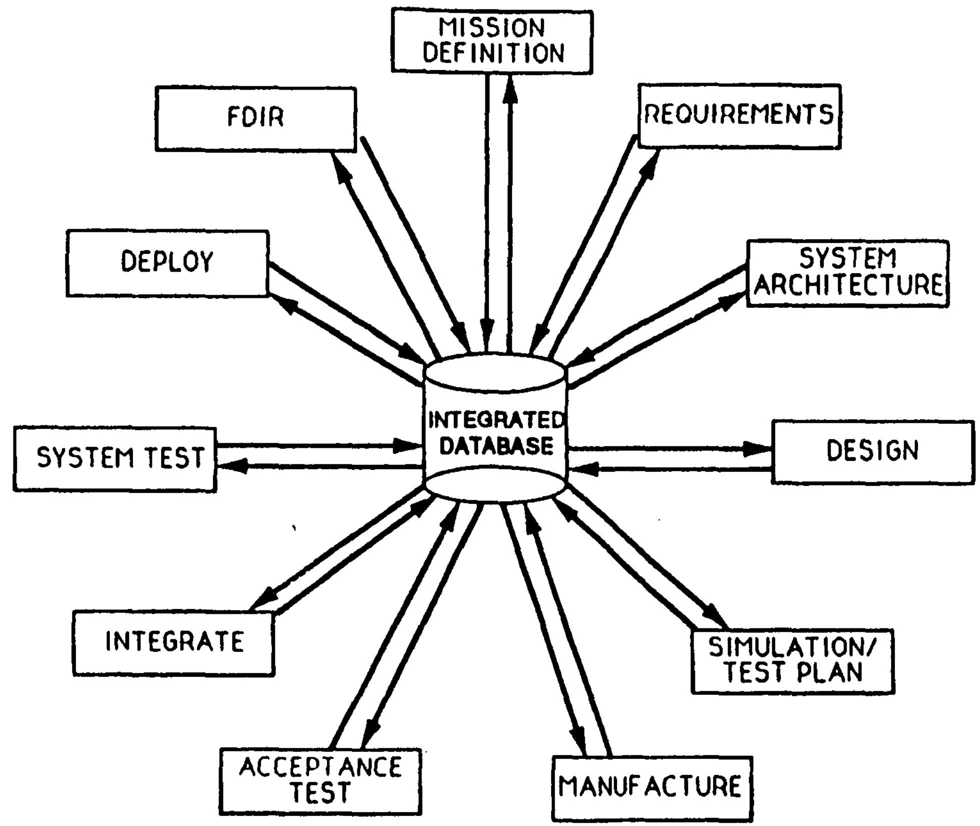




CLASSICAL DEVELOPMENT PROCESS



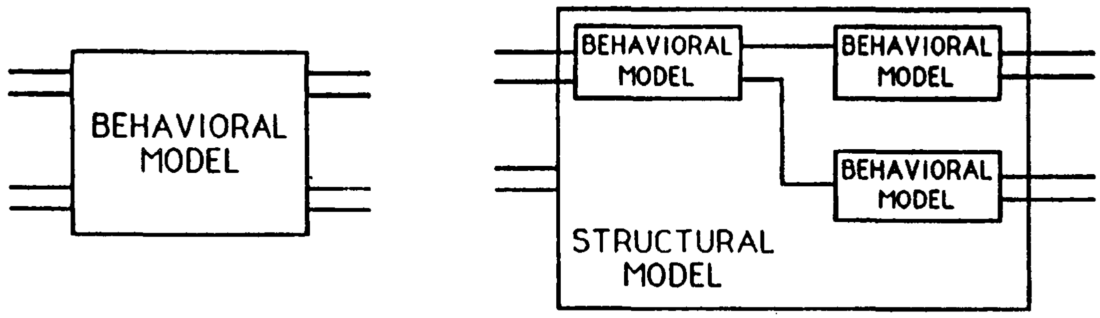
INTEGRATED DATABASE SOLUTION



- INTEGRATED/ SHARED DATABASES MADE POSSIBLE BY INFORMATION MODELING TECHNOLOGY
- SYSTEM COMPONENTS ARE DECOUPLED BY WRITING SPECIFICATIONS FOR BEHAVIORAL MODELS
- IMPACT OF TECHNOLOGY UPGRADES IS ASSESSED USING SIMULATION AGAINST EXISTING MODELS

ELEMENTS OF LIFE CYCLE TECHNOLOGY PROBLEM

- MODELING
  - BEHAVIORAL MODEL: INTERFACES AND FUNCTION OF COMPONENT
  - STRUCTURAL MODEL: IMPLEMENTATION OF COMPONENT
  - PHYSICAL MODEL: CONSTRUCTION OF COMPONENT



- SIMULATION
  - ACCURATE SIMULATION OF BEHAVIORAL MODEL INSURES SYSTEM INTEGRITY
  - ACCURATE SIMULATION OF STRUCTURAL MODEL INSURES ORU INTEGRITY
  - ACCURATE REPRESENTATION OF PHYSICAL MODEL INSURES MAINTAINABILITY AND RELIABILITY

PROGRAMMATIC RELATIONSHIPS

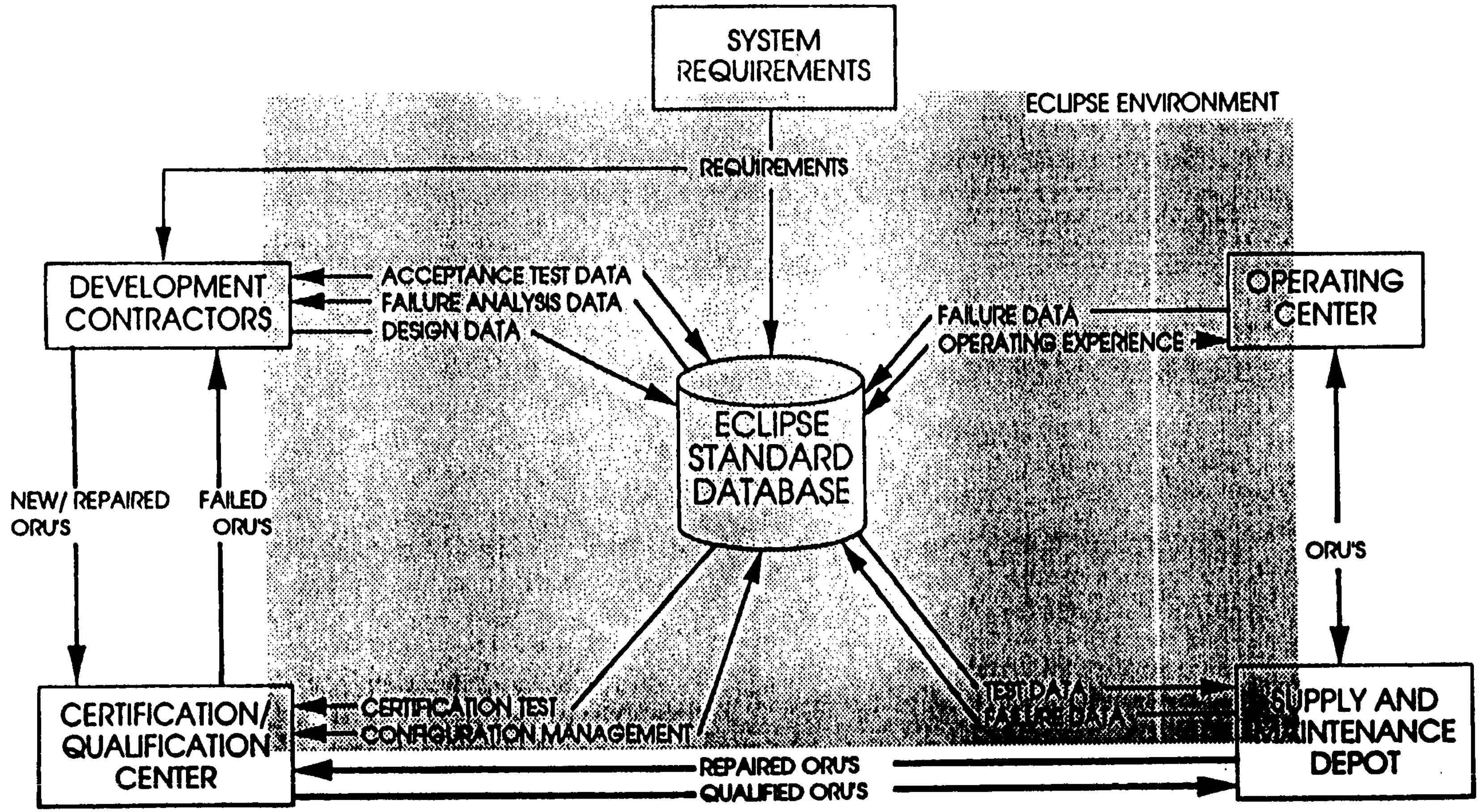
APPLICATIONS	TISSS V-BUSS , DAMES
SUPPORT ENVIRONMENT	EIS , IDS , ECLIPSE SSE , TMIS
SOLUTION FOUNDATION	CALS , VHDL , PDES, IDEF1X, SMAP MIL-STD-490A, MIL-STD-2167A
BASIC APPROACHES	STANDARDS LIFE-CYCLE SPECS, STDS. SIMULATIONS DESCRIPTIVE LANGUAGES INFORMATION MODELING
PROBLEM	ACQUISITION, DEVELOPMENT & SUPPORT OF COMPLEX SYSTEMS

ECLIPSE

(Eclectic Capability for Logistics Information and Product Support for Electronics)

- BACKGROUND
  - AIR FORCE LOGISTICAL CONCERNS WITH, AMONG OTHER THIINGS, LIFE CYCLE REPROCUREMENT, REMANUFACTURE, AND MODIFICATIONS
  - CALS INITIATIVE DEMANDS MACHINE- READABLE TECHNICAL DATA STANDARDS
- SCOPE
  - CONCEPT FORMULATION
  - ANALYSIS AND SYNTHESIS OF DATA FROM DoD, USERS, MANUFACTURERS
  - TRADE STUDIES
  - REQUIREMENTS DEVELOPMENT
- OBJECTIVE
  - LIFE CYCLE SUPPORT DATABASE (E.G., MASA SRD)
  - STANDARDS FOR MACHINE- READABLE FORMAT FOR TOTAL LIFE CYCLE
  - DEFINE ORU CERTIFICATION AND SUPPORT
  - INTEGRATION OF ON- BOARD DIAGNOSTICS WITH QUALIFICATION & MAINTENANCE TESTING

ECLIPSE ENVIRONMENT



SPACE STATION SYNTHESIS

DOD PROGRAMS

- CALS
- ECLIPSE
- IDS
- PDES
- VHDL
- EIS
- TISSS
- V-BUSS
- DAMES

SPACE STATION PROGRAM

- SSE
- TMIS
- LEVEL II INTEGRATION FACILITIES

- SPACE STATION TECHNOLOGY TRANSPARENCY STUDY MAXIMIZES LEVERAGE FROM EXISTING PROGRAMS

  - EVALUATE AVAILABLE RESOURCES
  - DETERMINE UTILITY TO SPACE STATION LIFE CYCLE
  - RECOMMEND IMPLEMENTATION PLAN
  - EXERCISE DMS AGAINST IMPLEMENTATION PLAN

TECHNOLOGY INVESTMENT AREAS

- SIMULATION AND MODELING
  - CURRENT CONTRACTORS DO NOT HAVE ORU MODELS AS PART OF THEIR DELIVERABLES
  - MODELS SHOULD BE DEVELOPED BY THE DESIGNER PRIOR TO ELEMENT DELIVERY
- INFORMATION MODELING
  - DEFINITION OF DESIGN REPRESENTATION SHOULD BE IMPROVED
  - DELIVERABLE SHOULD INCLUDE CONSISTENT REPRESENTATION ACROSS WORK PACKAGES

SPACE STATION EVA SYSTEM EVOLUTION STUDY

Presented at: THE SPACE STATION EVOLUTION SYPOSIUM
South Shore Harbour Resort and Conference Center
League City, Texas
February 6-8, 1990

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Study Manager

SPACE STATION FREEDOM
EVA SYSTEMS
EVOLUTION STUDY

ABSTRACT

Evaluation of Space Station Freedom support of manned exploration is in progress to identify SSF EVA system evolution requirements and capabilities. The output from these studies will provide data to support the preliminary design process to ensure that Space Station EVA system requirements for future missions (including the Transportation Node) are adequately considered and reflected. The study considers SSF support of future missions and the EVA system baseline to determine adequacy of EVA requirements and capabilities, and to identify additional requirements, capabilities, and necessary technology upgrades.

EVA demands levied by formal requirements and indicated by evolution mission scenarios are high for the out-years of Space Station Freedom. An EVA system designed to meet the baseline requirements can easily evolve to meet evolution demands with few exceptions. Results to date indicate that upgrades or modifications to the EVA system may be necessary to meet all forseeable hangar induced EVA environments. Work continues to quantify the EVA capability in this regard. Evolution mission scenarios with EVA in and around unshielded nuclear propulsion engines are inconsistent with anthropomorphic EVA capabilities.

NEW/UNIQUE REQUIREMENTS IMPLIED IN EVOLUTION STATION SCENARIOS

The results of this study indicate new or unique requirements above and beyond the baseline requirements implied in the evolution space station scenarios.

EVA RESOURCE DEMAND

The demand for EVA resource continues to be high and may exceed current baseline growth requirements of 3000 man-hours per year (250 EVAs per year).

EVA ENVIRONMENT

The evolution of Space Transfer Vehicles include upgrading the propulsion systems to nuclear propulsion engines. The impact on the EVA environment assuming the unshielded engines was assessed. This study concludes that EVA environments associated with unshielded NTR engines is incompatable with anthropomorphic EVA capabilities.

Thermal environments associated with STV servicing and transportation node hangars are more severe than typical SSF truss EVAs. Full duration EVAs in these thermal environments with the present SSF EMU baseline may not be possible without supplemental cooling.

QUARANTINE

Biological quarantine issues associated with SSF EVA must consider both inbound and outbound vehicle biological contamination.

CONTAMINATION DETECTION AND REMOVAL AT EVA WORKSITES

The EMU suit materials are proving to be fairly compatable with space vacuum exposures to contaminants associated with fuel and coolant system spills. The EVA System provides adequate means for contaminant removal from exposed EVA crewmembers prior to ingressing the airlock. The EVA System does not address cleanup of worksites, or space station or STV external hardware contaminated as a result of a spill.
This contingency should be investigated further to address if natural sublimation of spill fluids is adequate to support transportation node operations or if methods of enhanced sublimation are required to cleanup worksite spills.

HANDLING OF EVA CREW OPERATIONS DATA

EVA crewmembers will need access to a high quantity of EVA operational data in order to support the myriad space station and STV processing activity. The ability to support data access and transmission decreases with the implementation of UHF space-to-space communications with EVA personnel. Other means of data access, transmission, and display, other than crew worn cuff checklists, must be implemented to retain this EVA crew support data interface.

STUDY ACTIVITY

- Evaluation of EVA System Requirements for Transportation Node
  - EVA Resource Demand
  - Environment
    - Ionizing Radiation
      - South Atlantic Anomaly (SAA)
      - Nuclear Powered Engine Reactors
    - Thermal Environments
  - Quarantine
  - Contamination Detection and Removal
  - EVA Operations Data Handling

EVA DEMAND

- EVA resource required to support Transportation Node assessed
  - SSF Maintenance and Contingencies
  - User Support
  - LTV Refurbishment and Processing
  - MTV Assembly

- EVA demand for SSF outyears anticipated to be high
  - Peak resource requirements are consistent with peak transportation node activity
  - EVA demand without transportation node is also significant

- EVA demand requires routine EVA capability even with robotics
  - EVA and telerobotics must be balanced
    - Diving industry experience with robotics
      - Currently 30% task off-loading with robotics
      - 40% plateau projected for cost effective operations

- EVA system built to Phase C/D requirements best approach for meeting demand with LEO operational constraints
  - New SSF EMU - no prebreathe, low IV overhead, low volume regenerable
  - Two airlocks with automated service and performance checkout

ESTIMATE OF ANNUAL EVA RESOURCES

An assessment of EVA resources required to support the evolutionary scenario of space station as a manned exploration transportation role was conducted to establish the adequacy of the baseline.

The assessment considered the EVA resource requirement necessary to support space station maintenance, space station contingency operations, space station payload users, and manned exploration STV refurbishment and assembly activity.

This study assumed that SSF contingencies and user support were consistent with pre-scrub EVA resource allocations as defined in SSP 30000. EVA resource for SSF maintenance was based on post-scrub configuration estimates from the maintenance data base. Actual EVA requirements for SSF maintenance are assumed to be larger than these estimated due to SSF add-backs and expected growth beyond assembly complete.

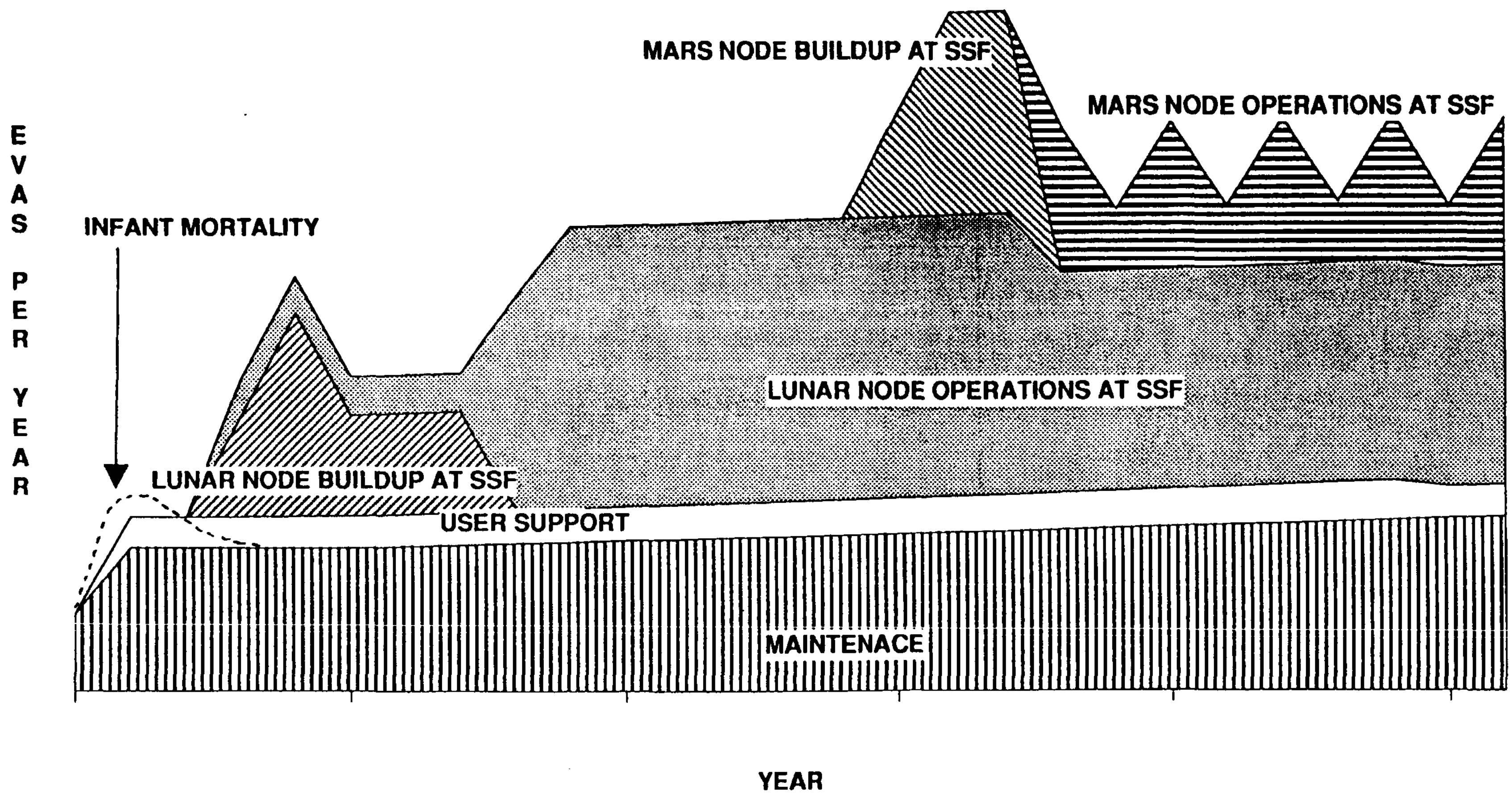
Data for EVA resource requirements for on-orbit STV processing was derived from on-going MDSSC-KSC studies (Ref's 9,10, and 22) concerning on-orbit refurbishment and assembly of Lunar Transfer Vehicles and Mass Transfer Vehicles respectively. STV mission loading was based on the OEXP presentation on Manned Exploration to contractors (Ref 5).

The results show that current EVA resource growth requirements of 3000 man hours may be insufficient even with robotics off-loading and assisting manned EVA tasks. Figure 6 shows an expected profile of EVA resource demand with time. Peak resource requirements are consistent with peak transportation node activity. SSF EVA resource requirement minus the transportation node are not insignificant.

ESTIMATE OF ANNUAL EVA DEMAND

	EVA Man Hours post-AC
■ SSF Maintenance ● Post-scrub configuration ● Add-backs will increase EVA demand ● Growth expected beyond AC configuration	> 702
■ SSF Contingencies ● Pre-scrub EVA resource allocation	104
■ User Support ● Pre-scrub EVA resource allocation	280
■ LTV Refurbishment and Processing ● On-Orbit Assembly/Servicing Task Definition Study — MDSSC-KSC, Nov 89 ● > 1100 man hours per vehicle ● Robotics off-loading not assessed	> 2200-3300
■ MTV Assembly ● On-Orbit Assembly/Servicing Task Definition Study — MDSSC-KSC, Nov 89 ● 432 man-hours per vehicle ● Robotics off-loading for fueling	432
■ Total	> 3718 - 4386

FIGURE 6: AMOUNT OF REQUIRED EVA



SOUTH ATLANTIC ANOMALY

The South Atlantic Anomaly (SAA) is an area of Low Earth Orbit (LEO) that contains higher levels of radiation than the surrounding atmoshpere. The SAA is located over the South Atlantic ocean and extends over certain areas of South America, specifically parts of Brazil, and Argentina, and covers Uruguay entirely. The SAA is somewhat fixed with respect to ground coordinates (latitide and longitude). The area and geometry (shape) of the SAA varies with altitude. The area of the SAA is greater at higher altitudes than at lower altitudes. Figure 7 defines the SAA geometry and approximate locations (Ref 11).

For a portion of each day, Space Station will encounter the SAA on consecutive orbits for only a portion of those orbits. As the area of the SAA increases with altitude, so does the number of consecutive orbits that pass through the SAA, the portion of each day containing those orbits, and the total SAA exposure time. In other words, the time each day available to perform EVA free of SAA exposure decreases at higher altitudes. It is highly desirable, and also a requirement, to minimize crew exposure to the SAA on a routine basis in order to minimize any increased health risk due to cumulative exposure. Space Station encounters with the SAA occur at earlier times each subsequent day for the entire range of Space Station orbital altitudes. This presents additional challenges to EVA scheduling, when Space Station operations are divided into two equal working shifts per day.

A preliminary study was performed to determine how Space Station EVA scheduling would be affected by the SAA. The study was based on the assumption that Space Station would orbit the earth at a constant altitude in a 28.5 degree orbital inclination. The two orbital altitudes chosen for this study were 175 and 225 nautical miles. A computer program was used to simulate two Space Station orbital scenarios in order to relate the time of day (24 hour time period) with the location (latitude and longitude ground coordinates) of the station and the SAA. The program generated a 30 day orbital profile that provided a statistical base of data regarding the time and duration of SAA encounters (Ref 12).

The results of this analysis are graphically represented in Figure 8. Specifically they are:

1. The duration of consecutive orbital passes through the SAA increases with orbital altitude.

2. On the average, the time of the consecutive orbit passes through the SAA precesses approximately 30 minutes earlier each subsequent day (precession times varies slightly from day to day). Precession time varies with orbital altitude.

3. In the long term, routine EVAs will have to be performed in alternating shifts in order to avoid the SAA passes.

4. EVA (based on two 12 hour working shifts) flexibility increases when orbital altitude decreases due to the reduced SAA exposure time and vica versa.

RADIATION PROTECTION OF ASTRONAUT IN SSF EMU

The following sections address radiation protection of an astronaut in a Space Station Freedom EMU.

The starting point for the data and analyses presented here is the definition of key issues and limiting assumptions for radiation protection of an EVA astronaut. The underlying issues are whether current EMU designs are adequate for: 1) the large number of mission critical EVA's required for servicing lunar and Mars bound vehicles, and 2) work with nuclear powered vehicles.

The data presented is based on analysis of calculations and data presented in a broader work entitled "Candidate Space Station EVA Space Suit Radiation Analysis Final Report" (CTSD-SS-241) by Kosmo, Nachtway, and Hardy (Ref 15). For data related to nuclear powered vehicles data was derived for reactor concepts based on a report to the Space Station Evolution group by Texas A&M and NASA Lewis Research Center (Ref 16).

Data was evaluated against a limiting set of assumptions concerning several exposure factors, such as duration, frequency, location, and type of protection. The key assumptions on which the calculations are based can be summarized as follows:

1) Maximum plausible amount of EVA per individual based on the recommendation of former astronaut Joseph P. Kerwin, MD:

    - 2 EVA's, 6 hrs/wk for 1.5 years (936 hrs/lifetime)
    - 2 EVA's, 6 hrs/wk for 1 year continuous orbit (624 hrs/lifetime)

2) Maximum permissible amount of EVA per individual (per SSP 30000):

    - 3 EVA's, 6 hrs/wk for 1.5 years (1404 hrs/lifetime)
    - 3 EVA's, 6 hrs/wk for 1 year continuous orbit (936 hrs/lifetime)

3) Space Station Freedom (no polar or GEO platform) location factors which match source calculations:

- 28.5° inclination
- 400-500 km (216-270 nm) altitude

4) Protection due to EMU configuration:

- Mark III standard design
- Mark III with radiation/meteoroid protection
- AX-5 standard design
- AX-5 with radiation protection

The calculation results presented for radiation exposure were weighed against standards outlined in the National Council on Radiation Protection and Measurements Recommendation to NASA. Their limits are set based on a radiation dosage that will add a 3% additional cancer mortality risk over an astronaut's career. For reference, this amount of increase in dosage increases the astronaut cancer mortality risk from the current public-wide average of 17% to 20%.

DISCUSSION OF RADIATION RESULTS

- Nominal EVA Doses

The results of this study are summarized in Table IV. It shows annual and lifetime doses for various EVA frequency scenarios corresponding to the assumptions discussed above. Protection cases listed are for baseline space station and a typical EVA space suit assembly (SSA), both with and without added radiation protection. Due to similarity in AX-5 and Mark III results, only AX-5 results are listed.

The lifetime limits are not approached with worst case results in any of the scenarios evaluated. Therefore, radiation protection is not needed. The annual limits were only exceeded for the worst case based on continuous EVA operations by the same person for a year in the highest orbit and deliberately running all 3 EVA's per week in the South Atlantic Anomaly (SAA). In this situation and others involving the SSA, it was found that a radiation protection garment offers no significant reduction in dose. Other study observations were that the AX-5 offered no significant improvement over the Mark-III hybrid SSA.

Other considerations are that operations requiring a significant number of SAA passes will not be possible, since OSHA requires that all reasonable precautions must be taken to minimize radiation. The OSHA requirements and reasonable operation planning would reduce EVA's in the SAA to a small fraction of the total. Study results and summarized data do not directly address the effects of solar storm effects on radiation levels. However, in low equatorial orbits, such as considered in this study, it is known that solar storm induced radiation builds up very slowly. In place procedures for monitoring solar activity and radiation at SSF during EVA will give ample warning in the unlikely event that an unacceptable radiation level was about to develop.

A key conclusion derived from the data presented is that no scars are required to provide protection for SAA operations. The baseline design for suits and EVA scenarios is adequate in most cases because crew durability limits are lower than radiation limits. Also U.S. Federal statutes require acceptable operation hits to avoid radiation exposure in the work place, that is, a minimum number of EVA's in SAA.

- Effect of Reactors on EVA Doses

All low mass shielding schemes for SP-100 reactors involve shadow shields. The shields only allow protection in a cone with a half angle of about 15° as shown in the attached illustration (Figure 11). This amounts to only 15% of the region surrounding the reactor as being safe. Even brief exposure in the other 98% of the volume around the reactor is lethal. This means that with the shadow shield protection method there can be absolutely no tolerance for failures in attitude control. Portable shielding also provides only highly directional protection with the same lethal consequences for loss of attitude control. As concluded in the previous section, radiation protection from a micrometeoroid garment offers no significant improvement.

The conclusion is that EVA around reactors is effectively impossible. For nuclear powered vehicles robotic separation of reactors and radioactive parts from non-radioactive parts will be required. Non-radioactive parts could then be transferred to EVA orbit.

ENVIRONMENT

- Ability of SSF EMU to meet anticipated radiation and thermal environments was assessed

- LEO Radiation
  - LEO exposure assessed against permissible and likely crew annual and lifetime EVA duty with plausable suit configurations
  - Conclusions
    - Suits adequate for assumed lifetime limits with annual limits exceeded only by worst on worst case
    - Federal statutes require routine EVA operationsd avoid SAA
      - Results in decreased EVA operational flexibility

- Radioactive reactors associated with Nuclear Powered Vehicles
  - All low mass shielding schemes involve shadow shields
  - Brief exposure to unshielded zones with anthropomorphic suit concepts is lethal
  - Conclusion
    - Failure tolerance of EVA near partially shielded reactors is unacceptably low

EVA RADIATION PROTECTION AT SPACE STATION FREEDOM

TABLE IV - EMU RADIATION DOSAGE SUMMARY

DATA SHOWN AS PECENT OF MAXIMUM ALLOWABLE

	ANNUAL - 3 EVAs/WEEK AT 500 KM ORBIT		LIFETIME - 2 EVAs/WEEK 18 MOS. ON-ORBIT TIME	
	NONE IN SAA	ALL IN SAA	NONE IN SAA	ALL IN SAA
MK-III	28.4%	102.9%	8.9%	13.9%
w/ Radiation Protection	27.4%	97.1%	8.9%	13.1%
AX-5	27.9%	101%	8.9%	13.6%
w/ Radiation Protection	15.9%	91.8%	8.9%	12.4%

SAA = SOUTH ATLANTIC ANOMALY

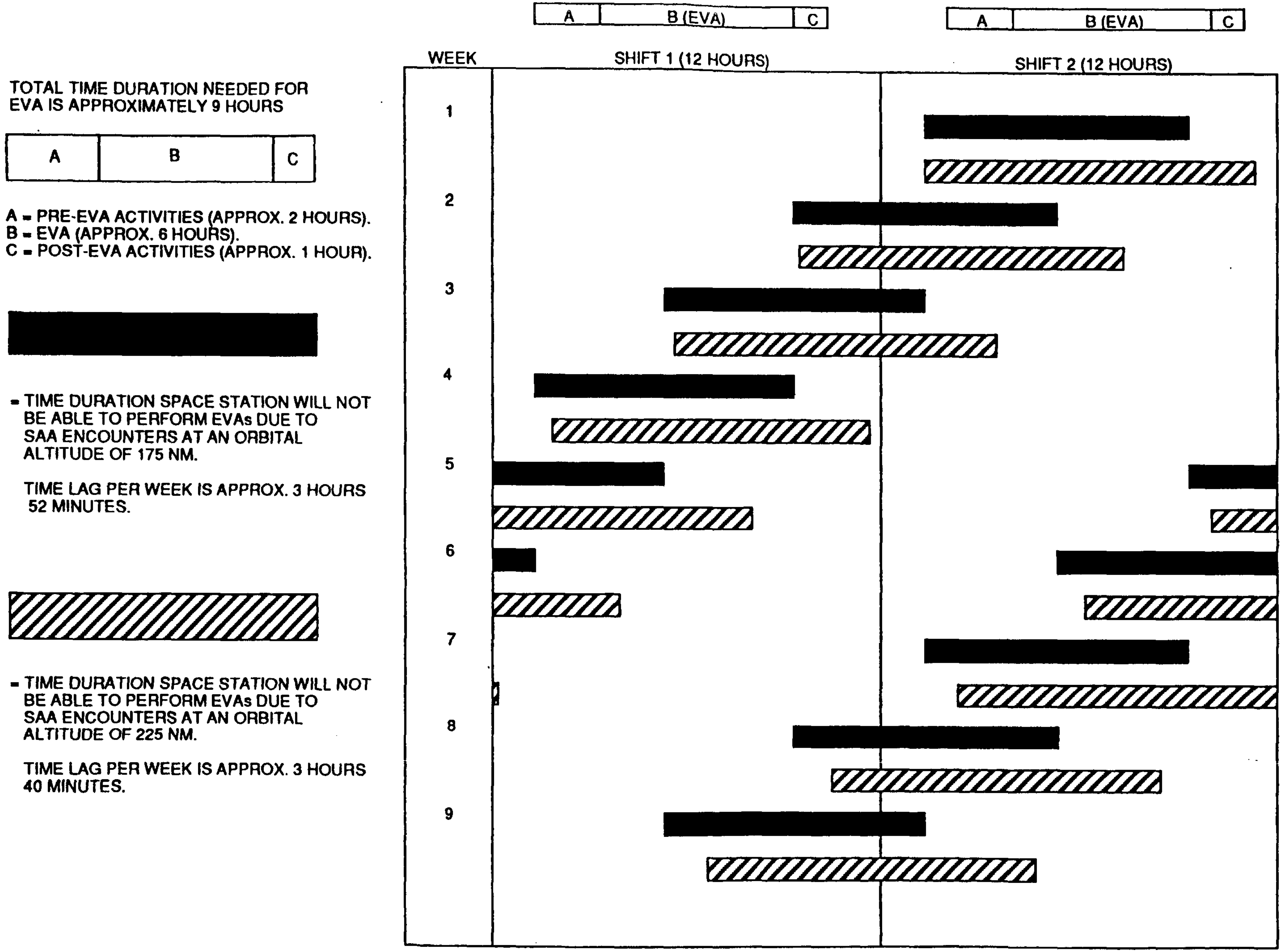


FIGURE 8 : SOUTH ATLANTIC ANOMALY V.S. SS EVA SCHEDULING

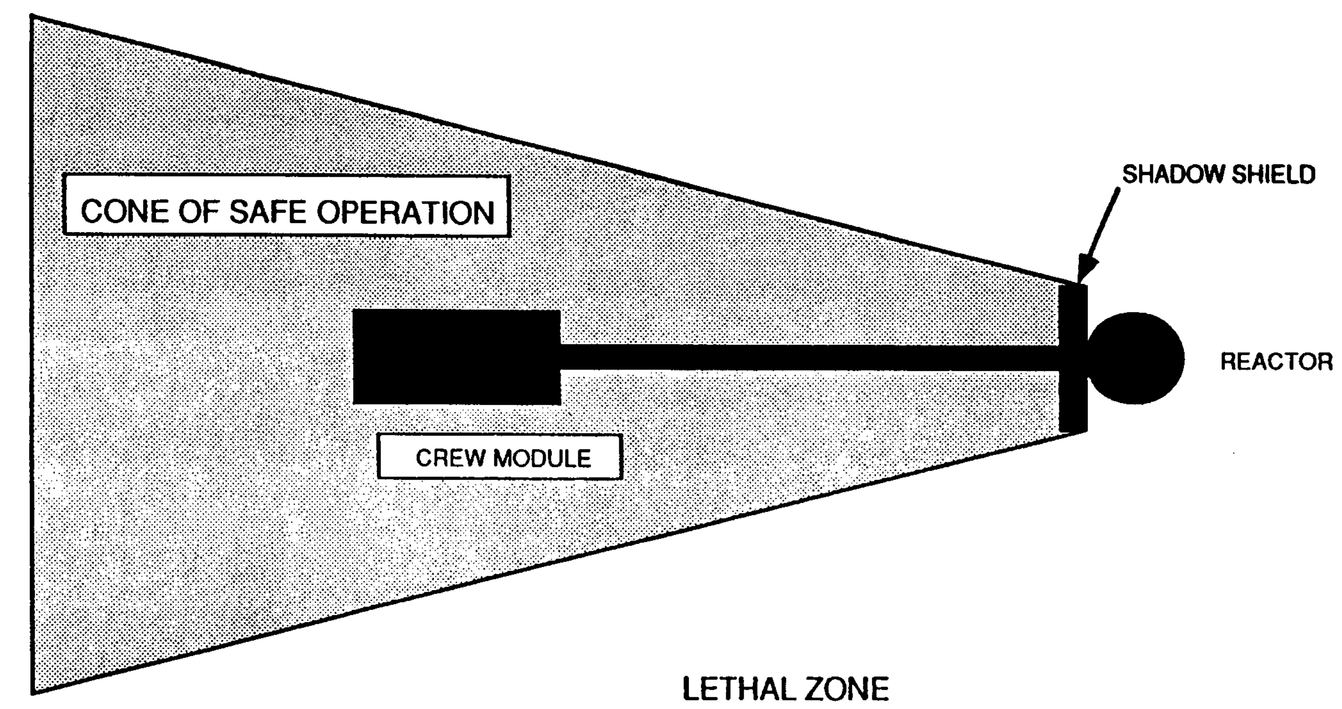


FIGURE 11: SAFE OPERATION IN SHADOW ZONE

EMU THERMAL PERFORMANCE

The Space Station EMU baseline uses a radiator in conjunction with a wax phase-change thermal storage material to reject EMU waste heat. Its performance is significantly effected by the thermal environments at EVA worksite locations. An analysis of LEO transportation node thermal environments and related EMU heat rejection estimates was conducted to determine the EVA thermal requirements for the evolutionary growth Space Station. At this time, evolutionary growth primarily refers to a LEO transportation node supporting a lunar outpost. The adequacy of the baseline EMU thermal performance in these environments was also assessed.

Approach

In this work new thermal analysis results for LEO are combined with prior analyses to compare thermal environments for a variety of Space Station Freedom (SSF) locations. A major part of this effort involved casting the results of prior SSF thermal studies into new formats allowing one-to-one comparisons of new and previous results. The final product of this effort is the comparison of exterior Space Suit Assembly (SSA) temperatures and EMU heat losses at the various SSF and LEO locations.

The solar and emmissive flux data versus orbital position was compiled from previous and new analyses for beta angles of 0 and 52 degees. Since the exact orientation of the EMU at any location is not known, the average flux for each location was calculated. Instantaneous and time averaged adiabatic equilibrium temperatures for EMU SSA material (beta cloth) were determined at each location. Based on estimates of suit insulation performance, suit and radiator areas,and radiator surface properties, instantaneous and time averaged suit and radiator heat leaks were calculated. Calculated heat leaks were then summed and compared to the nominal EMU design estimate of 941 BTU/hr.

A summary of thermal environments that have been evaluated is listed in Table II.

TABLE II - THERMAL ENVIRONMENT EVALUATED

STS ORBITER NOT PRESENT

LOC #	DESCRIPTION	TYPE OF AVERAGE	LESC SOURCE MEMO	MEMO ITEM #
1)	Forward of Nodes 3&4, in plane	cube average	25,520	D-1
2)	Between Modules, in plane	cube average	25,520	D-2
3)	Between JEM & ESA, in plane	cube average	25,520	D-3
4)	Next to HAL-Lab, in plane	cube average	25,520	D-4
5)	Near Node 1 next to Airlock	cube average	25,520	D-5
6)	Below U.S. Hab Module, next to PLM	cube average	25,520	D-6
7)	Above Airlock	cube average	25,520	D-7
8)	Outside Hyper. Airlock Hatch, in plane	cube average	25,520	D-8
9)	Aft of Truss	cube average	25,520	B
10)	Below Truss	cube average	25,520	B
11)	<u>Nominal Case</u> Below Lab Module	EMU flux	26,696	A
12)	<u>Cold Case</u> above ESA	EMU flux	26,696	B
13)	Solar Panel	EMU flux	25,520	C-3
14)	<u>Hot Case</u> Solar Panel	cube average	CTSD-0179	
15)	Hangar, open door	cube average	25,520	C-1
16)	Hangar, open door	cube average	25,520	C-2
17)	Hangar, closed door	cube average	this study	
18)	Hangar, open door	cube average	this study	

ORBITER PRESENT

LOC #	DESCRIPTION	TYPE OF AVERAGE	LESC SOURCE MEMO	MEMO ITEM #
1)	Orbiter Belly, near black tiles (possiblly analogy to near LTV Aerobrake)	cube average	25,926	
2)	Between U.S. Lab, U.S. Hab, and Nodes 1&2	cube average	25,926	
3)	Between JEM-ESA modules	cube average	25,926	
4)	Above U.S. Lab module	cube average	25,926	
5)	Above Node 1	cube average	25,926	
6)	Below Node 1	cube average	25,926	
7)	Outside of module cluster near ESA	cube average	25,926	
8)	Near Outside Hyperbaric Airlock Hatch	cube average	25,926	
9)	Btwn. Orb. Starboard Bay Door and Node 3	cube average	25,926	
10)	Orbiter windshield	cube average	25,926	
11)	Docking Mast inside payload Bay	cube average	25,926	

Results

The summed heat leaks for each environment location was compared to the baseline EMU design estimate of 941 BTU/hr. Heat leaks greater than 941 BTU/hr indicated that the baseline EMU would support a full duration EVA at that location. Heat leaks significantly less (< 850 BTU/hr) indicate that the ability to support a full duration EVA at that location would be compromised unless supplemental cooling was provided.

A list of HOT environments where full duration EVAs would not be ensured is given in Table III.
Of these locations, the hangar, orbiter belly, and between module cases are analogous to transportation node locations of the LTV hangar, an STV aerobrake, and STV modules at a SSF. Actual EVA performance in these locations is unknown since radiator performance is orientation dependent.

Conclusions

Some of the Hot environments evaluated are analogous to major servicing functions at the SSF transportation node. These would include EVA in an LTV hangar, EVA in front of the STV aerobrake tiles, and EVA around the STV module clusters.

Therefore, the following key conclusions are drawn from an evaluation of the summarized thermal environments:

1. Standard duration EVAs for Evolutionary Growth will require more performance from the EMU than from the "Nominal" baseline.

2. Supplemental cooling may be required if mission profile requires long operations in these environments.

HOT ENVIRONMENTS

(TABLE III - HEAT LEAK OF < 850 BTU/HOUR)

Heat Leak BTU/hr	LOC. #	Orbiter Present?	Beta Angle	Name
313	13	No	52	Solar Panel
460	14	No	52	Solar Panel
493	13	No	0	Solar Panel
698	18	No	52	Hangar
709	16	No	0	Hangar
755	1	Yes	0	Orbiter Belly, near black tiles
784	17	No	0	Hangar
791	17	No	52	Hangar
818	18	No	0	Hangar
830	2	No	0	Between U.S. Lab, U.S. Hab, and Nodes 1&2, in plane of raft
831	6	Yes	52	Below U.S. Lab next to PLM
842	2	No	52	Between U.S. Lab, U.S. Hab, and Nodes 1&2, in plane of raft
844	6	No	52	Below U.S. Hab next to PLM
847	2	Yes	52	Between U.S. Lab, U.S. Hab, and Nodes 1&2, in plane of raft

ENVIRONMENT (continued)

- EMU thermal performance assessed against environments analogous to evolution SSF EVA sites

- Approach
  - Flux data from previous and new SSF environment analyses was compiled for analogous EVA sites
  - EMU heat leaks calculated and compared to nominal design case

- Conclusion
  - Hottest environments analogous to major servicing functions
    - Hangar
    - Black aerobrake materials
    - Between modules

  - Standard duration EVAs for evolutionary growth will require more performance from EMU than the baseline nominal case

EVA BIOLOGICAL QUARANTINE ISSUES

- Current Policy and Policy Needs

The current NASA policy is well defined for outbound probes to planets, asteroids and comets under the Planetary Protection Policy. The procedure prescribed by this policy require reducing the biological load on the spacecraft below an amount that can be expected to reproduce.

The NASA policy is not well defined, however, for material returning from planets, asteroids or comets. Since Viking probes did not totally resolve the issue of whether or not there is life on Mars, future missions to Mars are likely to force a policy statement. Although the consensus of Viking researchers is that life has never existed on Mars, that is not good enough proof to avoid a quarantine. Government policy in this area reflects the lack of understanding of the problem by the public at large. For example, the science fiction movie "Andromeda Strain", despite its lack of real life credibility, probably accurately reflects current public understanding.

At any rate, consideration should be given to several aspects of Mars life or Mars "bugs". If Mars life exists, these bugs would already have been exposed to oxidants in the Mars soil as strong as hydrogen peroxide. Their survival of such strong oxidants would presumably make them resistant to many known types of sterilization. Mars life could also exist as tough spore-like phases capable of surviving hard vacuum outside a returning spacecraft. Heat sterilization would be a certain method of killing any life. Exposure to 200°C for a few minutes breaks down complex molecules like DNA required for replication. Heat sterilization would almost certainly be an acceptable sterilization procedure.

The conclusion is that some requirements will have to be set for biological quarantine for missions to and from planets, particularly Mars.

- Outbound Missions from Space Station

Both manned and unmanned Mars missions and other planetary probes may require concern with biological cleanliness and sterilization of hardware. Sublimator water vapor and other vented gases must be demonstrated to be sterile. Venting EMU designs using sublimators or hollow fiber membranes pose the problem of releasing unacceptable biological loads. All unmanned planetary probes assembled at the Space Station will have to conform to the current Planetary Protection Policy.

- Mars Rover/Sample Return (MR/SR) Quarantine

Unmanned return to SSF of Mars Rover recovered samples has been thought through in some detail. A report issued March 31, 1988 under NASA contract NAS 9-17878 entitled "Mars Rover Sample Return Mission Requirements Affecting Space Station" addresses the quarantine issues. The MR/SR would require Mars samples kept at less than -40°C. Weight constraints on the Mars-Earth return vehicle would imply that sample canisters be removed from the return vehicle at or near SSF. The SSF is not the preferred location for a sample return drop-off. The preferred approach is direct entry of the MR/SR vehicle with air snatch of the canister, possibly by rendezvous in orbit. Such a drop-off may involve the Shuttle RMS. If SSF is involved, then a preferred approach is a hatch mounted unit with airlocks similar to those on JEM. In that case the canister transfer would involve the following steps:

1) Capture and dock of return vehicle

2) Stowage of return vehicle in on orbit stowage canister and ASE for return to Earth in Shuttle Payload Bay

3) Extraction of return canister from return vehicle

4) Transfer canister to airlock for processing

5) Transfer canister and enclosing airlock to Shuttle Payload Bay for deorbit

- Manned Mars Return Quarantine

Manned missions to Mars are less likely to involve concern with biological isolation than the MR/SR. Quarantine of the crew for 8-12 months during the return trip should be adequate.

BIOLOGICAL QUARANTINE

- **Summary**

  - Biological quarantine policy will be the basis for some requirements for EVA for missions to and from planets such as:

    - Outbound missions assembled at space station.
    - Unmanned sample return (Mars Rover/Sample Return)
    - Manned Mars mission

- **Conclusions**

  - Biological quarantine is a relatively minor issue
    - Most planetary missions do not integrate into SSF
  - Quarantine of inbound manned Mars mission will be completed in transit from Mars to Earth.
  - Analysis of specific mission requirements and vehicle configuration necessary to any quarantine requirements
  - If quarantine deemed necessary at SSF, limiting biological load on outbound vehicles may result in the following impacts
    - Venting EMU systems may have to shut down
    - Overgloves may be necessary

ASSESSMENT OF CONTAMINATION DETECTION AND REMOVAL

In order to ensure the safe assembly and maintenance of future space vehicles, possible contaminants had to be identified and then researched. The facing page lists possible places these contaminants may be found. It was then necessary to research how these contaminants could affect a worksite, particularly EVA crewmembers. A decontamination station is presently being developed for the Space Station airlock. It is relocatable, though not portable. A smaller and more portable station would have to be developed for assembly and maintenance work done on the Station truss extension.

Before future assembly and maintenance can be done safely, more research must be completed in the following areas:
- Spill clean-up time
- How will the worksite be cleaned? EVA? Sublimation
- Are there some materials that cannot be cleaned from a worksite?

RESULTS

The following page lists some of the possible contaminants and the associated vehicles. Tests are presently being conducted to determine what each will do to certain materials should a spill result.

Materials from the EMU was tested at White Sands Test Facility (Ref 21) for compatibility with different "contaminants" including water. Of significant result is the impact monomethylhydrazine had on the suit MLI, as noted below. However, recent tests have shown that a new material has been developed that can withstand the corrosive property of monomethylhydrazine. A coating possible of eliminating helmet cracking is also being tested.

At last look, the decontamination station was bolted to the outside of the airlock, thereby making it relocatable but not necessarily portable. It could accommodate two crewmembers at once, operating simultaneously. The unit includes IR lamps that heat an area which increase sublimation rates of the contaminants, two portable contamination detectors, and PFRs for two crewmembers. Testing showed that exposure to one solar constant increased evaporation 5-10 times over ambient level of radiation. Therefore, the provided heat lamps will play a significant role in worksite cleanup. Other decontamination concepts include brushing of particles, direct contact heaters and neutralizing or catalytic agents.

CONTAMINATION DETECTION AND REMOVAL

- Compatability of EMU materials with known SSF hazardous contaminants was assessed
  - Data from previous and on-going materials testing at WSTF was reviewed
    - Test contaminants include ammonia, dinitrogen tetroxide, hydrazine, and monomethyl hydrazine
  - Results
    - modifications necessary to previous suit design to protect suit insulation layers and helmet visor from damage
    - Testing with modifications indicate no degradation

- Baseline EVAS Portable Decontamination and Detection capabilities
  - Tested contaminants detectable under vacuum conditions
  - Sublimation rates of contaminants significantly increase with IR lamps
  - Decontamination of EMU crew is accommodated
  - Decontamination of affected worksites and other external EVAS equipment not fully addressed
    - Detection unit is portable
    - Portable IR lamps for decontamination of affected worksites and other external equipment may be necessary if operations time is critical

EVA OPERATIONS DATA REQUIREMENTS

The baseline C&T System provided the capability to transmit high data rates over the Ku-band space-to-space communications link to the EVA crewmembers prior to Tanner Audit and Scrub 89 program redirections. This capability afforded EVA astronauts rapid access to EVA crew operations data. It also provided the EVA astronaut access to new data generated by ground personnel that addressed unforseen EVA circumstances. This capability is significantly reduced, if not totally eliminated, by the imminent implementation of a UHF space-to-space communications link to EVA.

Potential EVA tasks at space station were assessed to provide a preliminary estimate of EVA operations data requirements. Tasks include those necessary for EMU and EVA operation, SSF maintenance (AMIDD), LTV refurbishment (Ref 9), MTV assembly (Ref 10), and contingencies. It is assumed that the EVA crewmembers need access to the data equivalent of one NSTS EVA cuff checklist page for each task. This approach provided an order of magnitude estimate of the volume of EVA operations data to be maintained on-orbit. Preliminary results indicate that more than 645 separate EVA tasks are likely. This estimate is likely to increase as SSF designs, transportation node and STV configurations, and user requirements mature.

Other factors affecting EVA operations data requirements include the need to easily update EVA datafiles, and those data requirements associated with concurrent or shared robotics and manned EVA tasks. A summary of USA EVA experience indicates that the flexibility to quickly update/augment EVA operations is highly desirable. An average of sixty percent of Skylab and Shuttle EVA were to fix problems. A few EVAs required on-orbit mission planning prior to EVA. An ability to update or generate specific EVA operations data by ground and on-board personnel with subsequent transmission to EVA crewmembers will enhance the likelihood of mission success.

Of the options available for the handling and display of EVA information, the baseline configuration satisfied all data access, update, and display needs. Least desired would be a return to a carry-around printed cuff checklist. Printed cuff checklists are not easily revised, require special materials and printing processes for vacuum compatability, and would require IV time to replace cuff checklist pages. Remaining options do not satisfy all needs but should be further investigated. A portable electronic display that plugged into worksite power and data interfaces would satisfy rapid data access and update needs. Power/data interfaces may not be available or practical at all worksite locations. Downloading task specific information into a memory chip in each EMU prior to EVA eliminates the dependence on space-to-space or exterior data links but also eliminates real-time updates. It is estimated that the equivalent of 50 cuff checklist pages consisting of 60% text and 40% graphics can be stored on one 286 Kbyte chip with a power penalty of 0.4 watts.

ASSESSMENT OF EVA OPERATIONS DATA REQUIREMENTS

- Approach
  - Estimate quantity of EVA operations data for the evolutionary station
    - EMU and EVA equipment operations
    - SSF Maintenance
      - (SSF Assembly and Maintenance Implementation Definition Document)
    - Lunar Vehicle Refurbishment
    - Mars Vehicle Assembly
    - Contingencies
  - Assess other requirements for crew operations data
  - Assess best approach for accessing EVA operations data
    - RF link to EMU Display (Baseline)
    - Worksite display link to DMS database
    - Data downloaded to EMU memory prior to EVA

RESULTS

- Quick assessment of EVA tasks (prime, backup, and contingency) associated with the evolutionary SSF indicates that a high quantity of EVA operational data is maintained on-orbit

	TASKS
• SSF WP2 Maintenance Tasks (AMIDD)	
— ORU Replacement	280
— ORU Clearing	46
— ORU Lubrication	35
— ORU Adjustment	85
• Other SSF WPs	TBD (44)
• EMU Operations (NSTS EMU)	38
• Lunar Vehicle Refurbishment	
— Planned	44
— Planned Contingency	6
• Mars (Phobos/Gateway) Vehicle Assembly	
— Planned	38
— Planned Contingency (one per external system)	6
• Hanger Operations/Contingencies	TBD (5)
• EVA System Contingencies	TBD (5)
• MSC/EVA Workstation Operations	1
• User Support payloads approved	12

RESULTS (CONTINUED)

- U.S.A. EVA experience indicates that flexibility to easily update EVA operations data is highly desirable
  - 60% of recent EVA experience (Skylab, Shuttle) were to fix problems
    - Most of these were payload related
    - Some required real-time mission planning prior to EVA (fly swatter EVA)
- A need for near real-time operations feed back to EVA crewmember is also indicated
  - Update of robot and robot task status during robot assisted EVA tasks

- Of the options identified, the baseline configuration satisfied these needs
  - RF link to EMU display (best)

- A paper system is inadequate to support those needs
  - Cuff checklist update not easy
  - Special materials and printing process required
  - IV time for logistics
  - No real-time update

RESULTS

- Remaining options should be further investigated
  - Portable display plugged into SSF power and data ports at worksite
    - Satisfies data flexibility
    - High degree of power data/interfaces indicated
  - Download necessary operational data into a memory chip in the EMU prior to EVA
    - Satisfies data flexibility except for real-time interfaces
    - Equivalent of 50 pgs. of cuff checklist (60% text, 40% graphics) can be stored on one 286 K byte chip
    - Power penalty of .4 watt for data storage

POTENTIAL SSF EVA DTO'S TO SUPPORT TRANSPORTATION NODE

Assembly and servicing of lunar and Mars transfer vehicles will require extensive EVA operations not currently practiced. DTO's will be necessary for many of these operations to assure success and safety.

Aerobrake assembly is among the most challenging. Methods of manipulating and securing portions of these large structures as well as inspection and repair over the large surface must be tested due to the distance of these from current operations.

Safety critical operations such as fuel transfer and decontamination or EVA outside of LEO, such as in transit to Mars, should be identified and tested.

EVA relationship to telerobotics must be explored to be properly exploited. Telerobotic development will produce new tools that could be used effectively by EVA crewman. The telerobotic systems themselves must be evaluated as tools for EVA. Contingency scenarios for telerobot failure should also be tested as the reliance on telerobotic systems increases.

POTENTIAL SSF EVA DTOs TO SUPPORT TRANSPORTATION NODE

- Evaluate aerobrake assembly techniques
  - Torquing large number of bolts
- On-orbit fuel transfer techniques
- Aerobrake inspection and TPS repair techniques
- Practice possible contingency EVAs for Lunar and Mars vehicles during transit
  - TEIS manual jettison
- Evaluate special tool and end effectors
- Evaluate EVA backup capabilities and techniques to work around RMS/FTS contingencies during assembly and/or other prime robot tasks
- Evaluate decontamination scenarios
- Evaluate shared EVA crew and robotic tasks

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DATA MANAGEMENT SYSTEM (DMS) EVOLUTION ANALYSIS

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February 7, 1990

GOALS

- To Ensure DMS Provisions for Growth & Technology Insertion
  - Planned and graceful evolution
  - Technology transparency
  - System growth margins

- To Ensure DMS Provisions to Support New Requirements
  - Evolving operations & user requirements
  - New Initiative Missions requirements
    - Manned Lunar Base
    - Humans to Mars

NOTES - GOALS

The all encompassing goal for the Data Management System (DMS) Evolution Analysis task is to develop an advocacy for ensuring that growth and technology insertion issues are properly and adequately addressed during DMS requirements specification, design, and development. The most efficient methods of addressing those issues are via planned and graceful evolution, technology transparency, and system growth margins. It is necessary that provisions, such as those previously mentioned, are made to accommodate advanced missions requirements (e.g., Human Space Exploration Programs) in addition to evolving Space Station Freedom operations and user requirements .

OBJECTIVES

- Identify/Define/Understand Evolutionary Impacts on DMS
  - Growth on DMS baseline design
  - Lack of evolutionary planning
- Define/Identify/Recommend DMS Baseline Design Accommodations
  - For SSF evolution
  - For future space activities
- Evaluate/Analyze DMS Evolutionary Baseline Capability

NOTES - OBJECTIVES

In order to achieve the identified goal for the Data Management System (DMS) Evolution Analysis task, several objectives have been established.

It is important to identify and understand the impacts that growth (i.e., in requirements, capabilities, etc.) and the lack of planning for evolution can possibly impose on the DMS baseline design. However, before these impacts can be adequately assessed, the DMS baseline design evolutionary accommodations which have been presented by the Work Package 2 (WP-2) Contractor must be identified and analyzed. To analyze the described provisions in the WP-2 Contractor-provided documentation and to analyze and recommend the evaluation of DMS evolutionary baseline capabilities via prototyping in the DMS Testbed environment can assist in obtaining early details of DMS evolutionary capabilities. If no accommodations can be clearly identified from the WP-2 Contractor's documentation and prototype design, as part of this task, provisions to accommodate evolutionary requirements will be defined and recommended to pertinent personnel and organizations (i.e., DMS System Integration and Development Managers, JSC Project Office, WP-2 Contractor, etc.).

APPROACH

- Identification of DMS Evolutionary Requirements
  - Analysis of baselined documentation
- Identification of DMS Evolutionary Baseline Design Features
  - Hardware scars & software hooks
  - Technology transparency
  - Growth flexibility
  - System design margins
- Recommendations/Comments about DMS Design Approach

NOTES - APPROACH

All Space Station Freedom (SSF) requirements have impacts, either directly or indirectly, upon the Data Management System (DMS) because of the unique integrated relationships of DMS with other distributed systems.

The major thrust of the DMS Evolution Analysis activities is to investigate SSF evolutionary growth requirements together with currently proposed DMS plans, architectures, and capabilities, and to ascertain whether or not these are reconcilable.

Mission evolution requirements, which feed system-level requirements, are numerous and arrive from a variety of sources. Growth at the mission level implies growth/enhanced capability at the system level and imposes incremental resource requirements. Thus, mission resource requirements become part of overall systems requirements. SSF systems requirements are governed by SSP 30000, JSC 31000, and various other documents such as the DMS Architectural Control Document (JSC 30261).

This DMS Evolution Analysis task began with the analysis of NASA baselined requirements documents (SSP 30000 and JSC 31000) to identify/establish DMS evolutionary requirements. These requirements were compiled and are continually being monitored for changes that may result from requirement reviews. Once the requirements had been identified, the evolutionary baseline design features that were proposed by the Work Package 2 (WP-2) Contractor in accordance with the requirements are being analyzed. This includes the identification and assessment of hardware scars, software hooks, technology transparency, and system growth flexibility.

Any comments and/or recommendations that result from the analysis of the design approach will be presented to the WP-2 Contractor for consideration and/or integration into their technology analysis process.

SYSTEM GROWTH REQUIREMENTS (JSC 31000)

- Processing & Memory Capacity Margins
    - Local memory capacity
        - Growth from minimum 4 Megabytes up to 32 Megabytes
    - Flexible memory configuration
        - Memory increments by "plug-in" installation

- Data System Resources Addition
    - Spare network ports
    - Network segments additions

- Standard, Documented, Non-proprietary Interfaces

WP-2 BASELINE DESIGNS TO MEET JSC 31000 EVOLUTIONARY REQUIREMENTS FOR GROWTH

CORE CAPACITY	GROWTH	DESIGN APPROACH/SCAR
4 MIPS processor w/ 4 MByte memory	Support advanced AI appls. up to 32 MBytes	Technology upgrade to an 8 MIPS processor with direct card replacement; empty slots in ORU for added memory capacity
100 Mbps fiber optic network	Add payload system resources & services to support growth	Comprehensive modular design, resource margins, spare ports, & network expansion provisions
Magnetic disk MSU	DBMS w/ growth capacity	Commercial DBMS which is not size limited; media-independent MSU allows technology insertion (e.g., optical R/W media); spare ports

TECHNOLOGY TRANSPARENCY REQUIREMENTS (JSC 31000)

- No Major Redesign, Revalidation, or Program Interruption
  - System technology changes
  - Functional capability changes
  - Resource availability changes
- Modular Hardware and Software Designs
- Hooks & Scars
  - Automation & Robotics
    - Autonomous fault identification & recovery
  - Voice activation in Multipurpose Application Console

WP-2 BASELINE DESIGNS TO MEET JSC 31000 EVOLUTIONARY REQUIREMENTS FOR TECHNOLOGY TRANSPARENCY

CORE CAPABILITY	TECHNOLOGY TRANSPARENCY	DESIGN APPROACH/SCAR
Integrated Expert Systems (ES) in AC OMS for Monitor & Control	Evolutionary application of ES to advanced appls.; growth in AI technologies	Spare slots in ORUs & ports on network to add ES engines; seed ES's with hooks for modular expansions; expansions to maintenance, inventory management
	Complex information interfaces of telerobotics	ISO/OSI-based communication protocol allows generalized data passing capability with interface transparency
	Provision for insertion of new technologies at black box, ORU, subsystem & system level	Standard interfaces at all points comm., protocol, ORU backplanes, local buses, etc.; modular layered H/W & S/W to isolate effects of technology upgrades
	Evolutionary implementation of natural language, continuous speech recognition	Voice recognition incorporated into MPAC; standard interfaces to spare slots in MPAC to accommodate future advanced voice processors
	Onboard intelligent access to CAD/CAM/CAE databases	Commercially based DBMS promotes space ground compatibility with TMS

APPROACH (contd.)

- Impacts
  - General growth of DMS on baseline design
    - Benefits
    - Costs
  - Failure to scar assess
    - Growth capability limitations
    - Major design
      - Technology insertions (upgrades)
- Assessment of Applicable "Lessons Learned"
  - LaRC/Harris "DMS Technology Transparency" Study

NOTES - APPROACH (contd.)

Impact assessment of a system's design is an important part of the overall system analysis process. To date, the Data Management System (DMS) Evolution Analysis task has focused on the impacts in two particular areas - (1) the general growth of DMS on its baseline design, and (2) the failure to scar assess DMS design implementation.

Work Package 2 Contractor's DMS evolutionary design approaches are analyzed in terms of the expected benefits and costs. Benefits are quantified in terms of mission scenario impacts, productivity enhancements, safe designs, system reliability, ease of maintenance, use of common hardware and software, and flexibility to accommodate automation and robotics and other new technologies. Costs include initial hook and scar accommodations and life-cycle costs.

Certainly, to design a system to support a long-lived program, as Space Station, would be extremely costly and unbeneficial to neglect provisions for evolution (i.e., growth and technology insertion). Over a period of time, which could be relatively short with such rapid technological advancements, the cost of supporting obsolete elements/technology could become astronomical; therefore in such a case, replacement technology is more cost-effective. In the case in which new requirements are defined, new functions may be needed; and in turn, the implementation of these new functions may require new technology. If system growth and technology transparency capabilities have not been planned and provided, major redesign may be inevitable.

Lessons learned from previous experiences can be a valuable source. They can be used as guidelines or cheklists for design efforts. The Langley Research Center (LaRC)/Harris Corporation study, "DMS Technology Transparency", contains an applicable knowledge base for the Space Station DMS design.

NEAR-TERM PRODUCTS

- Generation of Reports
  - Contents
    - Report 1 - DMS evolution hooks & scars
    - Report 2 - DMS technology impact
  - Anticipated completion date
    - April 1990

NOTES - NEAR-TERM PRODUCTS

Two reports which discuss the to-date findings of the DMS evolution requirements and capabilities are being generated. One report (1) analyzes the requirements that may be imposed on DMS during the 30-year mission of Space Station Freedom (SSF) and (2) the software "hooks" and hardware "scars" that should be in place at the onset of the mission to ensure the ability of DMS to satisfy those long term mission requirements. These requirements include Lunar Base and Mars Mission support, and autonomous operation of SSF.

The other report analyzes trends in technological advances that may be of interest to the SSF Program for upgrdes to the DMS equipment during the 30-year mission of SSF. This report suggests baseline configuration that would best ease the insertion of these new technologies into an existing system.

These reported are to be completed by April 1990.

FUTURE PLANS

- Identify/Understand New Initiative Missions Requirements
    - Manned Lunar Base
    - Humans to Mars
- Study/Investigate DMS Accommodation Capabilities of New Initiative Missions Requirements

NOTES - FUTURE PLANS

The Human Exploration Initiatives (e.g., Lunar/Mars Missions) with their anticipated new architectures, systems concepts, and technologies, and innovative uses of existing technologies will most assuredly impose demands on Space Station Freedom (SSF) resources.

By reviewing presentation materials and documentation, the mission requirements that have potential impact on the SSF Data Management System (DMS) design can be identified and understood.

In order to avoid redesign or major systems disruption, it is necessary that the DMS design is adequately scarred to accommodate such mission requirements as referenced and more that will probably be later defined. Work Package 2 (WP-2) Contractor's DMS evolutionary plan has been developed to consider a wide range of potential growth requirements from various sources; however, as part of this DMS Evolution Analysis task, Human Exploration Initiatives requirements will be specifically compared with DMS capabilities obtainable with WP-2 currently proposed DMS architecture and design parameters.

SSF DMS DELTA BUILDUP FOR LUNAR / MARS INITIATIVES

First Node Event 1999 (delta to AC)	Lunar Mission Node 1 2000 (delta to 1st node event)	Lunar Mission Node 2 2003 (delta to LMN1)	Lunar & Mars Mission Node 2015 (delta to LMN2)
+Local bus & high rate links in LTV area (Support data comm for vehicle processing) +2 workstations (Control LTV processing activities)		+Local bus & high rate links in CSF area (Support data comm for CSF activities) +1 workstation (Control CSF processing activities)	+Local bus & high rate links in MTV area (Support data comm for MTV processing)

SSF DMS TOTAL SYSTEM REQUIREMENTS FOR LUNAR / MARS INITIATIVES

First Node Event 1999 (1st LTV mission)	Lunar Mission Node 1 2000 (expendable LTVs)	Lunar Mission Node 2 2003 (reusable LTVs)	Lunar & Mars Mission Node 2015
Assembly complete capability	Assembly complete capability	Assembly complete capability	Assembly complete capability
Local bus and high rate links in LTV processing area	Local bus and high rate links in LTV processing area	Local bus and high rate links in LTV & CSF processing area	Local bus and high rate links in LTV, MTV, & CSF processing area
10 fixed workstations	10 fixed workstations	11 fixed workstations	11 fixed workstations

FUTURE PLANS (contd.)

- System Analysis Updates
    - Influential Inputs
        - Changing/Evolving requirements
        - Design changes
    - Comments/Recommendations/Reports

- Investigation of System Representational Methodology
    - Purpose
        - To reconcile mission & system requirements with proposed DMS capabilities
    - Trade study for computer-aided system

- Inputs to DMS Advanced Technologies Evaluation/Study
    - Future capability needs
        - Enabling/Enhancing technology needs
        - Automation

NOTES - FUTURE PLANS (contd.)

At this phase in the Space Station Freedom (SSF) Program, requirements are still evolving, and so is the architecture. Consequently, the system analysis process which has been described for this Data Management System (DMS) Evolution Analysis task is not a "finite" process, instead it is very much iterative. As information is gathered and compiled, interim reports, comments, and recommendations will result.

The SSF DMS requirements and architectural design information currently is in a state of flux, owing to impending software and the overall DMS preliminary design reviews (PDR). Some of it is in document form, and some must be obtained through a series of dialogues with concerned individuals. Therefore, in order to reconcile requirements with the Work Package 2 proposed architectural and design capabilities, a special type of representational methodology will be investigated. This methodology could also assist in simulation processes, based upon various types of models and other system descriptions. In order to accommodate simulations, if so desired, trade studies will be performed for a computer-aided system for handling system representations, with requirement information as input, and with parameters, structures, and data suitable to drive simulators as output.

The system evolution analysis process is helping to reveal future capability needs which can possibly be fulfilled with the use of advanced technologies. It will prove useful to be able to evaluate the capabilities of candidate advanced technologies along with their upward compatibility with the already proven and presently used technologies. Inputs from this DMS Evolution Analysis task into the DMS Advanced Technologies Evaluation/Study task will help to ensure technology readiness for anticipated future capabilities.

SPACE STATION FREEDOM
CENTRAL THERMAL CONTROL SYSTEM EVOLUTION

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For Presentation at the Space Station Evolution Symposium
South Shore Harbour, League City, Texas
February 6-8, 1990

OBJECTIVE

The objective of the evolution study is to review the proposed growth scenarios for Space Station Freedom and identify the major CTCS hardware scars and software hooks required to facilitate planned growth and technology obsolescence.

The Station's two leading evolutionary configurations are: (1) the Research and Development node, where the fundamental mission is scientific research and commercial endeavors, and (2) the Transportation node, where the emphasis is on supporting Lunar and Mars human exploration. These two nodes evolve from the from the assembly complete configuration by the addition of manned modules, pocket labs, resource nodes, attached payloads, customer servicing facility, and an upper and lower keel and boom truss structure. In the case of the R & D node, the role of the dual keel will be to support external payloads for scientific research. In the case of the Transportation node, the keel will support the Lunar (LTV) and Mars (MTV) transportation vehicle service facilities in addition to external payloads. The transverse boom is extended outboard of the alpha gimbal to accommodate the new solar dynamic arrays for power generation, which will supplement the photovoltaic system.

The design, development, deployment, and operation of SSF will take place over a 30 year time period and new innovations and maturation in technologies can be expected. Evolutionary planning must include the obsolescence and insertion of the new technologies over the life of the program, and the technology growth issues must be addressed in parallel with the development of the baseline thermal control system. Technologies that mature and are available within the next 10 years are best suited for evolutionary consideration as the growth phase begins in the year 2000. To increase TCS capability to accommodate growth using baseline technology would require some penalty in mass, volume, EVA time, manifesting, and operational support. To be cost effective the capabilities of the heat acquisition, transport, and rejection subsystems must be increased.

OBJECTIVE

IDENTIFY PRINCIPAL HOOKS AND SCARS FOR SSF TCS GROWTH

- RESOURCE GROWTH - Physical Expansion
  - R & D Node: 300kW, +4 Modules, +4 Nodes, +3 Pocket Labs, CSF, Dual Keel
  - TRAN Node: 175kW, +2 Modules, +4 Nodes, +1 Pocket Lab, CSF, Dual Keel, LTV, MTV

- TECHNOLOGY GROWTH - Technology Upgrades
  - 30 Year Program Can Expect Technology Obsolesence
  - Continued Utilization of Baseline Technology Will Substantially Increase:
    - Radiator Area and Associated Sweep Volume
    - EVA Assembly Time
    - Orbiter Manifesting Penalities (Weight & Volume)
    - Orbital and Ground Operational, Maintenance, and Repair Support
  - Cost Effective Growth of the Evolutionary TCS Requires
    - Increased Capability in the Heat Acquisition, Transport, and Rejection Subsystems
    - More Automonous Monitoring and Controls
    - Essential Analytical Tools Must Be Developed

AGENDA

The presentation begins with a review of the TCS requirements for growth. The principal hooks and scars are then identified followed by the provisions for growth and design issues for each subsystem. The major technology issues are discussed, and finally the conclusions are presented.

AGENDA

- REVIEW OF TCS GROWTH REQUIREMENTS
- IDENTIFY THE PRINCIPAL CTCS HOOKS AND SCARS AT ASSEMBLY COMPLETE
- DESCRIBE THE PROVISIONS AND PERTINENT DESIGN ISSUES FOR EACH SUBSYSTEM TO ACCOMMODATE GROWTH TO THE R & D NODE OR TRANSPORTATION NODE
- IDENTIFY MAJOR TECHNOLOGY GROWTH ISSUES AND REQUIREMENTS
- CONCLUSIONS

TCS REQUIREMENTS FOR GROWTH

As a result of the program rephasing in late 1989, the most recent Space Station program documentation does not reference growth. Previous SSP documentation, such as the SSP 30000, JSC 31000, and SSP 30258, addressed growth issues of functionality, operation, TCS capacity, adding individual systems and elements, component modularity, and technology insertion. The JSC 31000 is a Johnson Space Center (WP2) document that reflects the higher level requirements specified in both the SSP 30000 and the TCS Architectural Control Document SSP 30258.

The most notable growth requirement is the fourfould increase in heat rejection for the R & D node at 325 kW, and for the transportation node it more than doubles at 200 kW. In general the requirements for growth are the same as for assembly complete. Modularity is very important to growth in that at the ORU level upgrades are technologically transparent and do not introduce integration problems. Modularity also supports the need for technology upgrades to be introduced without causing a major system interruption. .

TCS REQUIREMENTS FOR GROWTH

	TCS REQUIREMENT	APPLICATION
*	HEAT REJECTION CAPABILITY	75 kW (82.2 kW) --› 300 kW (325) or 175 kW (200)
	ON ORBIT RECONFIGURATION	VARIABLE TEMPERATURE LEVEL, HEAT LOAD
*	MODULARITY	SPACE ERECTABLE, REPLACEABLE
	SAFETY	95% MINIMUM OPERATIONAL CAPABILITY
	LEAK DETECTION	5% PER YR (PER LOOP) MAX LEAKAGE
	QUIESCENT OPERATION	10% OF FULL LOAD
	REDUNDANCY	TWO FAULT TOLERANCE
	ISOTHERMALITY	±2.0°C
	MONITOR & CONTROL	MINIMUM CREW INVOLVEMENT
*	TECHNOLOGY ACCOMMODATION	NO MAJOR SYSTEM INTERUPTION

PRINCIPAL HOOKS AND SCARS

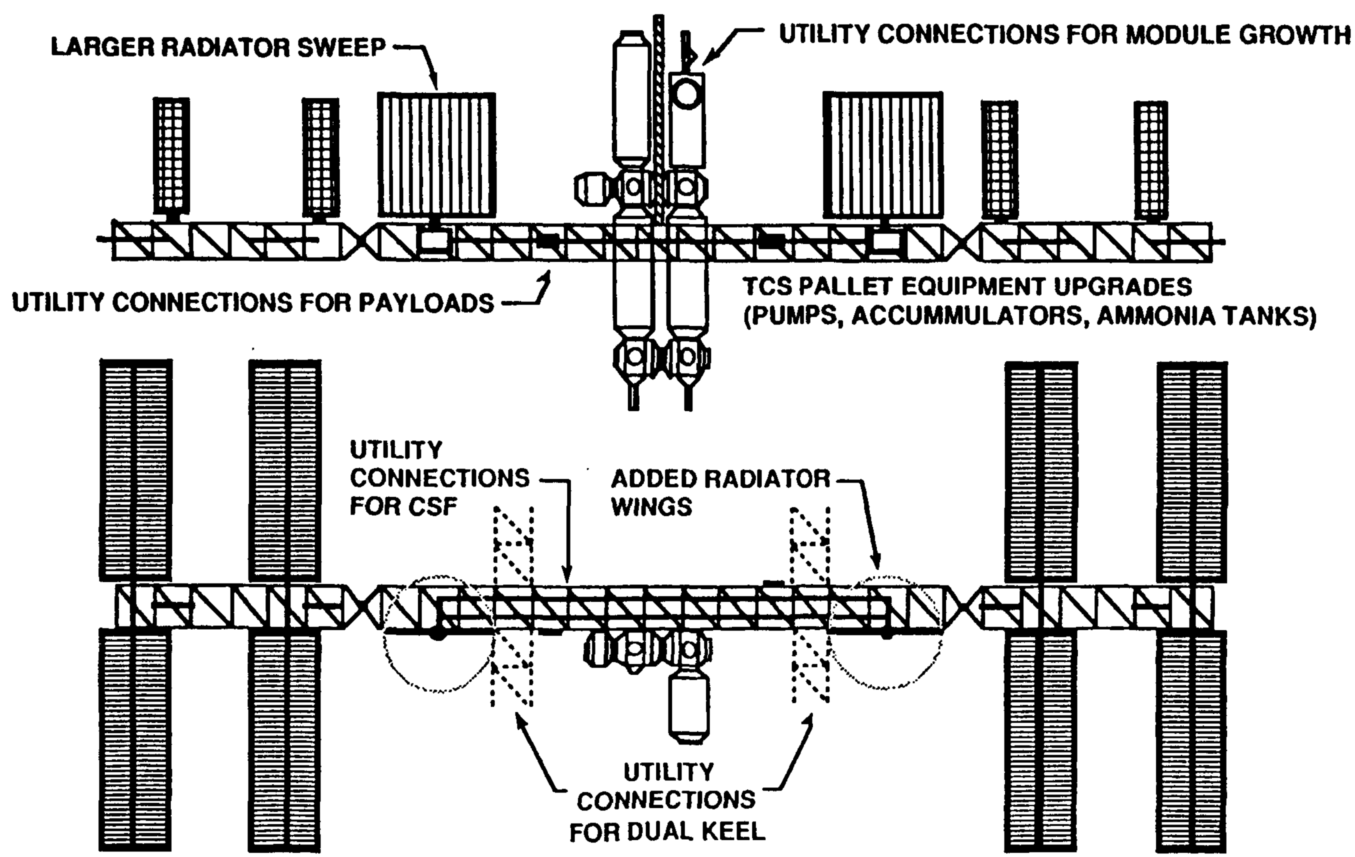
The principal scars to the CTCS to accommodate growth are similar for both the Research and Development node and the Transportation node. Growth elements include added modules; a dual keel with an upper/lower boom; a servicing facility; attached payloads and, in the case of the Transportation node, Lunar and Mars transportation vehicle servicing facilities.

The principal scars to the CTCS include:

- Utility connections for module growth, attached payloads, customer servicing facility, dual keel, LTV facility, and MTV facility.
- Larger thermal radiator wing sweep radius due to added radiator panels.
- Two added thermal radiator wings.
- Upgrading of TCS pallet equipment (pumps, accumulators, filters, etc.) to support the higher ammonia mass flow rates.
- Upgrading and expansion of the TCS monitoring and controls software and hardware to support the added TCS equipment.

PRINCIPAL HOOKS AND SCARS

PRINCIPAL HOOKS AND SCARS FOR R & D NODE AND TRANSPORTATION NODE ARE SIMILAR



EXPANSION OF TCS MONITORING & CONTROLS SUBSYSTEM (SHARED SPD AND MDM'S)

CTCS FLOW SCHEMATIC AND SUBSYSTEMS

The CTCS collects heat from heat sources and transports the heat to thermal condensers where it is rejected to space. It consists of two fully redundant ammonia loops (4 total), one operating at 2°C (35°F) and the other at 21°C (70°F). The moderate temperature loop (21°C) can be reconfigured to a low temperature loop if required. At assembly complete, the CTCS is designed for a maximum heat rejection of up to 82.2 kW, which is comprised of electrical (75 kW), metabolic (136.7 W/person), parasitic, and environmental thermal loads.

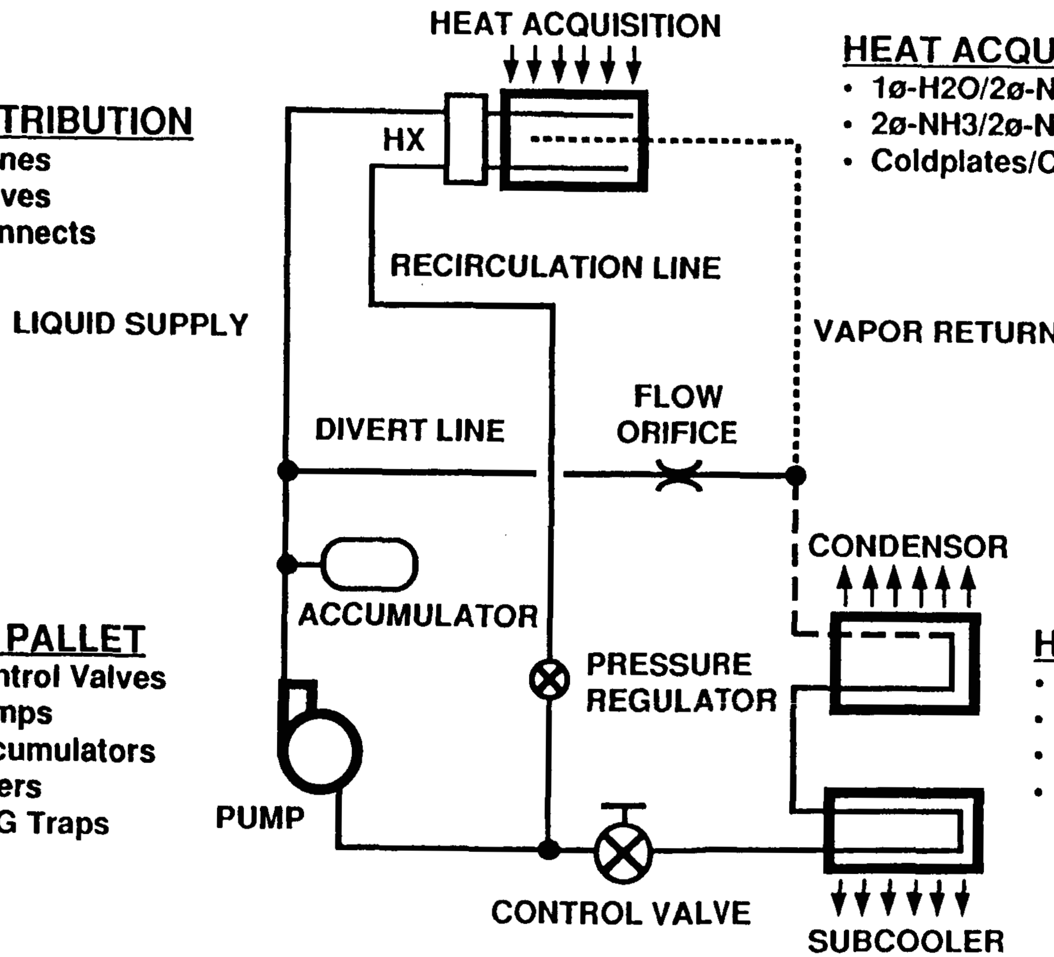
The heat acquisition devices (HAD's) collect heat from several different types of equipment, so several interface geometries are used. The HAD's absorb heat through an evaporation (latent heat) process which enables the bus to maintain a nearly constant temperature. The vapor is transported through the vapor lines to the condensers, and the unused liquid is returned to the pump after passing through a supply/return heat exchanger local to each HAD. The HAD's are mounted on the exterior endcones of the modules and nodes. The HAD's and condensers are interconnected by transport lines in utility trays which shield the liquid and vapor lines from damage caused by orbital debris. The pumping equipment and the thermal radiators are located at each end of the Transverse boom, inboard of the alpha gimbals. The pallet equipment includes pumps, filters, accumulators, and control valves. The heat rejection system consists of dual thermal radiator wings made of modular heat pipe radiator panels. The radiator wings are rotated about the X-axis to maintain a "cold" thermal environment during Earth-orbit. Radiator rotation is made possible through a rotary fluid coupler (RFC) mounted directly to the CTCS pallet. The RFC allows liquid and vapor to pass through the device yet enables continuous rotation through 360°.

The provisions for growth and design issues for the major CTCS subsystems: heat acquisition, heat transport, TCS pallet equipment, and heat rejection are discussed in the sections that follow.

CTCS FLOW SCHEMATIC AND SUBSYSTEMS

UTILITY DISTRIBUTION
- Transport Lines
- Isolation Valves
- Quick Disconnects

HEAT ACQUISITION
- 1ø-H2O/2ø-NH3 HAD
- 2ø-NH3/2ø-NH3 HAD
- Coldplates/Coldrails HAD



TCS PALLET
- Control Valves
- Pumps
- Accumulators
- Filters
- NCG Traps

HEAT REJECTION
- Radiator Panels
- Condensers
- Subcoolers
- Rotary Fluid Couplers

HEAT ACQUISITION GROWTH

Growth of the heat acquisition system is related directly to the number of new elements that are planned for growth. The Station elements and the corresponding number of heat exchangers for the assembly complete configuration increase from 40 at assembly complete to 141 for the R & D node and 101 for the Transportation node. For the purposes of assessing growth requirements it was assumed that the external payloads are actively cooled. The HAD total weight increases from 4660 lbs at assembly complete to 15570 lbs for the R & D node and 10890 lbs for the Transportation node.

To understand the impact on the CTCS of adding (capillary) HAD's, it is necessary to explain the operational characteristics of the HAD. HAD operation is dependent on specific line pressures in the supply, return, and vapor tubes. The pump supply pressure is throttled and mass flow rate is regulated by an orifice at the inlet of each HAD. The minimum flow rate depends on the HAD thermal capacity, but is approximately 150% of that required for the design heat load. The liquid first passes through a supply-return heat exchanger to raise its temperature from a subcooled state. This process also provides cooling to the low quality return liquid. The maximum HAD pressure occurs in the vapor line and is set by the saturation pressure corresponding to the bus operating temperature. The minimum pressure is in the return line and must exceed the bubble point pressure of the wick to prevent HAD dryout, which is about 10 psid below the vapor pressure. The HAD supply pressure, downstream of the orifice, is less than the vapor pressure but greater than the return line pressure. Some consequences of violating these pressure limits are (1) HAD flooding if the supply line pressure exceeds the vapor pressure; and (2) the HAD will become inoperable if the supply pressure falls below the wick bubble point pressure causing a loss of suction in the return line.

A pump, oversized during the growth phase, will impose a higher system supply pressure than initially required, but is necessary to support the longer supply line lengths and the new flow requirement that accompanies expansion. The complication arises with the flow redistribution. The flow control orifices, local to each HAD, must be adjusted individually as the system changes. Each adjustment depends, in part, on the particular HAD location and design heat load, and must also satisfy the pressure limits stated above. For growth, the orifices should be variable sizing and adjustable from remote locations by the TCS control system. Instrumentation will also be required at each HAD to measure flow rate and line pressures to assist in making the adjustments.

HEAT ACQUISITION GROWTH

RESOURCE	AC		R & D		TRANS	
	UNITS	HX/CP	UNITS	HX/CP	UNITS	HX/CP
MODULES	2 US, 2 I	12	6 US, 2 I	28	4 US, 2 I	20
RESOURCE NODES	4	8	8	16	8	16
POCKET LABS	-	-	3	6	1	2
ATTACHED PAYLOADS	-	-	18	36	8	16
CSF	-	-	1	3	1	3
LTV + MTV FACILITY	-	-	-	-	1	4
DDCU COLDPLATES	20	20	52	52	40	40
TOTAL HX	40		141		101	
TOTAL WEIGHT (LBS)	4660		15570		10890	

PROVISIONS FOR GROWTH

- VARIABLE FLOW ORIFICES WILL BE REQUIRED FOR CAPILLARY HAD'S TO ACCOMMODATE ADJUSTMENTS IN SYSTEM PRESSURE AND FLOW RATES ASSOCIATED WITH PHASED GROWTH
- GROWTH STUBS ARE REQUIRED ON THE SECONDARY (OR UMBILICAL) CTCS BRANCH FEEDS OFF THE TRANSVERSE BOOM FOR EXPANSION OF THE MODULES AND NODES

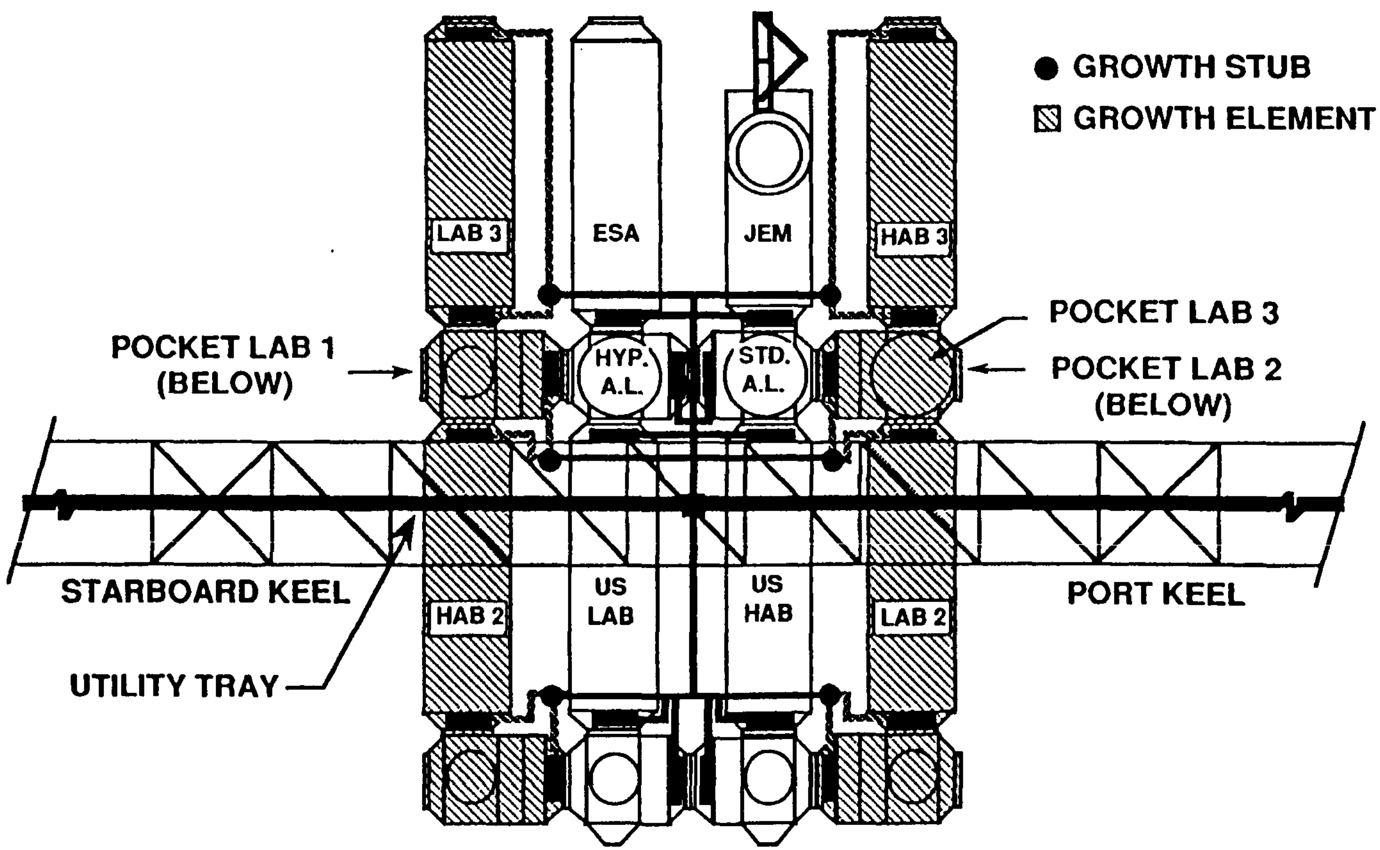
R & D MODULE CTCS FLUID DISTRIBUTION

A preliminary layout of the fluid distribution system for the R & D and node is shown, and is similar for the Transportation node. A characteristic of module growth for both nodes is that it occurs in the ±Y direction (along the transverse boom) - not in the ±Z direction. The ±X direction has always been preserved for orbiter docking maneuvers. Growth stubs will be required in the secondary (or umbilical) CTCS branch feeds to accommodate the expansion of the transport lines for the added modules, resource nodes, and pocket labs. These are required in both the primary and redundant distribution lines and consist of isolation valves and quick disconnects.

R & D MODULE ATCS FLUID DISTRIBUTION

(PRELIMINARY)

MODULE GROWTH IS IN THE ±Y DIRECTION. GROWTH STUBS ARE TO BE PROVIDED ON THE SECONDARY ATCS FLUID DISTRIBUTION BRANCH.



UTILITY DISTRIBUTION GROWTH

Ammonia distribution is baselined as part of a dedicated fluid utility system, meaning it is independent of EPS and DMS distribution lines. Two fluid trays run parallel with the transverse boom, one positioned in the upper and the other in the lower quadrant of the truss assembly. In each tray, the TCS transport lines consist of two liquid supply lines, two recirculation lines, two vapor lines, plus two liquid and two vapor crossover lines. The transport lines are not ORU's in the strictest sense, therefore, for growth, it is essential that the transport lines be sized for the mass flow rate corresponding to the highest expected heat rejection requirement over the life of the Station. The valves and quick disconnects must be sized accordingly. The transport lines should be sized at 325 kW for the R & D node and 200 kW for the Transportation node. For growth, the total line length increases from 7000 feet at assembly complete to approximately 13600 feet (2.6 miles). The weight of the transport lines (without ammonia), valves, and quick disconnects increases from 1610 lbs to approximately 10500 lbs.

Utility ports to accommodate future connections to the CTCS transport lines are necessary. The MDSSC "pop-up" utility port is essential for this growth provision and is installed as a link in the utility tray during Station assembly. The dual keel will extend in the $\pm Z$ direction and will require utility ports at PB4 and SB5. It is important that the heat rejection requirements on the upper and lower keel/boom be defined to allow proper sizing of the valve connections as a growth scar. The keels involve long line lengths and pressure drop will be a governing factor. The customer servicing facility will require a utility connection at SB3 (upper).

TCS growth requirements for other distributed systems are also being identified for growth planning. These include (1) Communications and Tracking, (2) Guidance, Navigation, and Control, (3) Extravehicular Activity Systems, (4) Data Management System, and (5) Propulsion. The results of these studies are not yet available.

From a growth perspective, the passive heat rejection requirement for attached payloads should be supplimented with a provision for active cooling. Passive heat rejection techniques require specific viewing orientations and could experience degraded performance as the Station changes, such as with the addition of the dual keel and other growth elements. The scar to the Station for including this provision is minimal and consists of a "pop-up" utility port.

UTILITY DISTRIBUTION SYSTEM GROWTH

ITEM	AC	R&D	TRAN.
LINE LENGTH (FT)	7000	13415	13605
VALVES/QD'S	390	1005	895
TOTAL WEIGHT (LBM)	1610	11170	9660

PROVISIONS FOR GROWTH

- LINES, VALVES, AND QD'S NEED TO BE SIZED FOR GROWTH
- DEPLOYABLE "POP-UP" UTILITY PORTS REQUIRED FOR DUAL KEEL (PB4, SB5) AND CUSTOMER SERVICE FACILITY (SB3)

DESIGN ISSUES

- TCS GROWTH REQUIREMENTS FOR DMS, GN&C, C&T, AND EVA HAVE YET TO BE SPECIFIED
- PTCS IS BASELINED FOR ATTACHED PAYLOADS AND PALLETS. PASSIVE HEAT REJECTION HAS RESTRICTED VIEWING REQUIREMENTS WHICH MAY BE DIFFICULT TO PRESERVE WITH GROWTH. CTCS UTILITY PORTS WILL BE REQUIRED IF ACTIVE COOLING IS REQUIRED IN THE FUTURE
- THERMAL REQUIREMENTS FOR DUAL KEEL ARE NEEDED FOR TCS GROWTH PLANNING

TCS PALLET GROWTH

The heat transport system consists of pumping equipment located on two TCS pallets and transport lines which are routed throughout the Station. The pumping equipment is essentially identical for each of the four thermal loops and includes: (1) for active components - pumps, accumulators, control valves; and, (2) for passive components - dual filter systems, noncondensible gas traps (NCG), and flow orifices. This equipment is located on the starboard pallet at SB7 and the on port pallet at PB6. Four supply and dump tanks are located on each pallet, but are common to all four loops. The thermal radiator wing and pallet equipment are interconnected through the rotary fluid coupler mounted to each pallet. Crossover lines interconnect the thermal radiator wings with each thermal loop, although only the radiator wing at the pallet where the loop pumping equipment is located is utilized under normal operation. The thermal radiator wing on the opposite pallet is available for redundancy. The HAD thermal load is equally divided, at each temperature, between the primary and redundant systems.

Growth requirements for the CTCS pallet equipment are not major since the quantity of equipment remains the same - only the size changes. The pumps (8), accumulators (2), filters (8), and noncondensible gas traps (4) are ORU's and will require upgrading to higher capacity units to accommodate larger ammonia mass flow rates. The most significant impact to pallet growth is the reserved volume allocation and fluid connections for the new forward rotary fluid couplers mounted on each pallet. The dual radiator wing are deployed in the fore (+X) and aft (-X) directions.

The Station ammonia inventory will increase with the addition of the new heat exchangers, transport tubing, and dual keel. The inventory is a function of the volume in the liquid and vapor lines where the addition of the dual keel has a large affect. The total ammonia inventory increases by approximately 41% - from 1860 lbm to 2625 lbm. The ammonia inventory at assembly complete will be insufficient and will require greater allocation for growth.

TCS PALLET GROWTH

QUANTITY DOESN'T CHANGE - ONLY SIZE

PROVISIONS FOR GROWTH

- FLUID HANDLING (ORU) EQUIPMENT IS INITIALLY SIZED FOR ___ kW. UPGRADING EQUIPMENT TO LARGER CAPACITY EQUIPMENT MAY REQUIRE INCREASED VOLUME ALLOCATION
  - PUMPS (8)
  - ACCUMULATORS (2)
  - FILTERS (8)
  - NCG TRAPS (4)
- LARGER FILL AND DRAIN TANKS TO ACCOMMODATE ADDED AMMONIA INVENTORY WITH ADDITION OF DUAL KEEL (INCREASES FROM 1600 LBM TO 3200 LBM)
- VOLUME ALLOCATION FOR ADDED FORWARD ROTARY FLUID COUPLERS REQUIRED ON EACH PALLET
- TCS FLUID CONNECTIONS REQUIRED IN EACH LOOP FOR ADDED ROTARY FLUID COUPLERS

HEAT REJECTION GROWTH

The heat rejection system is made-up of modular units consisting of heat pipe radiator panels, condenser modules, subcooler modules, and a supporting truss assembly. Each radiator wing is configured into four heat rejection sections to support the primary and redundant 35°F and 70°F thermal loops. The ammonia vapor enters a condensing unit, is liquified, and then routed to a subcooler unit to be further cooled below the the saturation point before returning to the pump. The condenser and subcooler units accommodate up to six panels and four panels, respectively. They are modular and can be increased with phased growth, and are physically secured by a modular transition beam and truss assembly. The radiator panels are modular and space erectable, due in part to a dry contact and pressurized interface with the condensing unit. This interface is advantageous because the radiator panels are easily installed and amenable to growth. At assembly complete, the total thermal load is divided equally between two radiator wings, and for growth is distributed over four wings.

The load fraction between the two loop temperatures is very important for growth planning. The load fractions, for baseline, are 36% on the 35°F loop, and 64% on the 70°F loop; however these are subject to change. They are impacted by customer loads and subsystem loads, which are still being defined. The radiator heat rejection is proportional to the fourth power of temperature and, therfore, the total number of panels is affected by the percentage of load at each temperature. Using standard design conditions the (net) orbital average heat rejection rates for the 35°F and 70°F thermal buses are approximately 960 W and 1500 W respectively. For the baseline load fractions the number of radiator panels increase from 82 at assembly complete, to 296 for the R & D node, and 188 for the Transportation node.

The heat rejection subsystem constitutes the largest persentage of the total weight of the CTCS. It is 65% of the total weight at 12075 lbs for assembly complete. For growth to the R & D node the weight increass to 39835 lbs and for the Transportation node it icreases to 26400 lbs.

HEAT REJECTION GROWTH

ITEM	AC	R & D *	TRAN *
RADIATOR WINGS	2	4	4
HEAT REJECTION SYSTEM			
Radiator Panels	74	280	172
Condenser Modules	14	48	32
SUBCOOLING SYSTEM			
Radiator Panels	8	16	16
Subcooling Modules	4	4	4
SWEEP RADIUS (FT) **	26	46	29
TOTAL WEIGHT (LBM)	12075	39835	26400

* ASSUMES 5% SAFETY FACTOR, AND 36% @ 2°C AND 64% @ 21°C
** ASSUMES 3 INCH PANEL SPACING

PROVISIONS FOR GROWTH

- CONDENSERS ARE MODULAR AT FIXED (6 PANEL) EXPANSION INCREMENTS
- CTB CONDENSER SUPPORT STRUCTURE MUST BE MODULAR
- SWEEP VOLUME FOR THERMAL RADIATOR WINGS BOTH FORE AND AFT OF TCS PALLETS MUST BE PRESERVED

HEAT REJECTION (CON'T)

In the case of the R & D node, the radiator wing sweep radius is affected by the available clearance between the EPS thermal radiator and the 6.9 foot corridor required for EVA. The nearest EPS thermal radiators are positioned one bay outboard of the alpha gimbal at PA1 and SA1. The clearance between the thermal radiator wing and the EPS radiator does not accommodate the EVA corridor and, in fact, could result in physical interference depending on which radiator spacing is used. At a radiator spacing greater than 1.75 inch, physical contact will result. Preliminary testing at Johnson Space Center has shown that 1 inch spacing can be achieved for assembly and maintenance; however, even at 1 inch, the EVA corridor is limited to 2.6 feet. No physical interference or EVA clearance problems were found to exist for growth to the Transportation node.

HEAT REJECTION GROWTH ... Con't

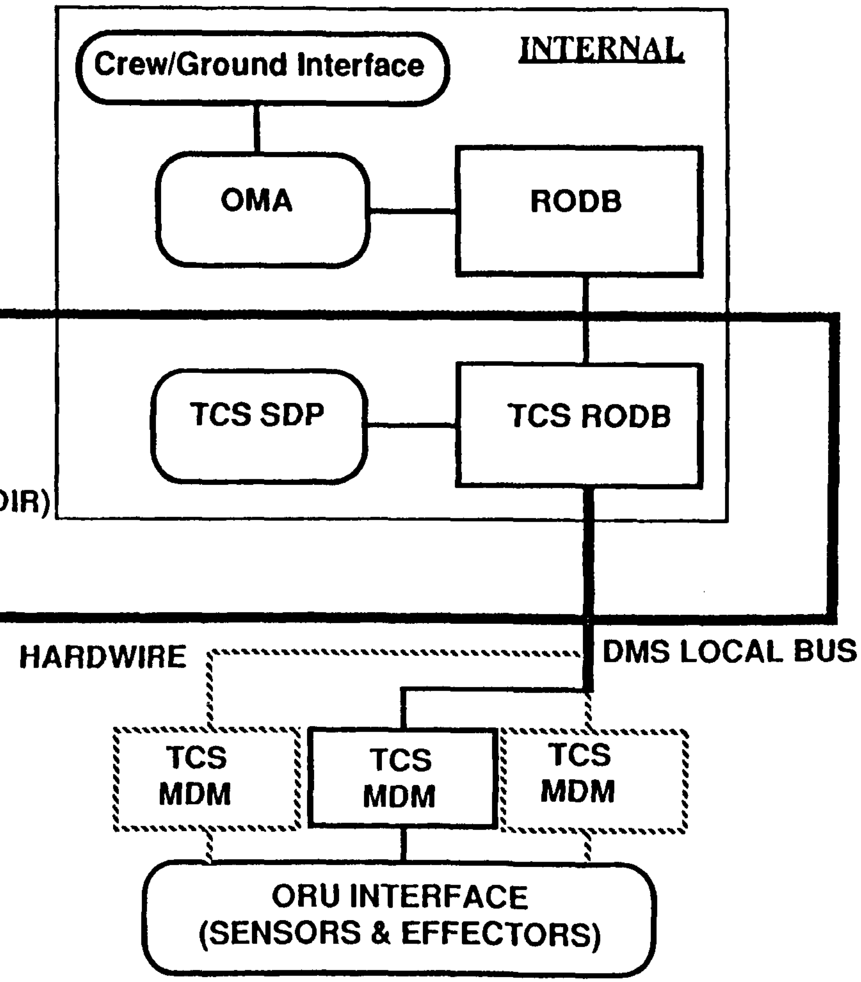
DESIGN ISSUES

- PANEL-TO-PANEL RADIATOR SPACING AFFECTS RADIATOR TOTAL SWEEP DIMENSION. FOR R & D NODE, WITH 1 INCH PANEL SPACING ONLY 2.6 FT CLEARANCE IS AVAILABLE BETWEEN CTCS AND EPS THERMAL RADIATORS. THE REQUIRED EVA CLEARANCE IS 7 FT .
- HEAT LOAD SPLIT BETWEEN 2°C AND 21°C THERMAL LOOPS AFFECTS TOTAL NUMBER OF PANELS (36% LOAD ON 2°C BUS, 64% LOAD ON 21°C BUS). THIS LOAD FRACTION IS SUBJECT TO CHANGE.
- PRESENCE OF CSF REDUCES RADIATOR HEAT REJECTION BY 1% (β=0) to 5% (β=52).

TCS MONITORING AND CONTROL HIERARCHY

The TCS monitoring and control subsystem consists of a three tier hierarchy. Tier I is the highest level, and involves general directives issued from the crew (or ground) and provides information concerning the health and status of a particular subsystem, such as the TCS. At Tier II, the TCS shares a standard data processor (SDP) with other subsystems and communicates with Tier I through a run time object data bases (RODB). Detailed software procedures to operate, identify faults, and initiate corrective action resides at Tier II. Tier III, unlike Tier I or Tier II, is external to the manned modules and involves hardware dominated equipment rather than software. It is at Tier III where the interface with the external ORU's occurs, via sensors and effectors, and the most significant impact to growth is realized. MDM's are used for data acquisition and provide the interface with the SDP by way of the shared local bus.

TCS MONITORING AND CONTROL HIERARCHY



TIER I - STATION OPERATION

- Subsystem Directives, Health, and Status

TIER II - SUBSYSTEM OPERATION

- TCS Software Procedures
- Component Status and Performance Data
- Fault Detection, Identification, and Recovery (FDIR)
- External Local Bus Interface

TIER III - ORU OPERATION

- Data Acquisition and Signal Conditioning
- External Hardwire Interface

MONITORING AND CONTROL GROWTH

Physical growth of the monitoring and control system is proportional to the quantity of ORU's and distribution lines added to support the physical expansion of the Station. Each Tier of the monitoring and control subsystem is impacted by growth: Tier I involves software hooks; Tier II involves hooks and possibly scars if the local bus capacity is an issue; and, at Tier III the impacts are primarily hardware oriented. Identification of scars at the Tier III level is essential for growth since it is external to the pressurized modules and volume must be reserved for hardware and connections.

At assembly complete, the total number of signals for TCS monitoring and controls is approximately 4,200, and increases to 12,000 for the R & D node and to 10,000 for the Transportation node. The signals are made-up of instrument and valve status indications (open/close and condition), commands, and instrument readings. Instrument redundancy is also included. The total number of sensors increase from 675 at assembly complete to 1050 for the growth configurations. Additional signals translate directly into more MDM's. The TCS baseline makes use of "mini"-MDM's which have 64 available ports as compared to 256 ports for standard MDM's. Each MDM is hardwired to the DMS local bus and requires an access port near its location. MDM's are generally shared with other distributed systems, but considering the number of added signals for TCS alone, it can be conservatively estimated that at least 120 additional mini-MDM's will be required. An alternative is that the mini-MDM's be replaced with standard MDM's which have excess capacity at assembly complete. At Tier II, software upgrades are expected due expanded Station resources and TCS expanded FDIR capability. Tier I will also require software upgrades to reflect the changes in Tier II.

MONITORING & CONTROL GROWTH

PROVISIONS FOR GROWTH

- TIER III - EXTERNAL SCARS
  - ADDED SENSORS (T, P, ΔP, Q) INCREASE FROM 675 TO 1050. EXPERT SYSTEM TECHNOLOGY WILL INCREASE THIS FURTHER.
  - VOLUME ALLOCATION FOR MDM'S. TOTAL NUMBER OF SIGNALS INCREASE FROM 4200 TO 12000. THIS TRANSLATES TO 120 ADDED MINI-MDM'S (64 PORTS EA).
  - LOCAL BUS INTERFACE PORTS FOR ADDED MDM'S
- TIER II - INTERNAL HOOKS
  - (SDP) SOFTWARE UPGRADES
  - (RODB) INCREASED MEMORY ALLOCATION
- TIER I - INTERNAL HOOKS
  - SOFTWARE ENHANCEMENTS

DESIGN ISSUES

- BASELINE DOES NOT FULLY SUPPORT AUTOMATED FAULT RECOVERY
- SUBSTANTIAL INCREASE IN SYSTEM COMPLEXITY WITH GROWTH OF HARDWARE COMPONENTS

TECHNOLOGY GROWTH

Technology issues may be organized into specific areas of focus: academic, component, and system issues. Academic issues refer to state-of-the-art models, methods, and techniques. Component issues pertain to individual hardware items that could emerge as as result of advances in discipline issues and increased operational experience. The distinction between component and system issues is that changes at the component, or ORU, level are by nature technologically transparent, where system level changes are not and may involve integration problems.

Several academic issues play a role in the technical development of thermal equipment for space applications. A fundamental issue includes the need for mechanistic models for two-phase flow in microgravity environments. Without complete confidence in the analytical tools, the designer is forced to imposed greater conservatism into the design, which will increase component mass and cost. Another issue of fundamental interest is the long-term stability of surface properties of coating materials. Space applications of thermo-optical coating include thermal radiators, multi-layer insulations, antennas, booms/structure, and PV solar arrays to name a few. A fundamental understanding of the degradation in the mechanical and thermo-optical properties due to atomic oxygen depletion, solar radiation (UV), ionizing radiation, and micrometeroids and debris needs to be established.

At the ORU level, improvements to component performance, weight, volume, safety, and reliability, can be implemented through component replacement; therefore, scars are not required. Internal issues still remain, such as whether or not new pressure or temperature levels are called for and if these affect the performance of other equipment. Improvements are expected at the component level as discipline issues are resolved and operational experience with ORU's grow.

System level improvements signify improvements involving a basic departure from baseline hardware components and include some form of integration question. Besides the overall benefit of the technology insertion, integration issues are the drivers for hooks or scars. Hooks and scars are very challenging this context because the integration problems are to be resolved before the actual components are invented. A primary candidate for a system level improvement includes a higher capacity heat pipe radiator that may require a new condenser design to match its capability. This may in-turn involve a new truss structure for physical support. Several concepts relevant to the thermal control system can be discussed such as heat pump cycles, to raise the system operating temperature, and thermal bus condensers that eliminate the dry contact thermal resistance. A significant technological advancement will be the introduction of AI technology into the monitoring and control system.

TECHNOLOGY GROWTH

- **ACADEMIC ISSUES**
  - ESTABLISH FUNDAMENTAL UNDERSTANDING OF MICROGRAVITY TWO-PHASE FLOW TECHNOLOGY WITH ASSOCIATED ANALYTIC DESIGN AND SIMULATION TOOLS
  - LIFE OF THERMO-OPTICAL COATING MATERIALS DUE TO DEGRADATION WITH ATOMIC OXYGEN DEPLETION, SOLAR AND IONIZING RADIATION, AND METEROID/DEBRIS

- **COMPONENT LEVEL ISSUES - ORU REPLACEMENT**
  - MINIMIZE INCREASE OF RADIATOR AREA (~65% CTCS WEIGHT, VOLUME) WITH HIGHER HEAT FLUX RADIATOR PANELS
  - ACHIEVE BETTER CONTACT CONDUCTANCE BETWEEN THERMAL BUS AND RADIATORS
  - INCREASE HEAT FLUX CAPABILITY OF $H2O/NH3$ HEAT EXCHANGER

- **SYSTEM LEVEL ISSUES - INTEGRATION ISSUES**
  - ADVANCED HEAT PIPES - ARTERIAL FLOW, COMPOSITES, ETC
  - HEAT PUMP CYCLE - HIGHER TEMPERATURE FOR HEAT REJECTION PURPOSES
  - CONDENSERS - INTEGRAL CONCEPTS
  - INSTRUMENTATION - TWO-PHASE VOID FRACTION, LEAK DETECTION
  - MONITORING AND CONTROLS - EXPERT SYSTEMS
  - THERMAL STORAGE (CAPACITANCE)

CONCLUSIONS

The hook and scar assessment for evolution of Space Station Freedom to the Research and Development node and Transportation node is complete for this phase of evolution definition. In general, the baseline CTCS equipment is designed with modularity as a priority and can accommodate new components resulting from technology enhancements.

Fundamental to the hooks and scars for growth are that the CTCS transport lines, valves, and quick disconnects are sized for the maximum growth power allocation.

For resource growth, the principal hardware scars are grouped into one of two categories: (1) fluid connections for modules, external payloads, servicing facilities, and the rotary fluid coupler, and (2) volume allocation for larger thermal radiators and added MDM's. Dedicated SDP's and software hooks may accompany the added sensors for data acquisition. Clearance between the CTCS thermal radiators and EPS thermal radiators is an issue for growth to the R & D node. It is recommended that an option for active cooling of the attached payloads be provided.

For technology growth, the hooks and scars are not so clearly defined. The most significant hardware contribution will come from enhanced radiator concepts that offer both greater heat rejection and reduced weight. The motivation is tha continued use of the baseline heat rejection technology the radiator mass and volume will become significant, if it is not already. A fundamental understanding of two-phase flow in microgravity along with the analytical simulation and design tools will assist in achieving this goal. Introducing AI technology into the TCS monitoring and controls system is highly desirable and will necessitate the need for added sensors, MDM's, and dedicated processor requirements. This will serve to minimize EVA and reduce orbital and ground operational support. However, since it is still early in the development of expert system technology, these needs are not clearly understood.

CONCLUSIONS

- SIZE TRANSPORT LINES, VALVES, QD'S FOR GROWTH POWER ALLOCATION.
- PRINCIPAL SCARS TO CTCS INCLUDES:
  - FLUID CONNECTIONS FOR MODULES, PAYLOADS, DUAL KEEL, SERVICING FACILITIES, AND RFC.
  - VOLUME ALLOCATION FOR THERMAL RADIATORS AND MDM'S.
- FOR GROWTH TO THE R & D NODE, CLEARANCE BETWEEN CTCS AND EPS THERMAL RADIATORS IS A POTENTIAL PROBLEM. FOR THE TRANSPORTATION NODE, PHYSICAL AND EVA CLEARANCE IS PROVIDED.
- THE CTCS COMPONENT THAT HAS THE BIGGEST IMPACT ON GROWTH IS THE THERMAL RADIATOR; BOTH IN VOLUME ALLOCATION AND WEIGHT.
- DEPENDENCE ON ONLY PASSIVE COOLING OF TRUSS MOUNTED EQUIPMENT (APAE'S, PALLETS) WILL NOT BE ADEQUATE FOR GROWTH. BLOCKAGE EFFECTS DUE TO GROWTH SHOULD BE INCLUDED AND UTILITY PORTS FOR FUTURE CONNECTION TO THE CTCS SHOULD BE PROVIDED.
- MONITORING AND CONTROLS SHOULD BE MORE AUTOMATED USING AI TECHNOLOGY. SOFTWARE AND AUTOMATION APPLICATION DEVELOPMENT IS STILL AT "INFANCY STAGE" WHICH INSTILLS A LEVEL OF UNCERTAINITY WITH REGARD TO GROWTH REQUIREMENTS.
- FULLY VERIFIED THEORETICAL MODELS AND DESIGN ALGORITHMS DO NOT EXIST FOR MICROGRAVITY TWO-PHASE PROCESSES, RESULTING IN OVERLY CONSERVATIVE DESIGN HARDWARE.
- A STRONG EMPHASIS HAS BEEN PLACED ON MODULARITY IN BASELINE REQUIREMENTS WHICH PROVIDES A LEVEL OF FLEXIBILITY TO ACCOMMODATE GROWTH.

SPACE STATION EVOLUTION SYMPOSIUM
6-8 FEBRUARY 1990
LEAGUE CITY, TEXAS

EVOLUTIONARY SPACE STATION GN&C STUDY

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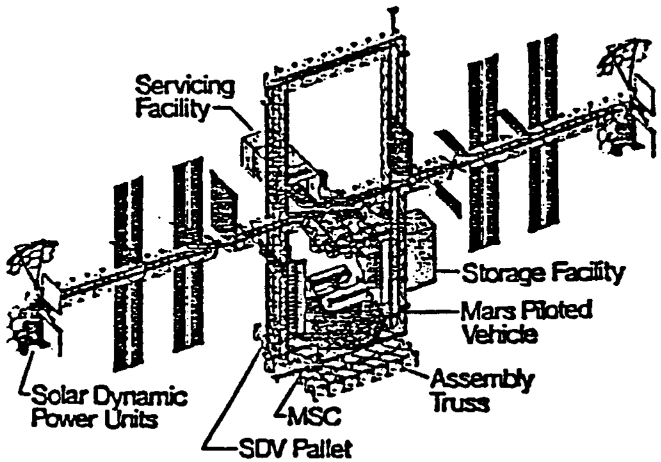
INTRODUCTION

THE GUIDANCE, NAVIGATION AND CONTROL TECHNIQUES AND EQUIPMENT TO SUPPORT EVOLUTIONARY STATION CONCEPTS ARE BEING ANALYZED TO ASSESS THE IMPACT ON THE BASELINE GN&C SYSTEM.

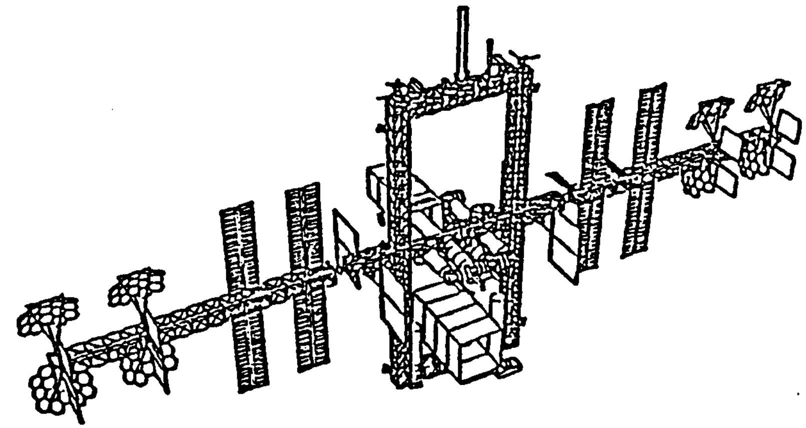
- THREE FUNCTIONAL AREAS OF GN&C WILL BE ADDRESSED
  - ATTITUDE CONTROL
  - TRAFFIC MANAGEMENT
  - REBOOST

- A SUMMARY OF THE MISSION CONCEPTS, STATION CONFIGURATIONS, SIMULATION RESULTS, AND PRELIMINARY ASSESSMENTS OF THE BASELINE GN&C SYSTEMS ARE PRESENTED.

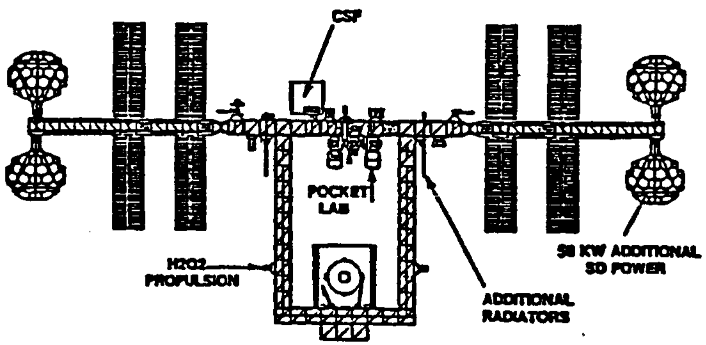
MARS EVOLUTION REFERENCE CONFIGURATION



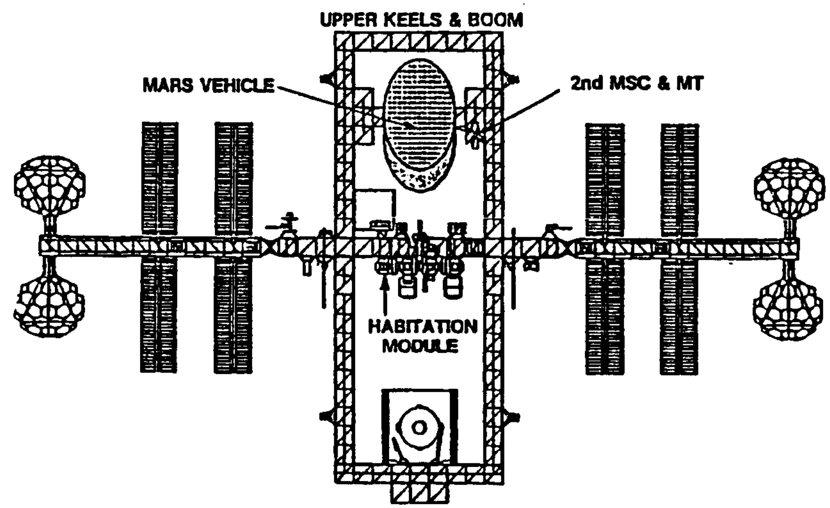
R&D SPACE STATION



LUNAR MISSION NODE 2



LUNAR/MARS TRANSPORTATION NODE



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Configuration Mass Properties

Configuration	Mass (slugs)	Center of Mass (ft)			Moment of Inertia (slug ft^2 x 10^6)			Product of Inertia (slug ft^2 x 10^6)		
		X	Y	Z	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{XZ}	I_{YZ}
Assembly Complete (MB-15)	17723	-4.99	5.17	11.41	88.897	16.696	98.337	-0.517	-0.138	-0.0635
Research & Development	44615	-8.63	0.68	26.18	875.58	253.34	695.36	1.619	4.298	-2.762
Mars Evolution Reference Configuration	30531	2.56	-0.5	23.38	396.97	111.72	333.24	1.35	-2.97	4.72
Lunar Node II	33511	-4.82	-0.72	69.65	226.91	199.63	293.52	-0.518	-6.12	3.02
Lunar/Mars Configuration	44171	-5.45	-0.83	28.11	694.08	451.59	304.88	-0.761	-1.74	3.66

ATTITUDE MAINTENANCE REQUIREMENTS

ATTITUDE CONTROL	$\pm$5 DEGREES/AXIS WRT LVLH $\pm$2.5 DEGREES/AXIS/ORBIT MAX
MAXIMUM ATTITUDE RATE	0.02 DEGREES/SECOND/AXIS WRT LVLH

REFERENCE - SPACE STATION PROGRAM DEFINITION AND REQUIREMENTS, SSP 30000

ATMOSPHERIC DENSITY DESIGN CRITERIA

PHASE DISCIPLINE	DESIGN	ASSEMBLY/ SERVICING	OPERATIONS
CONTROL (CMG)	$F_{10.7} = 230$ Ap = 140 CONTINGENCY Ap = 400	$F_{10.7} = 230$ Ap = 140 CONTINGENCY Ap = 400	$F_{10.7} = 230$ Ap = 140 CONTINGENCY Ap = 400
PROPULSION/ REBOOST SIZING	$F_{10.7} = 230$ Ap = 35	$F_{10.7} = 230$ Ap = 35	$F_{10.7} = 230$ Ap = 35

REFERENCE - SPACE STATION PROGRAM NATURAL ENVIRONMENT FOR DESIGN, JSC 30425

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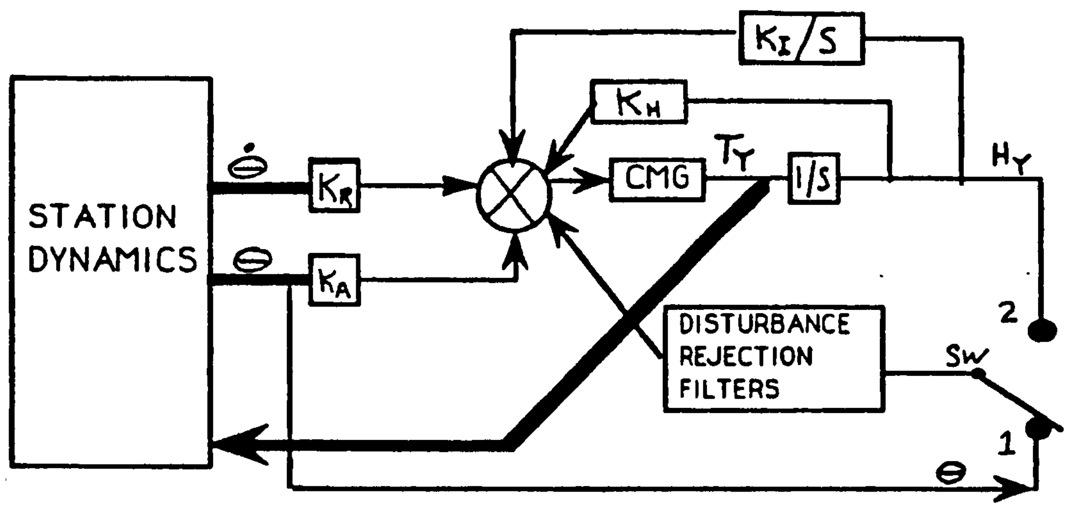
ATTITUDE CONTROL

ATTITUDE CONTROL WITH CONTROL MOMENT GYROS (CMGS)

- BASELINE APPROACH - PROVIDE CONTINUOUS CLOSED-LOOP CONTROL OF CMG MOMENTUM AND STATION ATTITUDE
- USES GRAVITY GRADIENT TORQUES TO PREVENT CMG MOMENTUM BUILD UP - CONTROLS THE SSF ABOUT TORQUE EQUILIBRIUM ATTITUDE (TEA)
- CONTROL LOOPS CAN BE CONFIGURED TO EMPHASIZE ATTITUDE CONTROL OR MOMENTUM CONTROL (SWITCHES AND GAIN VALUES)
- ATTITUDE CONTROL EMPHASIS MODE USED FOR THIS STUDY
- BASELINE MOMENTUM STORAGE CAPABILITY - 21,000 FT-LB-SEC (SIX 3500 FT-LB-SEC CMGs)

ATTITUDE CONTROL AND STABILIZATION (ACS) TEST BED
(OUT-OF-PLANE MOMENTUM CONTROL LOOP)



DISTURBANCE REJECTION FILTERS - PROVIDES REJECTION OF CYCLIC AERODYNAMIC DISTRUBANCES

- CYCLIC COMPONENT AT ORBITAL RATE CAUSED BY DIURNAL VARIATION OF ATMOSPHERE
- CYCLIC COMPONENT AT TWICE ORBITAL RATE CAUSED BY SOLAR PANEL ROTATION

SWITCH POSITION 1 - ATTITUDE CONTROL EMPHASIS
SWITCH POSITION 2 - MOMENTUM EMPHASIS

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FIGURE 2. MERC EXAMPLE RESULTS

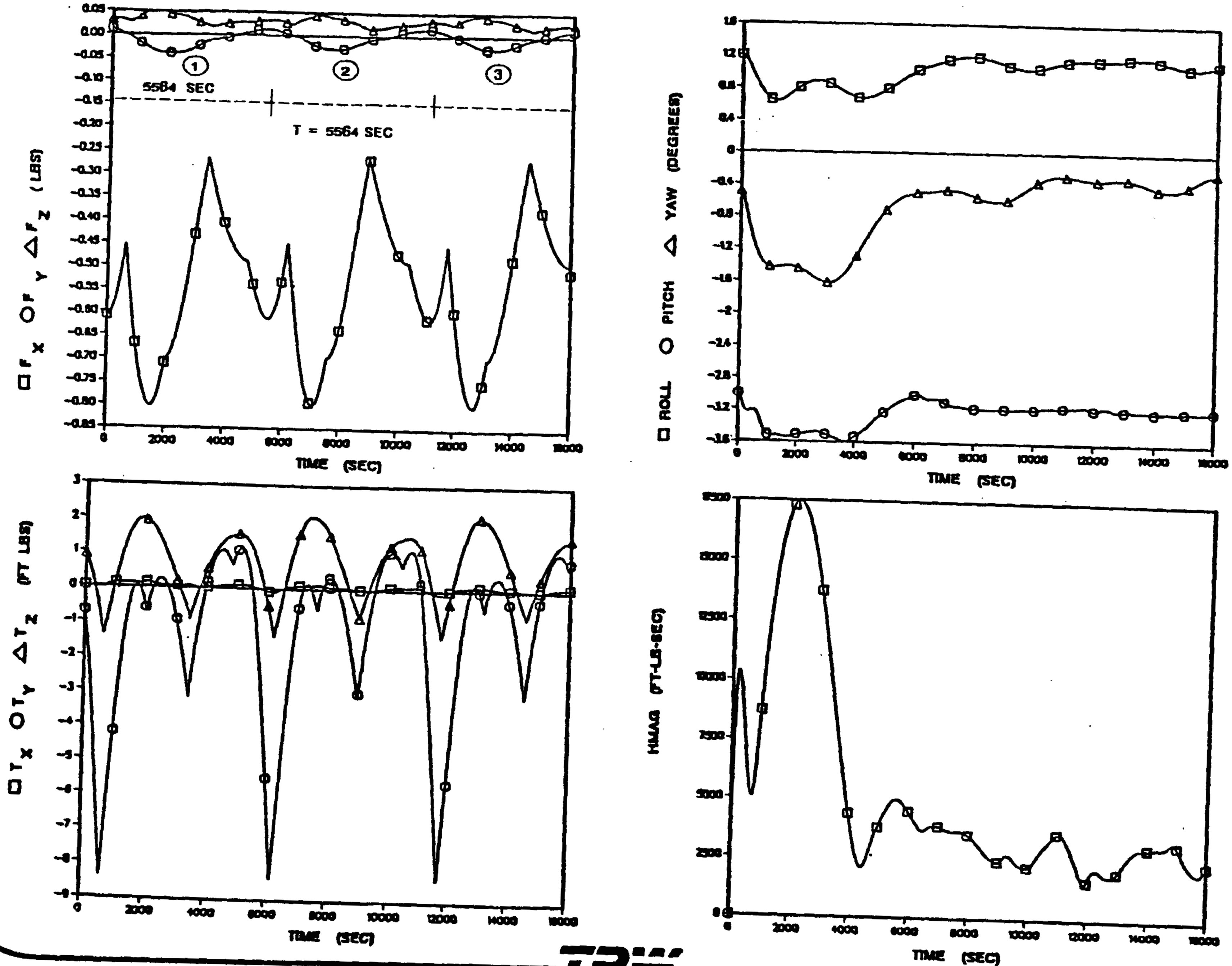

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TABLE II. MOMENTUM MANAGEMENT BUDGET

BASELINE MOMENTUM STORAGE CAPABILITY	21,000 FT-LB-SEC
BUDGET FOR CMG FAILURE OR CMG DOWN FOR MAINTENANCE	3500 FT-LB-SEC
BUDGET FOR RCS TO CMG CONTROL SWITCH-OVER, EVA, IVA, VENTING AND MRMS ACTIVITY	8600 FT-LB-SEC
AVAILABLE FOR NATURAL ENVIRONMENT DISTURBANCES, ROTATING MACHINERY AND RESERVE FOR MASS PROPERTY UNCERTAINTIES	8900 FT-LB-SEC (ASSUME 8000 FT-LB-SEC AVAILABLE FOR NE DISTURBANCES)

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Attitude Control Results

Configuration	Torque Equilibrium Attitude (DEG)			Attitude Control		Peak Steady State Momentum
	Roll	Pitch	Yaw	Max DEG/ORB	DEG/SEC	FT LB SEC
Research & Development	0.55	0.23	-0.1	0.82 Yaw	All Axes < 0.001	6200
Mars Evolution Reference Configuration	1.1	-3.1	-0.3	1.1 Yaw	All Axes < 0.002	3000
Lunar Node II	-0.8	5.0	0.2	0.5 Yaw	All Axes < 0.002	10000
Lunar/Mars	3.2	1.3	-0.5	1.5 Roll	All Axes < 0.005	12000

TRAFFIC MANAGEMENT
(REFERENCE - LESC-27244 "TRAFFIC MANAGEMENT EVOLUTION REPORT," 9/28/89)

THE MISSION CONCEPT CHOSEN FOR TRAFFIC MANAGEMENT ANALYSIS INVOLVES THE RENDEZVOUS OF A VEHICLE TRANSFERRING FROM THE STATION TO A CO-ORBITING TRANSPORTATION NODE

SSF: ORBITING IN A 200 NM CIRCULAR ORBIT

TN: STATIONKEEPING IN A STABLE FORMATION IN A CO-PLANAR ORBIT BEHIND THE SSF

- AT VARIOUS PLACEMENT RANGES WHILE STATIONARY ON THE SSF V-BAR

- AT VARIOUS PLACEMENT RANGES WHILE IN A STATIONKEEPING ELLIPSE

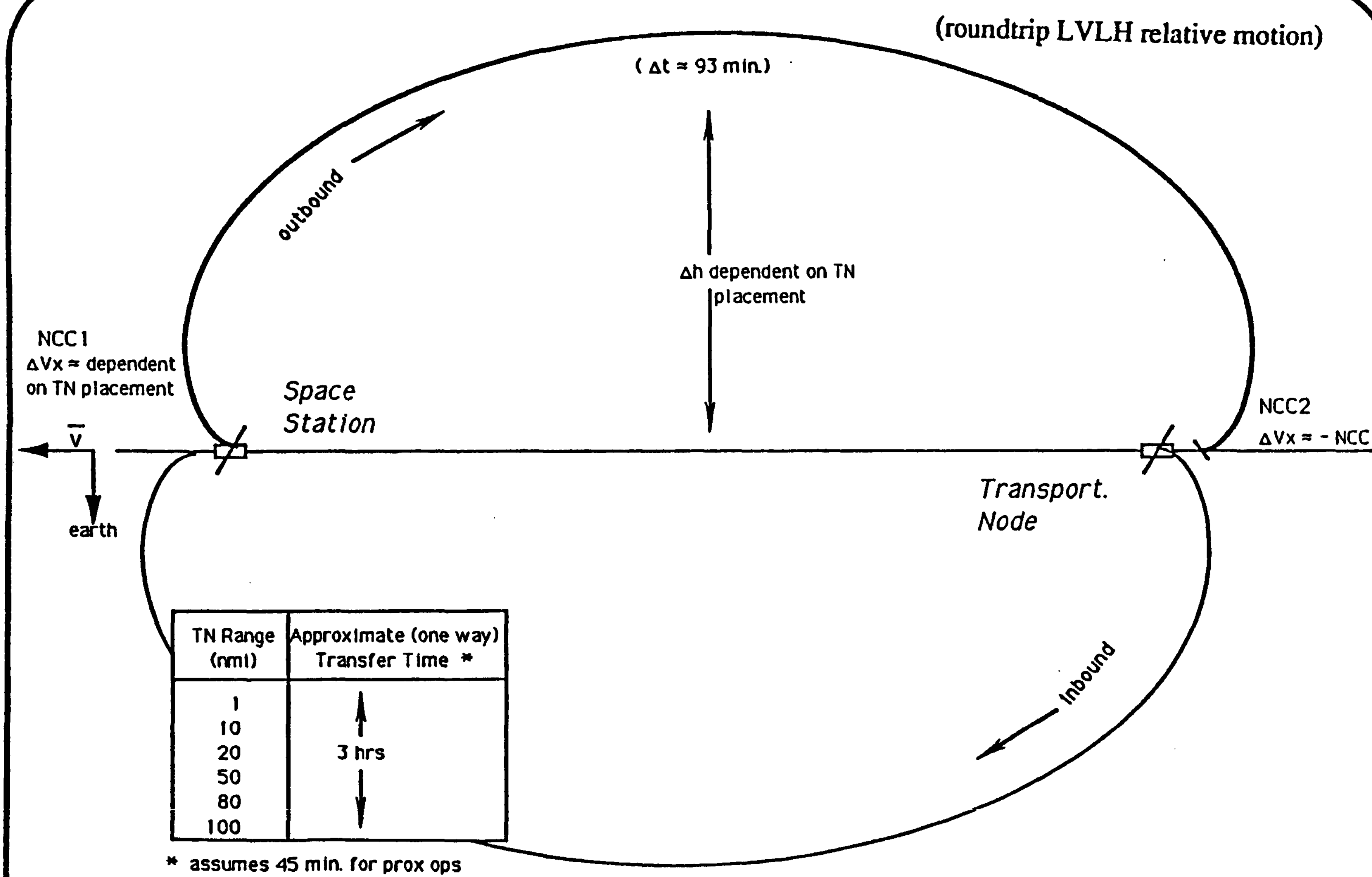
TRANSFER VEHICLE: MASS OF 6400 LBS WITH A 300 SECOND SPECIFIC IMPULSE AND ONBOARD RELATIVE NAVIGATION CAPABILITY OF EITHER RENDEZVOUS RADAR OR RELATIVE GPS NAVIGATION

TRAFFIC MANAGEMENT

INVESTIGATED THREE TYPES OF RENDEZVOUS TRAJECTORIES

- TWO IMPULSE TRANSFER
- MINIMUM TRANSFER TIME
- PASSIVE COLLISION AVOIDANCE TRANSFER

TRANSFER TIMES, DELTA-VELOCITY AND PROPELLANT REQUIREMENTS WERE DETERMINED FOR EACH TYPE OF TRAJECTORY



TN Range (nmi)	Approximate (one way) Transfer Time *
1	3 hrs
10	
20	
50	
80	
100	

* assumes 45 min. for prox ops at both the station and transp. node

FIGURE 2. TWO IMPULSE TRANSFER BETWEEN THE SPACE STATION AND A TRANSPORTATION NODE

TRW DEFENSE SYSTEMS GROUP

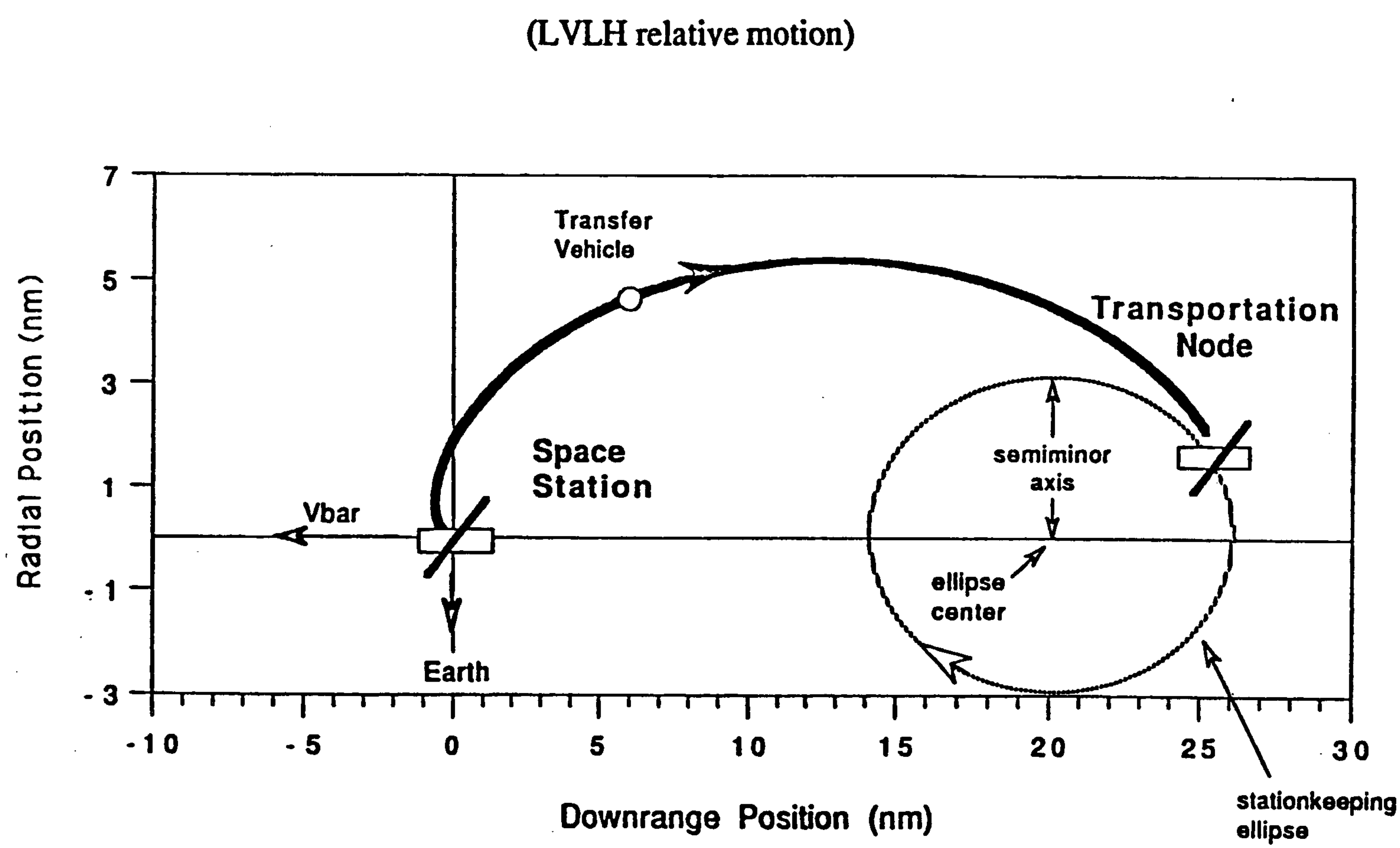
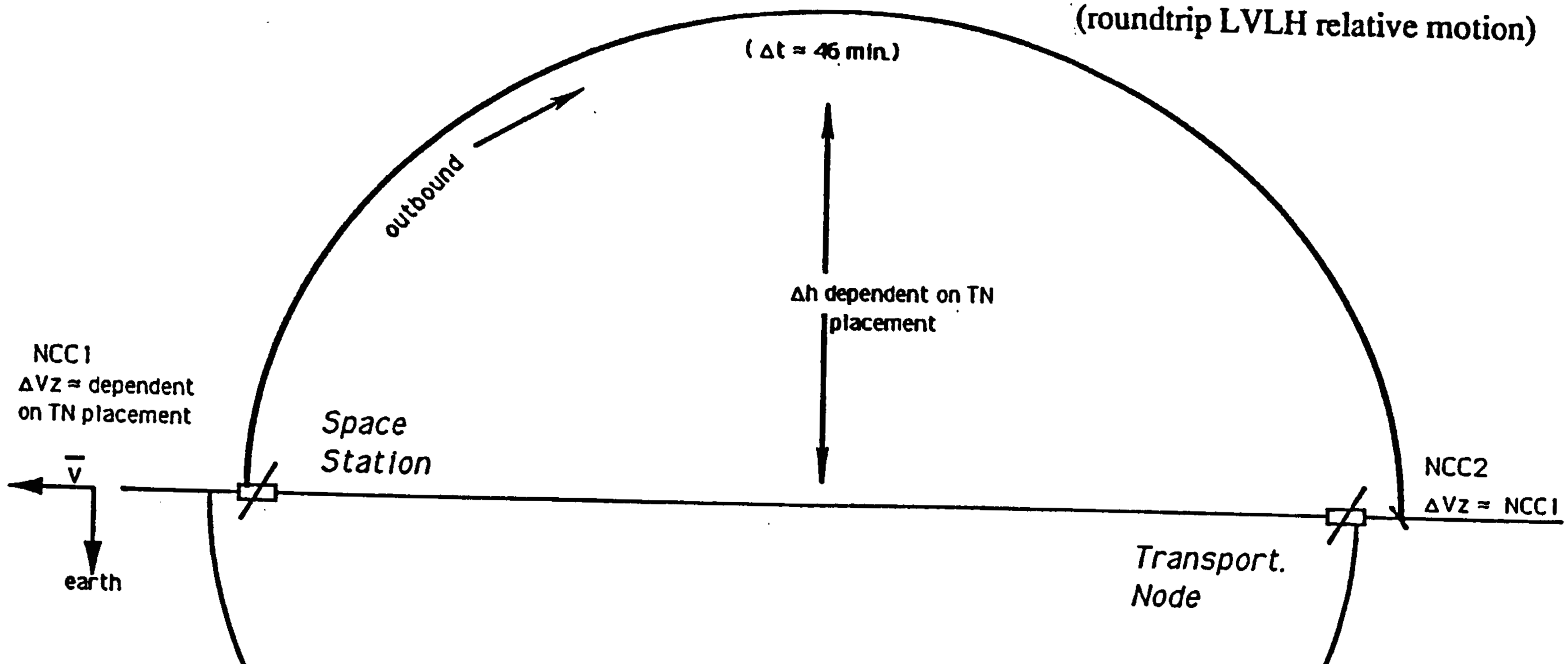


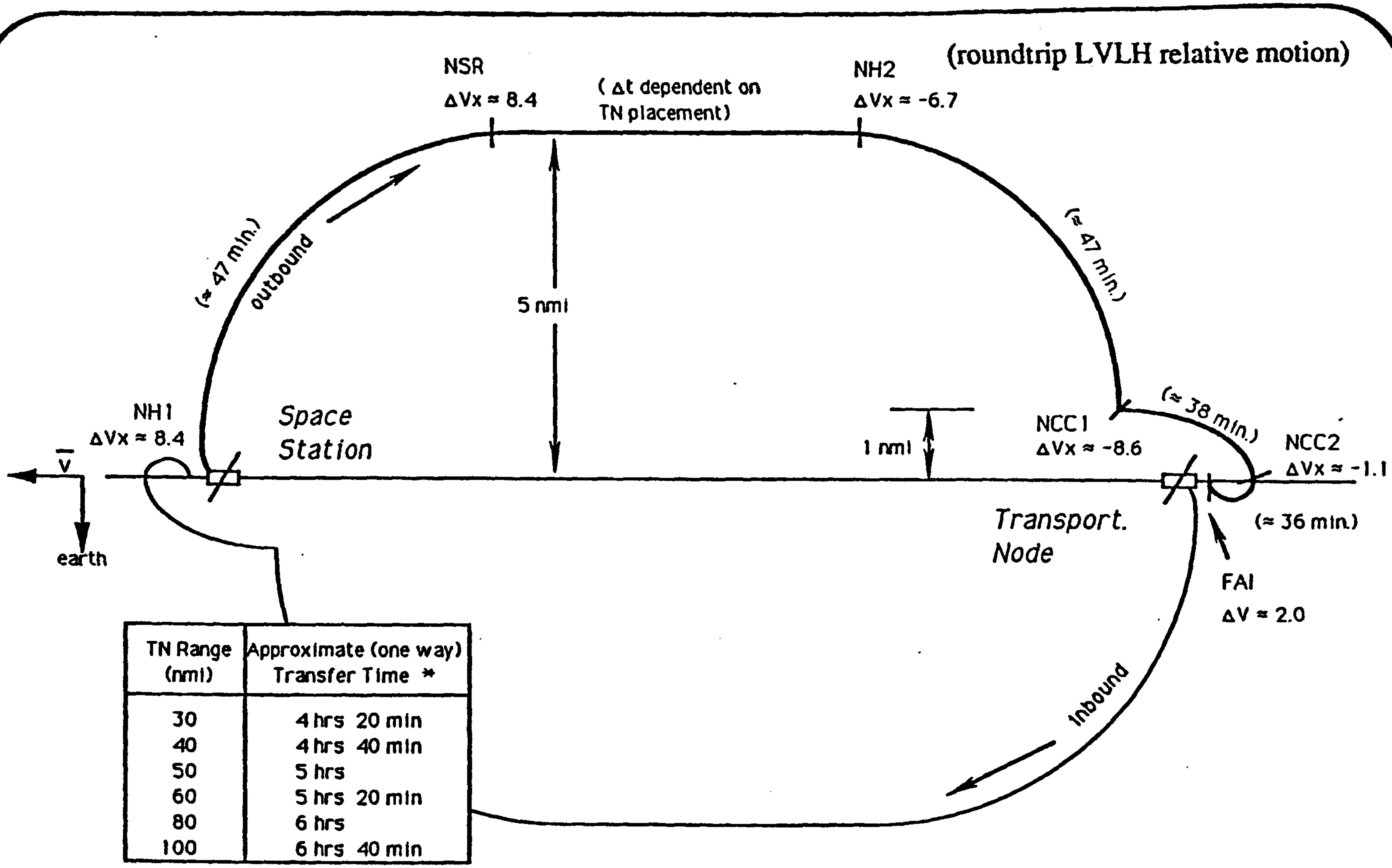
FIGURE 1. TRANSFER FROM THE SPACE STATION TO A TRANSPORTATION NODE IN A STATIONKEEPING ELLIPSE



TN Range (nmi)	Approximate (one way) Transfer Time *
1 10 20 50 80 100	2 hrs 16 min

* assumes 45 min. for prox ops at both the station and transp. node

FIGURE 3. MINIMUM TIME TRANSFER BETWEEN THE SPACE STATION AND A TRANSPORTATION NODE



TN Range (nmi)	Approximate (one way) Transfer Time *
30	4 hrs 20 min
40	4 hrs 40 min
50	5 hrs
60	5 hrs 20 min
80	6 hrs
100	6 hrs 40 min

* assumes 45 min. for prox ops at both the station and transp. node

FIGURE 4. PASSIVE COLLISION AVOIDANCE TRANSFER BETWEEN THE SPACE STATION AND A TRANSPORTATION NODE

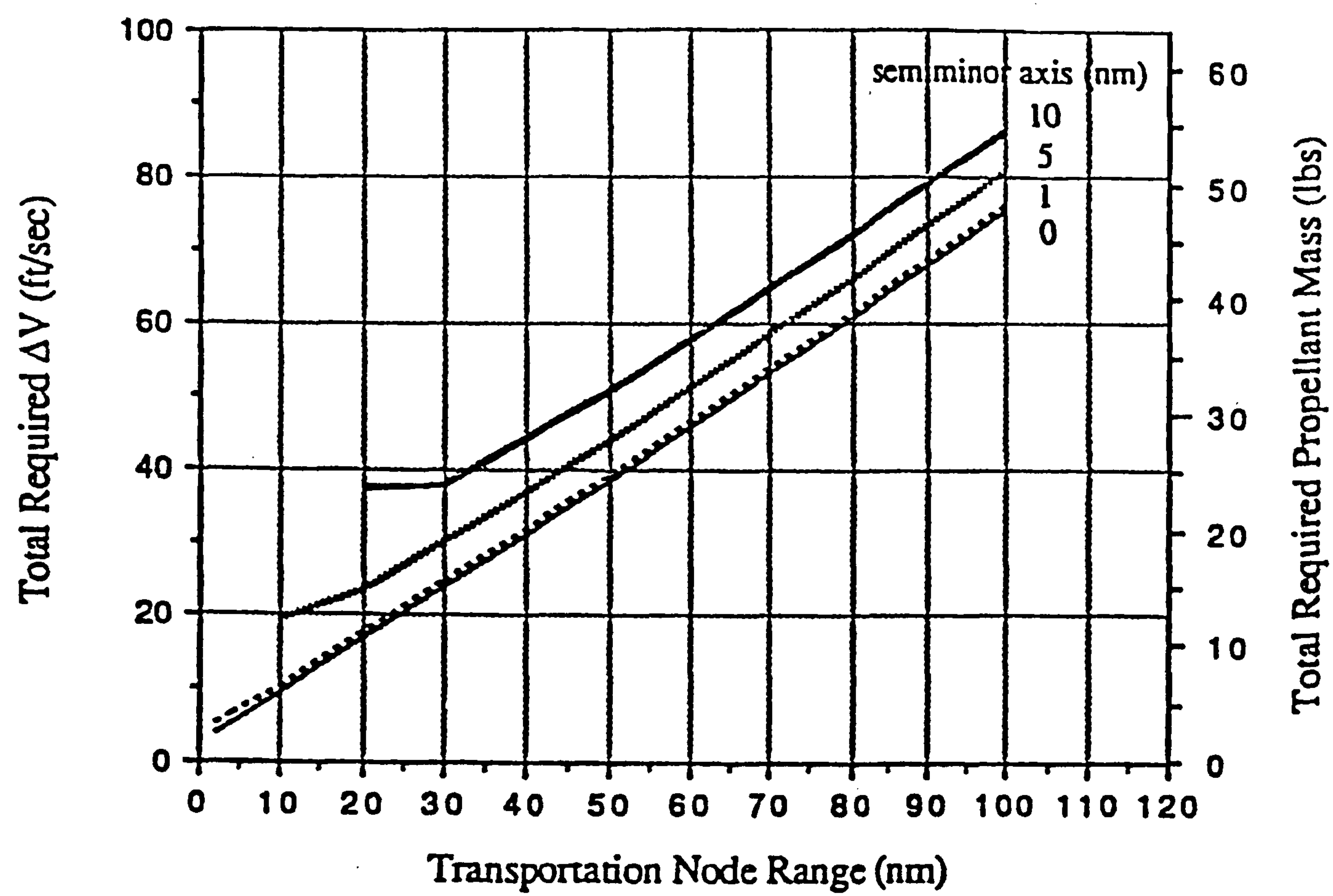


FIGURE 8. ESIMATED ΔV AND PROPELLANT REQUIREMENTS FOR THE TWO IMPULSE TRANSFER

REBOOST

REBOOST ANALYSIS - DETERMINED OPERATING ALTITUDES, IMPULSE REQUIREMENTS AND REBOOST BURN TIMES FOR VARIOUS THRUST LEVELS FOR EACH CONFIGURATION.

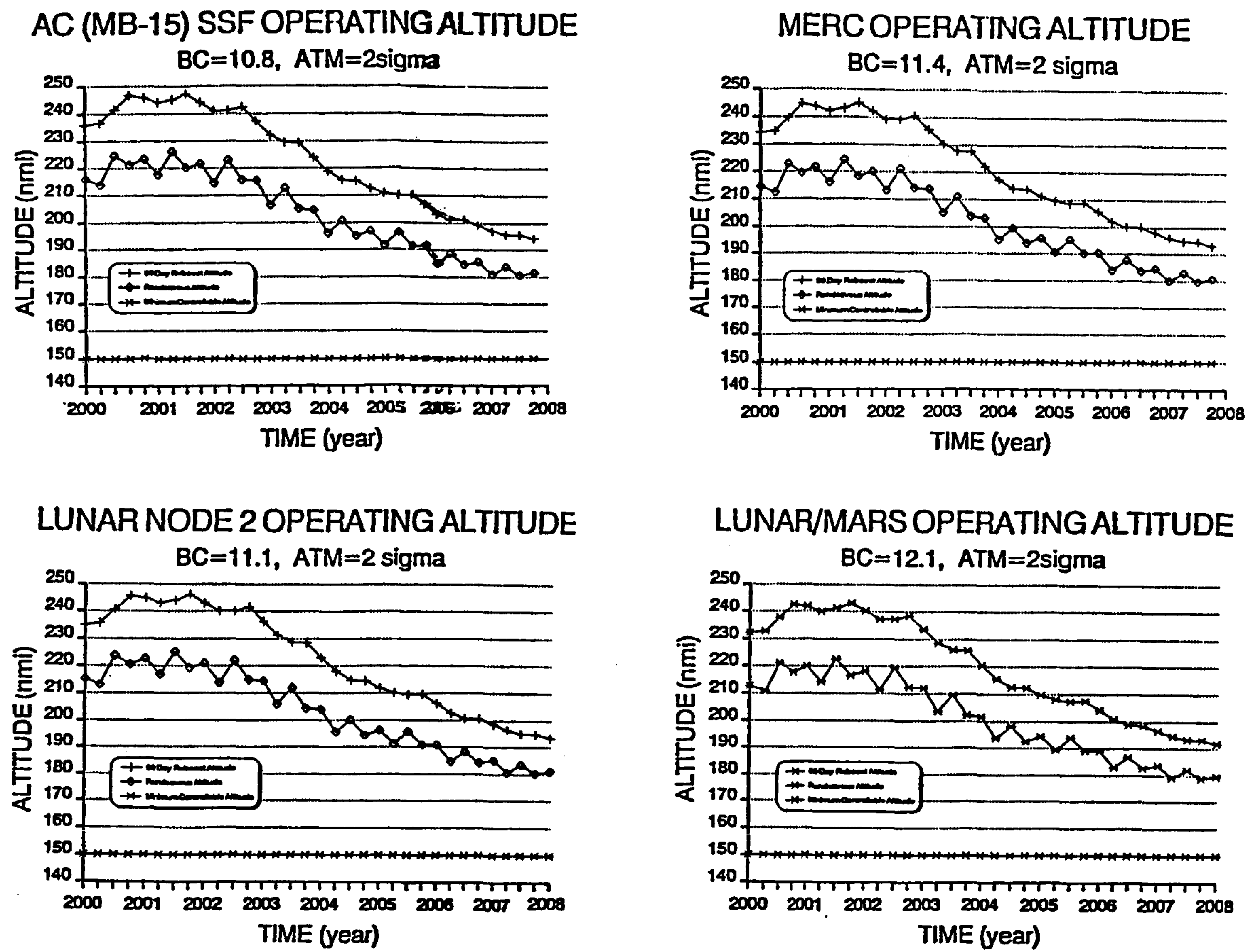


FIGURE 9. STATION OPERATING ALTITUDES

TRW
DEFENSE SYSTEMS GROUP

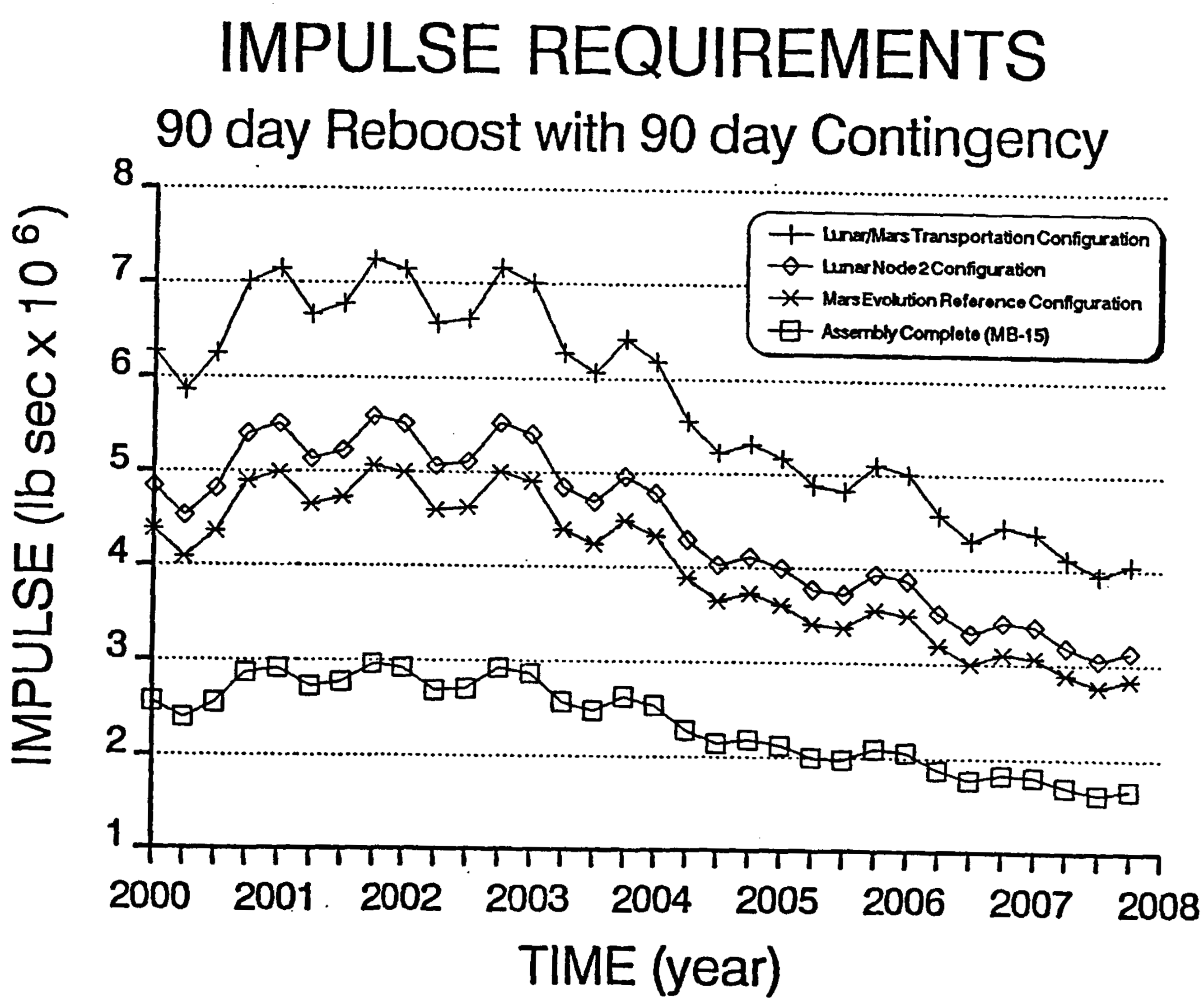


FIGURE 10. IMPULSE REQUIREMENTS

TRW DEFENSE SYSTEMS GROUP

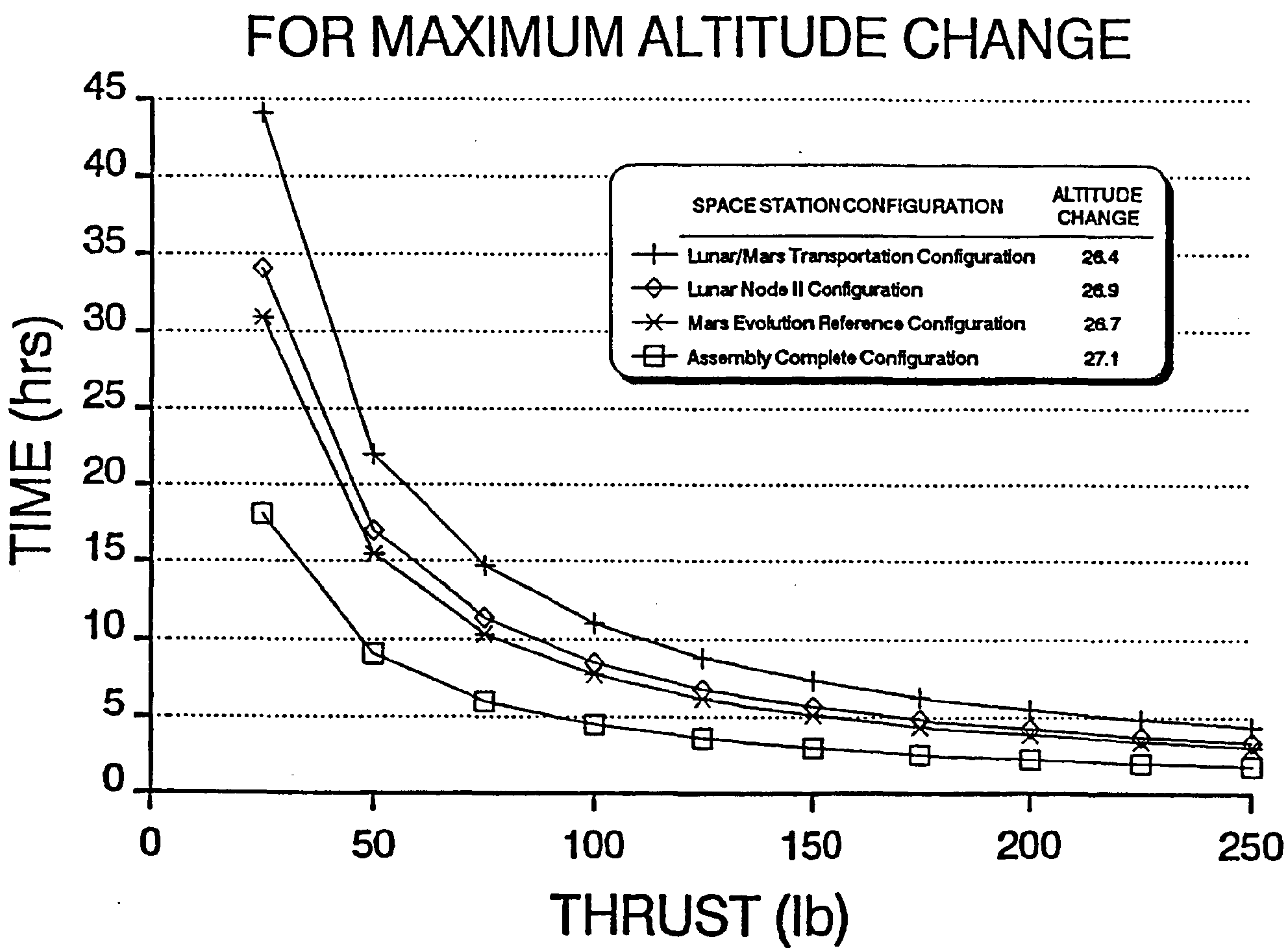


FIGURE 11. TOTAL REBOOST BURN TIME

TRW DEFENSE SYSTEMS GROUP

CONCLUDING REMARKS

- ATTITUDE CONTROL
  - EVOLUTION CONFIGURATIONS MAY REQUIRE ADDITIONAL MOMENTUM STORAGE CAPABILITY
  - LUNAR NODE II CONFIGURATION PITCH TEA AT ATTITUDE MAINTENANCE REQUIREMENT BOUNDARY (5 DEGREES)
- TRAFFIC MANAGEMENT
  - TRANSFER TIMES BETWEEN THE SSF AND SEPARATE TRANSPORTATION NODE MAY PRECLUDE A CREW "COMMUTE" CONCEPT
- REBOOST
  - EVOLUTION CONFIGURATIONS REBOOST REQUIREMENTS EXCEED BASELINE IMPULSE AND THRUST LEVEL CAPABILITY

COMMUNICATIONS AND TRACKING

DISTRIBUTED SYSTEMS EVOLUTION STUDY

ABSTRACT

THE COMMUNICATIONS AND TRACKING (C & T) TECHNIQUES AND EQUIPMENT TO SUPPORT EVOLUTIONARY SPACE STATION CONCEPTS ARE BEING ANALYZED. EVOLUTIONARY SPACE STATION CONFIGURATIONS AND OPERATIONAL CONCEPTS WERE USED TO DERIVE THE RESULTS TO DATE. A DESCRIPTION OF THE C & T SYSTEM BASED ON FUTURE CAPABILITY NEEDS IS PRESENTED. INCLUDED ARE THE HOOKS AND SCARS CURRENTLY IDENTIFIED TO SUPPORT FUTURE GROWTH.

INTRODUCTION

JSC TRACKING AND COMMUNICATIONS DIVISION (TCD) HAS BEEN TASKED TO EXAMINE THE EVOLUTION COMMUNICATION AND TRACKING REQUIREMENTS FOR SPACE STATION FREEDOM (SSF). THE STUDY IS STRUCTURED TO BEGIN THE ANALYSIS BY PAIRING THE INITIAL OPERATIONAL CAPABILITY OF SSF C&T SYSTEM AND ITS MERITS AGAINST KNOWN OPERATIONAL REQUIREMENTS. THE EVOLUTION C&T FUTURE NEED REQUIREMENTS ARE THEN IDENTIFIED. ULTIMATELY, THE STUDY CONCLUDES WITH RECOMMENDATIONS FOR MODIFICATION TO THE SSF C&T SYSTEM AND THE REQUIRED HOOKS AND SCARS TO ENSURE AN UNIMPEDED EVOLUTION PROCESS.

Text for C&T Functional Diagram

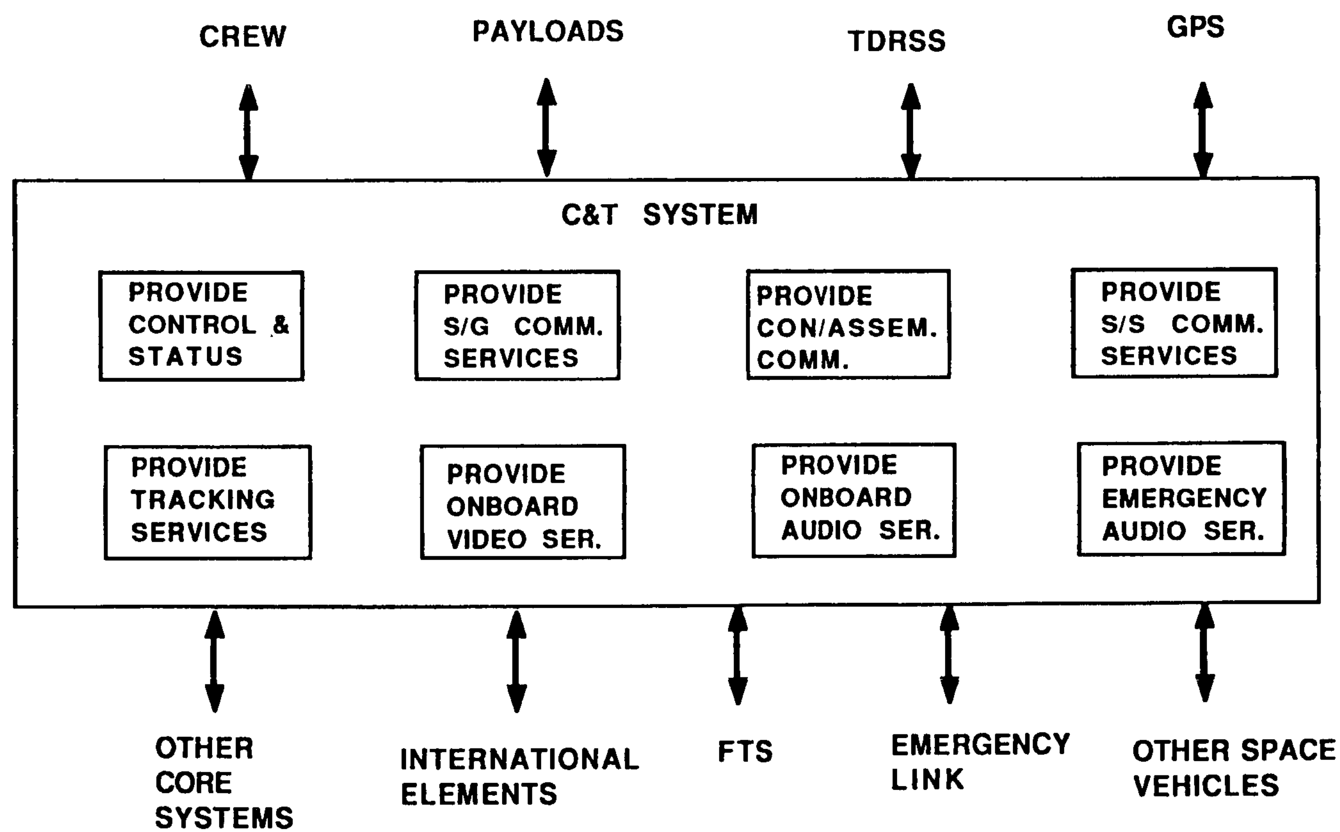
The Space Station Freedom C&T system consists of centralized and distributed redundant components that provide for:

1. Space-to-ground communications services.
   Transmission, reception and signal processing of audio, video, telemetry, command, data, text, and graphics between the SS freedom and TDRSS ground station.
2. Space-to-space communications services.
   Transmission, reception and signal processing of audio, video, telemetry, command, data, text and graphics between the SS freedom and space interoperating elements including FTS, EVAs, international elements, etc.
3. Space-to-ground assembly/contingency communications services.
   Transmission, reception and signal processing of audio, telemetry, and command between the SS Freedom and ground station during assembly and contingency phases.
4. Tracking services.
   Delivery of tracking and area-traffic control information and reference time signals to other Space Station systems.
5. Control and monitoring services.
   Monitoring the functioning of the C&T system and reporting status, performance and configuration data.
6. Onboard audio services.
   Processing and distribution of audio signals within the Space Station.
7. Onboard video services.
   Processing and distribution of video signals within the Space Station.

COMMUNICATIONS AND TRACKING FUNCTIONAL BLOCK DIAGRAM

WILLIAM CULPEPPER

FEB. 7, 1990



Text for Future Capability Needs

The operation of SS Freedom in the evolutionary time frame has several tasks to upgrade communications system to support new requirements with new technology insertion including (a) accommodation of high data rate payloads, and scientific experiments, (b) interface with Advanced Tracking and Data Satellite System (ATDRSS) (which can provide up to 650 Mbps space-to-ground data transmission capability), and (c) support of larger numbers of space-to-space interoperating elements or users including those inter-planetary (Mars and Moon) exploration vehicles at extended communication distance.

The tracking tasks can be broadly lumped into four categories including (a) rendezvous and docking/berthing monitoring and control, (b) proximity operations monitoring and control, (c) orbital debris monitoring, and (d) crew and equipment retrieval support. Items (b) and (d) can be lumped together into one class. Requirements definition for these tracking operations is difficult and complex. Our study is examining requirements definition, but also performing analysis to portray differing sensor performance within scenario classes.

Examination of the issues for future capability needs allows identification of hooks and scars, the most important of which are discussed further in this presentation.

COMMUNICATIONS:

IDENTIFY MISSION AND TECHNOLOGY DRIVERS AND DEFINE HOOKS AND SCARS REQUIRED FOR THE COMMUNICATIONS SYSTEM(S) TO SUPPORT REQUIREMENTS AND NEW TECHNOLOGY INSERTION INCLUDING:

- ACCOMMODATION OF HIGH DEFINITION TV
- ACCOMMODATION OF HIGH DATA RATE PAYLOAD AND EXPERIMENTS.
- INTERFACE WITH THE ADVANCED TRACKING AND DATA SATELLITE (ATDRSS)
- SUPPORT OF LARGER NUMBERS OF SPACE-TO-SPACE LINK USERS AND EXTENDED COMMUNICATIONS DISTANCES FOR NSTS AND OTHERS LIKE MOON AND MARS.

TRACKING:

IDENTIFY DRIVERS, HOOKS AND SCARS REQUIRED FOR SYSTEMS TO SATISFY THE FUTURE NEEDS AND NEW TECHNOLOGY FOR :

- RENDEZVOUS AND DOCKING MONITORING AND CONTROL
- ROBOTIC AND OTHER PROXIMITY OPERATIONS MONITORING AND CONTROL.
- ORBITAL DEBRIS MONITORING .
- CREW AND EQUIPMENT RETRIEVAL SUPPORT

Text for WP-2 Evolutionary Growth Plan

The current MDAC WP-2 Evolution Growth Plan for the communications system calls for adding the S-band feed to the Space-to-ground TDRSS parabolic antenna to support the S-band link for providing contingency when the normal space-to-ground Ku-band link fails or is for any reason unable to provide communications function.

The current growth plan also provides video support for the serving facility and additional payloads up to a maximum of 18. The NTSC video signal will be distributed in the red, green, and blue (RGB) components instead of composite form to improve the picture quality.

For the Space-to-Space communications services, the current growth plan calls for (a) addition of one omni antenna for the servicing facility, (b) implementation of switch matrices to support up to 16 antenna mounted equipment (AME) and 8 transceiver/modems in each node, (c) additions of transceiver/modems in each node to support more interoperating elements, and (d) additions of baseband signal processing (BSP) equipments to fully support additional transceiver/modems in each node except that no more than 2 video forward channels and 8 video return channels need be supported.

SPACE-TO-GROUND SUBSYSTEM

- USE OF THE S-BAND FEED IN THE TDRSS PARABOLIC ANTENNA

VIDEO SUBSYSTEM

- PROVIDE SUPPORT FOR THE SERVICING FACILITY AND ADDITIONAL PAYLOADS UP TO A MAXIMUM OF 18.
- PROVIDE PROVISIONS TO DISTRIBUTE RED, GREEN AND BLUE (RGB) COMPONENT VIDEO SIGNALS

SPACE-TO-SPACE SUBSYSTEM

- ONE ADDITIONAL OMNI ANTENNA FOR THE SERVICING FACILITY
- SWITCH MATRICES TO INDIVIDUALLY SUPPORT UP TO 16 ANTENNA/AME EQUIPMENT AND EIGHT TRANSCEIVER/MODEMS IN EACH NODE
- ADDITIONAL TRANSCEIVER/MODEMS IN EACH NODE
- BSP EQUIPMENT TO FULLY SUPPORT ADDITIONAL TRANSCEIVER/MODEMS IN EACH NODE EXCEPT THAT NO MORE THAN TWO VIDEO FORWARD CHANNELS AND EIGHT VIDEO RETURN CHANNELS NEED BE SUPPORTED

Text for WP-2 Evolutionary Growth Plan (Continued)

The MDAC Wp-2 Evolution Plan calls for additional local controllers, bus couplers, buses, dedicated mass storage units, network couplers, processors for the Control and Monitor subsystem to accommodate anticipated growth demand for supporting more complicated communications and tracking tasks. Also, knowledge based expert system with necessary software will be installed to assist and expedite executions of various C&M tasks.

The MDAC Wp-2 Evolution Plan also calls for the addition of a Laser Docking Sensor, and a tracking support RADAR for the Tracking Subsystem. The evolution study supports these recommendations, but concludes that the infrastructure to effectively use those tools is missing for the Space Station. A device to coordinate data from various tracking inputs is necessary. A Tracking Processor is proposed to meet that need.

CONTROL AND MONITOR SUBSYSTEM

- EXPERT SYSTEM SOFTWARE
- EXPERT SYSTEM DECISION EXPLANATION FACILITY
- ADDITIONAL C&M PROCESSORS
- ADDITIONAL C&M NETWORK COUPLERS (I.E. RING CONCENTRATORS)
- ADDITIONAL LOCAL CONTROLLERS
- DEDICATED MASS STORAGE UNITS
- ADDITIONAL LOCAL BUS COUPLERS
- ADDITIONAL LOCAL BUSES

TRACKING SYSTEM

- RADAR FOR DOCKING AND BERTHING
- LASER RANGING FOR DOCKING AND BERTHING

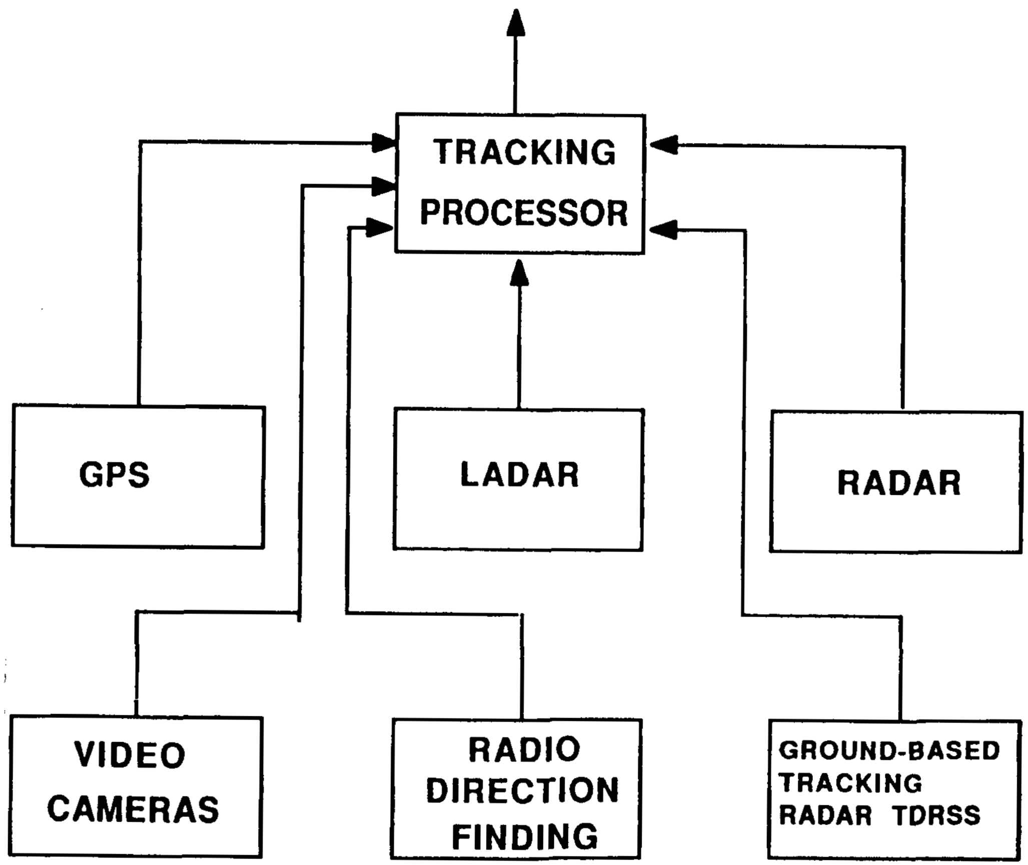
Text for The Evolution Tracking System

The block diagram shown in the facing slide relates the components of the evolution tracking system for Space Station Freedom as it is currently envisioned. Very little of the structure shown is available to Station operations at IOC. The focus of the slide, the tracking processor, is a vital recommendation. It is critical to functional growth of Freedom's orbital operations. With suitable sensors it can increase operational safety, efficiency, fault tolerance, and allow autonomy, while decreasing crew overhead, ground-based support, and docking vehicle cost.

The IOC baseline tracking configuration for the Station is currently based upon the Global Positioning System (GPS). Video cameras, while present, are primarily conceived of as manually controlled viewing aids for the astronauts. Coordination of data for tracking purposes is not possible. While the MDAC WP-2 Evolution Plan calls for the addition of a RADAR and LADAR (LAser Detection And Ranging) system, a plan for the tracking system coordinated growth with the associated processing capability has not been forged. The work here serves to coalesce such a plan, describing desired sensors, desired processing capability, and at least some of the rationale for our decisions.

Note that no quantities are given for the numbers of each species of sensory input shown in the facing slide. The optimum sensor quantities and placement issues have not been resolved, but primary considerations will be obscuration and the minimum number of viewing sensors (of specific types) to provide a given position and velocity error for given scenarios. The only sensor shown in the slide not normally considered in other work in this area is Radio Direction Finding (RDF). It is inexpensive, reasonably accurate, and requires no special action on the part of the observed party (except that he casually emit some communications or radar energy).

THE EVOLUTION TRACKING SYSTEM



Text for The Evolution Tracking System (Tracking Processor Rationale)

As mentioned on a previous slide, the tracking processor is a vital recommendation for the evolutionary requirements of the tracking system. In considering the rationale for this suggestion, there are at least three fundamental classes of scenarios which require tracking services on SS Freedom : rendezvous and docking/berthing, monitoring EVA actions (including Crew and Equipment Retrieval System -CERS- support), and the detection of approaching (baneful) objects (including debris). Each one calls for differing sensor capabilities, but common processing requirements can be identified. The last two scenarios mentioned mandate sensory capabilities onboard Freedom, and support the philosophy of a tracking processor. That is, in critical situations, speed and accuracy are required, and sometimes necessary for survival.

The rendezvous and docking class of tracking requirements is complex, but generally there can be two kinds of vehicles: those that are bristling with sensors, and those that will depend upon Freedom for approach guidance and control. For either of these vehicle classes, Station personnel must hold the rendezvous abort (veto) power (SSP 30000 specifies this for unmanned vehicles). Thus, even for craft with exemplary sensory capability, Freedom's attitude must be that of "Trust but Verify". In either case, vehicles must be tracked, and the integration of various tracking tools to support this capability calls for a tracking processor.

Perhaps the most beneficial aspect of the tracking processor will be its autonomy. It will automatically configure the available sensors to maintain maximum tracking accuracy. This implies a robust fault tolerance on the system level through the ability to generate the pointing estimates for the targets even as one sensor may fail or become obscured. The decision to abort a rendezvous for instance, would then be based solely upon the available accuracy of the state estimates for the target.

The tracking processor (with the appropriate sensors) will allow autonomous (supervised) rendezvous and docking operations at SS Freedom. Unmanned, inexpensive ELV resupply missions could be mounted for Freedom. Taking that one step further, the tracking processor philosophy is the bridge to capability in a multi-vehicle or multi-target environment. While this is not explicitly defined to be the case in most of the scenarios we have encountered, multiple target tracking and control must not be precluded (SSP 30000). It is much more possible in preparation for grand planetary missions, where many astronauts and free flyers may need to be tracked during large spacecraft assembly operations.

- IMPORTANT FOR THE THREE TRACKING SCENARIOS
  - RENDEZVOUS AND DOCKING/BERTHING
  - MONITOR EVA (CERS)
  - DETECT APPROACHING (BANEFUL) OBJECTS
- "TRUST BUT VERIFY" EVEN MANNED APPROACHES
- RESPONSIBLE FOR AUTONOMOUS TRACKING SYSTEM CONTROL (E.G. TARGET HANDOVER, OPTIMAL SENSOR ALLOCATION)
- NECESSARY FOR AUTONOMOUS RENDEZVOUS AND DOCKING/BERTHING
- REQUIRED FOR SAFE AND EFFICIENT UTILIZATION OF CREW IN MULTI-VEHICLE /TARGET ENVIRONMENTS
- ESSENTIAL FOR FAULT TOLERANCE THROUGH RAPID SENSOR RECONFIGURATION

Text for the SSF Evolution Tracking Sensor Group

The ultimate collection of sensors for SS Freedom's evolution is based upon a variety of technologies, each sensor class capable of providing some part of the tracking parameter group to a certain accuracy in a given scenario. One dependable element long used has been ground-based tracking RADARs. That, in combination with the processing of TDRSS communications data, exists as terrestrial support for Freedom operations. While ground-based tracking shall remain as a valid contingency tool, SS Freedom operational philosophy must try to move toward maximum independence from ground-based support, for safety and associated overhead cost reasons.

A powerful new tool for long and mid-range applications for low Earth orbit is the Global Positioning System. Effective use of GPS should obviate the need for ground-based tracking, although it requires that the vehicles communicate GPS information to one another. Work is currently being performed to determine what degradation may be expected from this technique as the docking craft approaches an object such as SS Freedom. GPS is the core element in developing the tracking sensor suite.

Currently in the MDAC WP-2 Evolution Plan, LADAR and RADAR afford the Station significant capability. We have chosen the title "LASER based tracking tools" to describe a class of tools which would include a LADAR sensor. The model for any LADAR type system will be the Laser Docking Sensor (LDS) being built now for a flight experiment aboard the OMV. The typical scenarios for using LDS type tools involve using retroreflectors on the targets, which offers greater range, and a simplified mechanism for orientation determination at close range. The RADAR system would offer data on targets not specifically outfitted for the LADAR (noncooperative). This would be critical for scenarios involving crew retrieval, where an EMU (or EEU) might need to be tracked to provide targeting data for equipment such as an EVA Retriever. Both the LADAR and RADAR system technology can benefit from Strategic Defense Initiative (SDI) developed space qualified versions of similar systems.

Radio Direction Finding techniques are inexpensive and a reasonably accurate means for locating casual emitters (communications or RADAR) in the Station environment. Like using camera video as a tracking tool, RDF three dimensional accuracy will be better in the mid to near range type applications. At longer ranges it will operate to deliver bearing information for pointing other sensors. It will greatly reduce acquisition time for tracking processor coordination.

Video cameras mounted across the Station for exterior viewing requirements can also be used effectively for tracking. Like RDF, accuracy is a function of the viewing geometry. This implies greatest possible baseline for maximum long range accuracy. Noncooperative attitude determination is difficult, but can be done in coordination with range images with some success. Light sources on the target are extremely beneficial for both attitude, and long range viewing. Strobe illumination from the Station can be used for long range viewing and under darkened conditions.

- GPS

  P(Y) CODE RESOLUTION

- LASER BASED TRACKING SYSTEMS

  E.G. LASER DOCKING SENSOR

- RADAR

  CCZ COVERAGE ONLY

- RADIO DIRECTION FINDING (RDF)

  S-BAND, KU-BAND, POSSIBLY X-BAND

- VIDEO CAMERAS (VARYING WAVELENGTH SENSITIVITY POSSIBLE)

- TERRESTRIAL

  TDRSS DATA, SPACE OBSERVING RADAR

Text for Tracking Processor

Inputs to the tracking processor will include both video and digital communications as shown entering the "Video Communications" and "Digital Communications" boxes in the facing slide. All video input formats will initially conform to NTSC, and should in the future be HDTV compatible (bandwidth and format). Using separate red, green, and blue channels on the initial installation would be preferable to NTSC, but the resources to accommodate differing standards and the additional communication requirements would be costly. Digital information can come both from local and remote GPS and RDF sensors, or from ground-based sources (processing TDRSS data, or space observing radar installations such as USSPACECOM). Included with the video or digital data, or built into a database, must be estimates of error so that proper modelling can be given for each data type.

Only a subset of the video inputs can be expected to have pertinent information at one time. This may be different types of information from normal camera video to RADAR. This is passed to the video processing stages. A typical architecture is depicted, others are possible. The first step in the data reduction process is "High Data Volume Video Processing" which transforms the image information into products for the "Video Post-processing", which is more sequential in nature. Data reduction through the video processing must attain ratios of at least 100,000:1. The final product from the video processing, as it is from the digital communications, is an estimate of position and orientation.

Requiring consistency between the data representations allows the "Tracking and Control Processor" element within the tracking processor to view the remainder of the system as virtual sensors, each delivering a measure of position and orientation of the target as well as a model of its error which allows the system to be more adaptive and incorporate new virtual sensors more easily. This sub-system is responsible for weighting the position estimates from each virtual sensor, and arriving at a true estimate of target position. From this estimation, it can generate both positioning control for the sensors and any illumination corrections that can be made, as shown leaving this module in the figure.

The tracking processor system, to clarify, is responsible for measuring the position and orientation of all targets. It will control the positioning and configuration of its sensors to acquire that data. It will supply data as required to GN&C and others.

Certainly the most expensive portion of the tracking processor is the video processing, loosely consisting of the top three boxes in the figure. An initial approach to incorporating this capability may be to process only one video input at a time, but to switch or multiplex between other useful inputs as resources allow. More channels can be processed simultaneously when additional permanent resources can be installed.

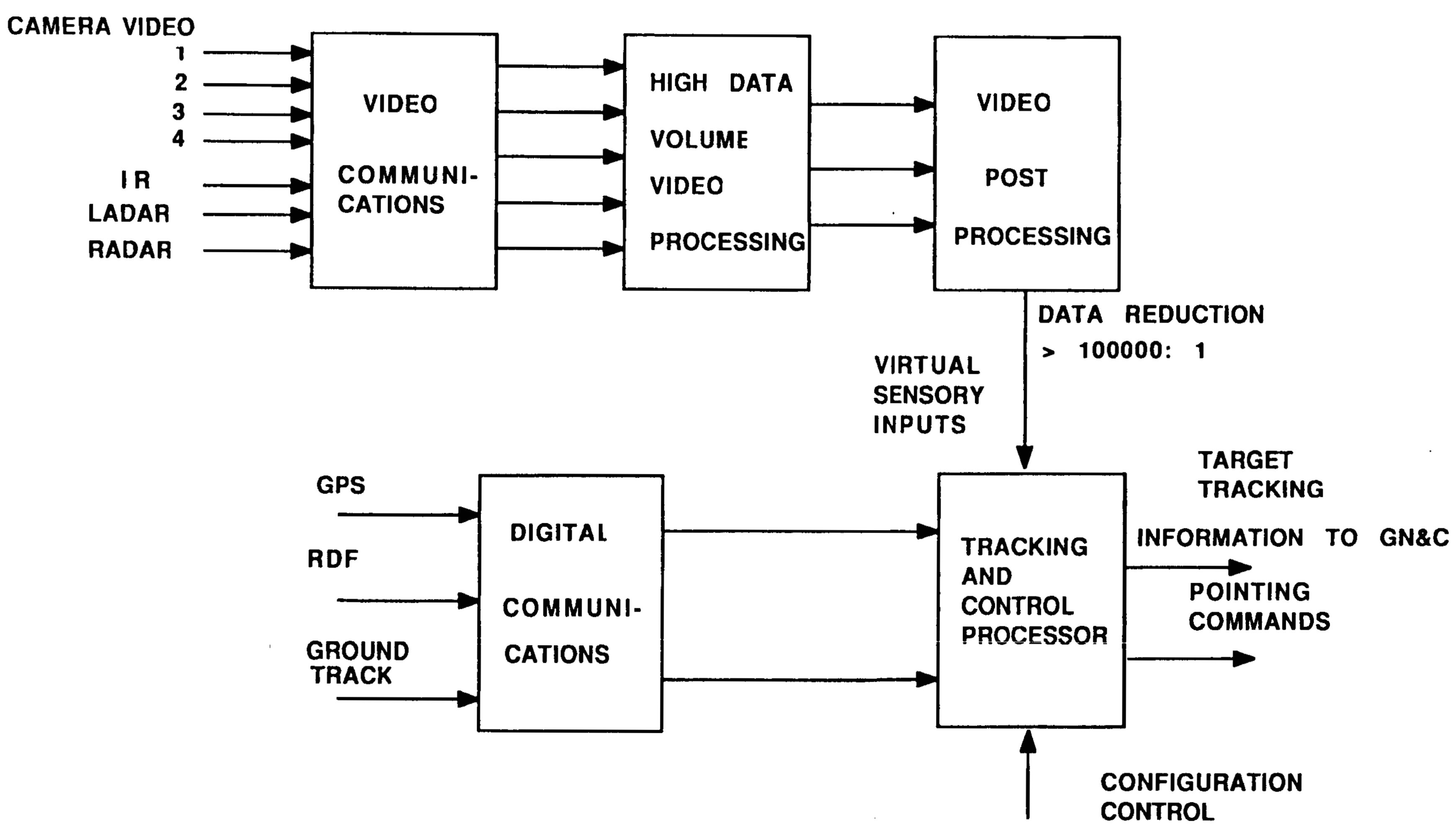
When considering growth for the tracking processor, additional video-type inputs have the greatest impact. Whenever additional targets must be tracked, additional processing capability is required for the tracking and control process. But this is almost insignificant compared to the additional computational requirements needed for video processing when more sensors must be processed simultaneously.

THE EVOLUTION TRACKING SYSTEM

TRACKING PROCESSOR

WILLIAM CULPEPPER

FEB. 7, 1990



Text for Processing Considerations

The actual processing performed in each of the main blocks of the tracking processor diagram has significant impact on the amount of computational power that must be available. For example, large volume video-data processing may use algorithms as computationally expensive as surface modeling, or as simple as edge enhancement. These algorithms suggest both conventional processing schemes like image pipeline processors and the emerging optical image processors.

Video post-processing may be more symbolic in nature such as for stereo matching or knowledge-based vision. Candidate schemes could include optical image processing on a reduced scale, or loosely-coupled parallel processors, which are receiving widespread acceptance.

The tracking and control algorithms are not less critical than the preceding algorithms and may present significant processing requirements as well. A Kalman filter of many variables can require significant vector processing. The remaining tasks can best be performed by a sequential processor.

The video processing algorithms described are, for the most part, in widespread use today and have hardware available to make the algorithms feasible in real-time systems. An example is the simple yet powerful technique of thresholding and blob analysis for targets at long range. These techniques (e.g. centroid tracking) may apply to LADAR, RADAR, or even passive electro-optic sensors when dealing with cooperative targets. The processing requirements of this class of algorithms are readily attainable for RS-170 video resolution now (at frame rates). Resolution greater than that attainable through the NTSC standard (such as HDTV), can be performed at less than frame rates, but still fast. Within the evolution time frame, higher resolution capability should also be available at frame rates.

HIGH DATA VOLUME VIDEO PROCESSING

ALGORITHMS: FUSION, JUMP-BOUNDARY DETECTION, INTENSITY GRADIENTS, CORRELATION MATCHING, PHANTOM, SUPPRESSION, STEREO MATCHING SURFACE MODELING, CONNECTIVITY ANALYSIS

HARDWARE: PIPELINE PROCESSORS, PARALLEL PROCESSORS, OPTICAL IMAGE PROCESSING

VIDEO POST PROCESSING

ALGORITHM: IMAGE CORRELATION, SENSOR FUSION, CODED TARGET DISCRIMINATION, MODEL-BASED VISION, KNOWLEDGE-BASED VISION, STEREO AND MULTI-CAMERA PROCESSING, COORDINATE TRANSFORMATIONS

HARDWARE: OPTICAL PROCESSORS, LOOSELY-COUPLED PARALLEL PROCESSORS, VECTOR PROCESSORS

TRACKING AND CONTROL

ALGORITHM: KALMAN FILTERING, CURVE REGRESSION, SENSOR POSITIONING, ILLUMINATION CONTROL, CALIBRATION

HARDWARE: VECTOR PROCESSORS, SEQUENTIAL PROCESSORS

Text for Hooks and Scars (Communications, Space-to-Ground Subsystem)

Hooks and scars will be provided for the C&T system to ensure that growth to the assembly complete functional requirements can be achieved. As a minimum scars will include cabling, brackets, and penetrations as required.

For the communications space-to-ground links. Hooks and scars shall be provided to install the Ka-band system compatible with the Advanced Tracking and Data Relay Satellite System (ATDRSS), which can support up to 50 Mbps forward link and 650 Mbps return link with increased bandwidth capability and less interference. In addition, a full rate S-band system, which provide 300 Kbps forward link and 6 Mbps return link, shall also be installed for use with ATDRSS to improve contingency data transmission capability.

In order to transmit data to selected ground stations to achieve high volumes of maximum traffic efficiency, provision for installation of a multi-beam antenna subsystem is provided. This subsystem will operate independent of Space-to-Ground TDRSS subsystem. High data rate can be transmitted to the desired ground station by pointing the appropriate antenna beam toward that station.

COMMUNICATIONS

1. SPACE-TO-GROUND SUBSYSTEM

- ADDITION OF KA-BAND SYSTEM
  - PROVIDE INCREASED BANDWIDTH CAPABILITY, LESS INTERFERENCE AND GROWTH THAT ARE INHERENT WITH ATDRSS:

    TO SUPPORT

    FORWARD LINK - 50 MBPS

    RETURN LINK - 650 MBPS

- ADDITION OF FULL-RATE S-BAND SYSTEM
  - PROVIDE INCREASED BANDWIDTH FOR USE WITH ATDRSS

    TO SUPPORT

    FORWARD LINK - 300 KBPS

    RETURN LINK - 6 MBPS

- ADDITION OF MULTI-BEAM ANTENNA SYSTEM
  - PROVIDE FOR INSTALLATION OF A MULTI-BEAM ANTENNA SUBSYSTEM INDEPENDENT OF THE SPACE-TO-GROUND TDRSS SUBSYSTEM TO TRANSMIT DATA TO SELECTED GROUND STATIONS TO ACHIEVE HIGH VOLUMES OF MAXIMUM TRAFFIC EFFICIENCY

Text for Hooks and Scars (Communications, Space-to-Space Subsystem, etc.)

For the space-to-space subsystem, fiber optic cable installation will be provided at IOC. This installation will save considerable cost when the baseline coaxial cables are replaced to increase transmission efficiency. Scars will also be provided to accommodate additional interoperating elements including interplanetary space vehicles such as lunar and Mars exploratory spacecraft. In order to support interplanetary missions at much increased communication distance, hooks and scars will be provided for upgrading of baseline space-to-space antenna size, increasing of RF power amplifier, and/or employing most efficient modulation/coding scheme.

Hooks and scars will be provided to support high definition TV (HDTV) for the Video Subsystem when the HDTV technology is mature. HDTV requires much wider bandwidth and complicated signal processing. The baseline video signal distributions are in the analog NTSC composite forms, which not only require conversions to RGB prior to being transmitted to the ground but also are easily subject to noise disturbance during transmission. Provisions for digital distributions in discrete RGB forms will be provided to improve transmission quality and efficiency. Video signal compatibility shall also be provided for interfacing with international elements.

The flat-screen technology will be integrated into the Control and Monitor Subsystem to improve display quality and reduce power, size, and weight. Provisions will be provided for the CMS to accommodate the advanced synchronous optical network (SONET). The CMS shall also be provided to integrate a special computer system for voice acquisition/recognition, language-to-text, and text-to-language capability. This capability is needed to improve command sequences and the modes of operation of the C&T system.

2. SPACE-TO-SPACE SUBSYSTEM

- PROVIDE FOR INSTALLATION OF FIBER OPTIC CABLE AT IOC
- ENABLE COMMUNICATION WITH ADDITIONAL VEHICLES (INCLUDING INTERPLANETARY)
- PROVIDE FOR UPGRADING OF ANTENNA SIZE , RF POWER AMPLIFIERS, AND/OR EMPLOYING MOST EFFICIENT MODULATION/CODING SCHEME TO SUPPORT INCREASED COMMUNICATION DISTANCE (INCLUDING MOON AND MARS)

3. VIDEO SYBSYSTEM

- PROVIDE FOR PROVISIONS TO SUPPORT HIGH DEFINITION TV, DISTIBUTIOIN SYSTEM DIGITIZATION FOR TRANSMISSION TO GROUND STATION, AND INTERFACE WITH INTERNATIONAL ELEMENTS

4. CONTROL AND MONITOR SUBSYSTEM

- INTEGRATION OF FLAT-SCREEN TECHNOLOGY AND INTERFACES INTO CMS
- ACCOMMODATION OF AN EVOLUTIONAL ADHERENCE TO THE SYNCHRONOUS OPTICAL NETWORK (SONET)
- INTEGRATION OF COMPUTER SYSTEM FOR VOICE ACQUISITION/RECOGNITION, LANGUAGE-TO-TEXT AND TEXT-TO-LANGUAGE CAPABILITY

5. AUDIO SUBSYSTEM

- INTEGRATION OF AUDIO SIGNAL FORMATS INTO INTEGRATED SERVICE DIGITAL NETWORK (ISDN)

Text for Hooks and Scars (Tracking)

Part of the philosophy of the SSF evolution tracking system design has been to minimize the resultant scarring. To help accomplish this, the sensor node concept was put forth (described in more detail below.) Due to the lack of sensor processing capability existing in the IOC design however, scarring for the tracking processor has taken on a more significant nature. The tracking processor as it has been defined here must have fast response to switching requests on the video bus. It must control selection of video sources, and timing of video synchronization. Today's technology for video rate processing offers a significant scar for both volume and power. A card cage full of video rate pipeline may use almost a kilowatt of power, and occupy a quarter rack space.

Sensor hooks and scars are less significant to Station conceptualization. Creating sensors compatible with the fiber optic video acquisition network on the exterior of the Station guarantees the ability to move them as necessary, and acquire data at up to 20 MHz. Thus, RADAR and LADAR units which have been designed to the sensor node network standard, require no scarring for installation. As node members, each would be identified, and any special processing algorithms required for tracking using that sensor would be loaded. It mildly compounds the duty of the tracking processor software to have sensor variety, but the flexibility offered for exterior reconfigurability greatly outweighs the software issue.

Sensors which would provide only small amounts of digital data will not benefit from sensor node placement. Techniques such as RDF will use low data rate communications such as the Station's LAN service. Depending upon the ultimate positioning of the RDF receivers, special LAN runs may have to be made to support communications. Depending upon the update rate that is forced on the RDF system, a direct RF link between one or more of the units may also be necessary.

TRACKING

- PROVIDE FOR INSTALLATION OF A TRACKING PROCESSOR
  - MUST CONTROL IOC VIDEO CROSS POINT SWITCH/MUX, AND VIDEO TIMING
  - UP TO 1 RACK VOLUME DEPENDENT ON TECHNOLOGY USED
  - UP TO SEVERAL KILOWATTS OF POWER (DEP. ON TECH. USED)
- PROVIDE FOR INSTALLATION OF A RADAR
  - IF SENSOR NODE COMPATIBLE, NO SCARRING
  - HOOKS PRIMARILY TO TRACKING PROCESSOR
- PROVIDE FOR INSTALLATION OF A LADAR
  - IF SENSOR-NODE COMPATIBLE, NO SCARRING
  - HOOKS PRIMARILY TO TRACKING PROCESSOR
- PROVIDE FOR INSTALLATION OF AN RDF SYSTEM
  - MAY NEED RF LINK BETWEEN UNITS
  - DATA OUTPUT COULD USE DMS LAN OR PAYLOAD LAN
  - HOOK PRIMARILY TO TRACKING PROCESSOR

Text for Hooks and Scars (Tracking, Continued)

The term Sensor Node Network describes a slightly modified version of the Station video network ensuring long term growth of the tracking system through reconfigurability. Sensor identification and commands can continue to be placed using video timing windows, but the nature of the command groups should be broadened to enable operation with other types of sensors. Important scarring must exist to have sufficient coverage of the network to allow growth and alteration. The sites should be regular and widely distributed. The nodes can be designed to be inexpensive, and might number from tens of sites to one hundred sites. With appropriate thought given to the choice of connectors (etc.), EVA astronauts and pieces of automation may feed high bandwidth (secure) communications to and draw power from, the sensor node network.

One issue of importance for a reconfigurable system must be that of calibration. The ultimate accuracy of the system depends upon the pointing error of each of its components. The position of each of the node sites may not be accurately known, and structural obscuration may change over long periods as the Station evolves. The pointing may also be affected by structural composition for electromagnetic techniques. Thus, position, viewing envelope, and pointing deviation (if any) must be identified for the network elements. There are many possible calibration methodologies. Scarring must include fiducials for each of the sensor groups on and off the Station. Small sites on the Station including pointing targets, luminous point sources, and retroreflectors are inexpensively arranged. Also recommend some form of a remote (possibly tethered) fiducial, which may be moved a known distance away in a controlled direction, to offer similar services. The off Station fiducial would support RADAR and RDF calibration, in addition to offering a more realistic test and calibration environment for the other sensors.

TRACKING (CONTINUED)

- PROVIDE FOR MANY MORE SENSOR NODES (VIDEO COMPATIBLE)
  - SS FREEDOM GROWTH WILL REQUIRE RELOCATION AND ADDITION OF VARIOUS SENSORS (VIDEO CAMERAS, LADAR, RADAR) IMPLYING:
    - POWER AND BIDIRECTIONAL COMMUNICATIONS SENSOR NODES SHOULD BE PLACED AT REGULAR INTERVALS ALONG STATION STRUCTURE
      - SCAR FOR MORE VIDEO NODES
      - BETTER COMMUNICATIONS FOR EVA ACTIVITIES
    - SENSORS MUST HAVE A COMPATIBLE COMMUNICATIONS SCHEME TO ALLOW SENSOR NODE INDEPENDENCE (VIDEO BASED)
    - CALIBRATION SCHEME MUST BE DEVISED TO ACCOUNT FOR RECONFIGURABILITY
      - FIDUCIALS ON SSF
      - FIDUCIAL ON A TETHER

DYNAMIC CHARACTERISTICS OF SPACE STATION FREEDOM MARS & LUNAR EVOLUTION REFERENCE CONFIGURATIONS

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Introduction

One concept for a manned mission to Mars uses an evolutionary version of Space Station Freedom (SSF) as a transportation node. The station is modified by the addition of dual keels, an upper and lower boom, additional laboratory and habitation modules, increased power and an assembly platform. With these modifications the station is called the Mars Evolution Reference Configuration (MERC). The mass of the station is 65 percent greater than the mass of SSF and its moments of inertia through the mass center are greater by approximately a factor of four. Over a period of months, several flights from Earth to low-Earth-orbit carry the components of a manned Mars piloted vehicle (MPV) to the MERC where the vehicle is constructed on the assembly platform. After each flight the station is reboosted to an appropriate altitude, such that the orbit decay due to atmospheric drag forces lowers the spacecraft to the proper altitude at the appropriate time for rendezvous with the next assembly flight. When the assembly process is completed, the MPV, which has a mass of approximately 200,000 lbm, is situated on the evolutionary station. The mass increase of the MERC with MPV system over SSF is 112 percent and the moments of inertia about axes through the mass center increase by up to a factor of 12. When the MPV is assembled, inspected and verified, the mission is ready to proceed and the MPV is moved from the station to a staging area and mated with fueled trans-Mars injection stages for the flight to Mars.

This presentation describes a finite element model of the MERC formulated to investigate the expected low frequency modes and its variation with the addition of a large payload. A basic reboost procedure using near-continuous firing of reaction control system jets is proposed with off-modulation of the jets used to control flight attitude. The reboost procedure is described with the closed-loop attitude control dictating jet on/off cycling based on feedback signals which contain both the rigid body rotation information and the elastic rotations local to the attitude sensor. The presentation contains a description of the dynamic response at critical points of the station during the reboost and concludes with results of a brief study of the dynamic characteristics of a Lunar transportation node configuration.

INTRODUCTION

- O EVOLUTIONARY CONCEPTS OF SPACE STATION FREEDOM WILL HAVE MORE MASS AND BE MORE FLEXIBLE THAN THE ASSEMBLY COMPLETE CONFIGURATION.

- O FUNDAMENTAL STRUCTURAL FREQUENCIES WILL BE REDUCED AND WILL APPROACH THE CONTROL BANDWITH OF THE ATTITUDE CONTROL SYSTEMS.

- O THE CURRENT STUDY EVALUATES THE STRUCTURAL, DYNAMIC AND CONTROL CHARACTERISTICS OF EVOLUTIONARY CONFIGURATIONS CONSISTENT WITH TRANSPORTATION NODE CONCEPTS.

- O THE PRESENTATION DESCRIBES:
  - FINITE ELEMENT MODEL OF A MARS EVOLUTIONARY REFERENCE CONFIGURATION
  - STRUCTURAL DYNAMIC MODES AND FREQUENCIES OF THE CONFIGURATION WITH AND WITHOUT A MARS PILOTED VEHICLE
  - A BASIC REBOOST PROCEDURE WITH ACTIVE ATTITUDE CONTROL
  - THE DYNAMIC RESPONSE AT CRITICAL POINTS OF THE STRUCTURE DURING REBOOST

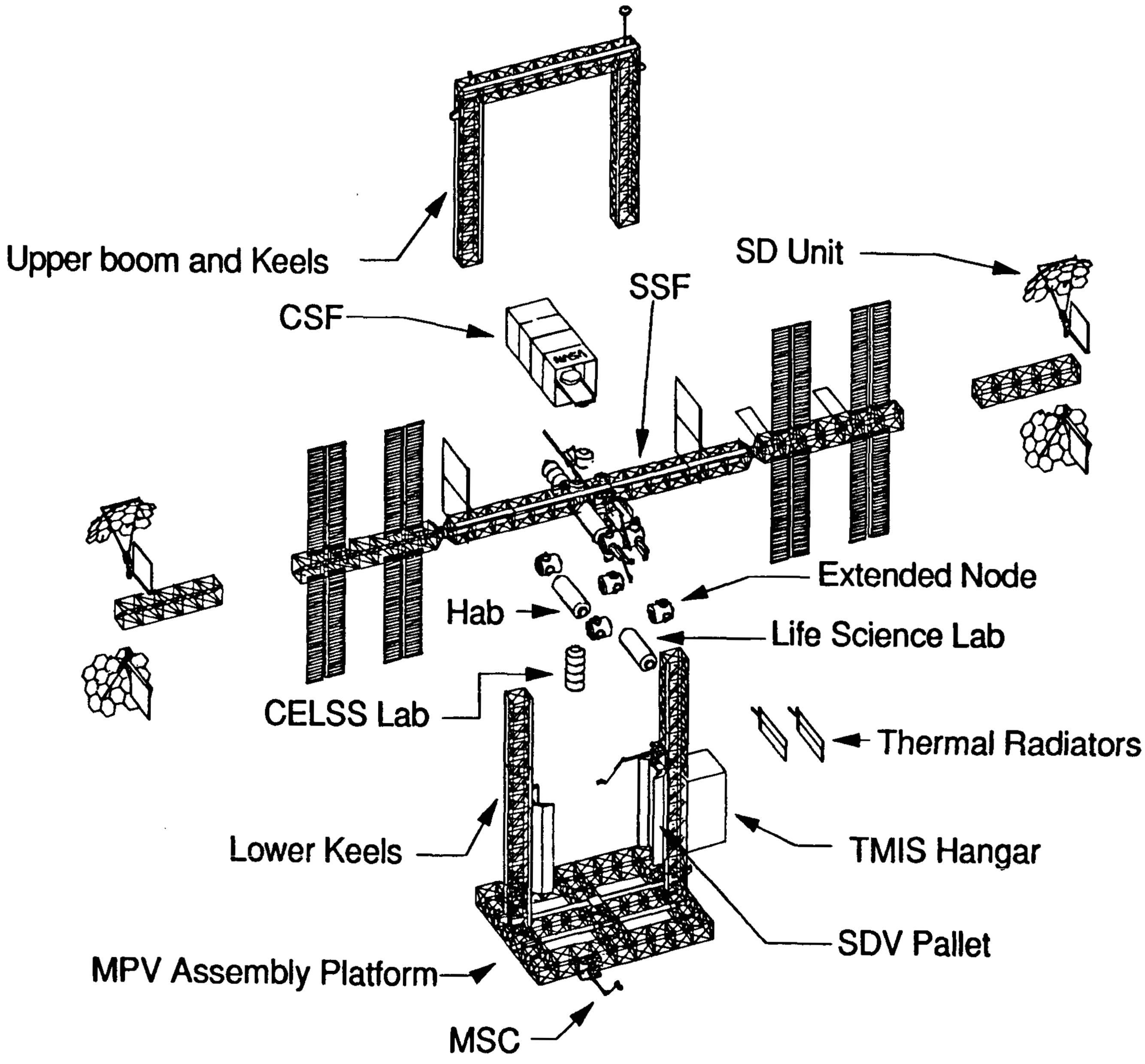
- O THE PRESENTATION CONCLUDES WITH RESULTS OF A BRIEF STUDY OF THE DYNAMIC CHARACTERISTICS OF A LUNAR TRANSPORTATION NODE CONFIGURATION

pac 11/6/89

MERC ADDITIONS TO SPACE STATION FREEDOM

The MERC is an evolutionary version of Space Station Freedom configured to provide assembly and verification facilities for the Mars evolution mission. The SSF is modified by the addition of dual keels, an upper and lower boom, additional laboratory and habitation modules, the customer servicing facility (CSF), a trans-Mars injection stage (TMIS) hangar, increased power, and a MPV assembly platform with a mobile service center (MSC) as shown in the figure. The planar dimensions of the MERC are approximately 215 m by 135 m. The primary truss structure is constructed using 5 m square orthogonal tetrahedral truss bays. The truss structure supports the pressurized modules, a combined photovoltaic (PV) and solar dynamic (SD) power generation system, the vehicle assembly and verification subsystems, and a central thermal radiator system. The habitable area of the MERC is located at the center of the transverse boom and consists of seven modules: the US habitation module, the US laboratory module, the European Space Agency module, the Japanese experiment module, the life science lab, the closed environmental life support lab (CELSS), and a dedicated Mars habitation module. The lower keels and the MPV assembly platform provide docking/berthing areas for Mars mission vehicles and their associated equipment.

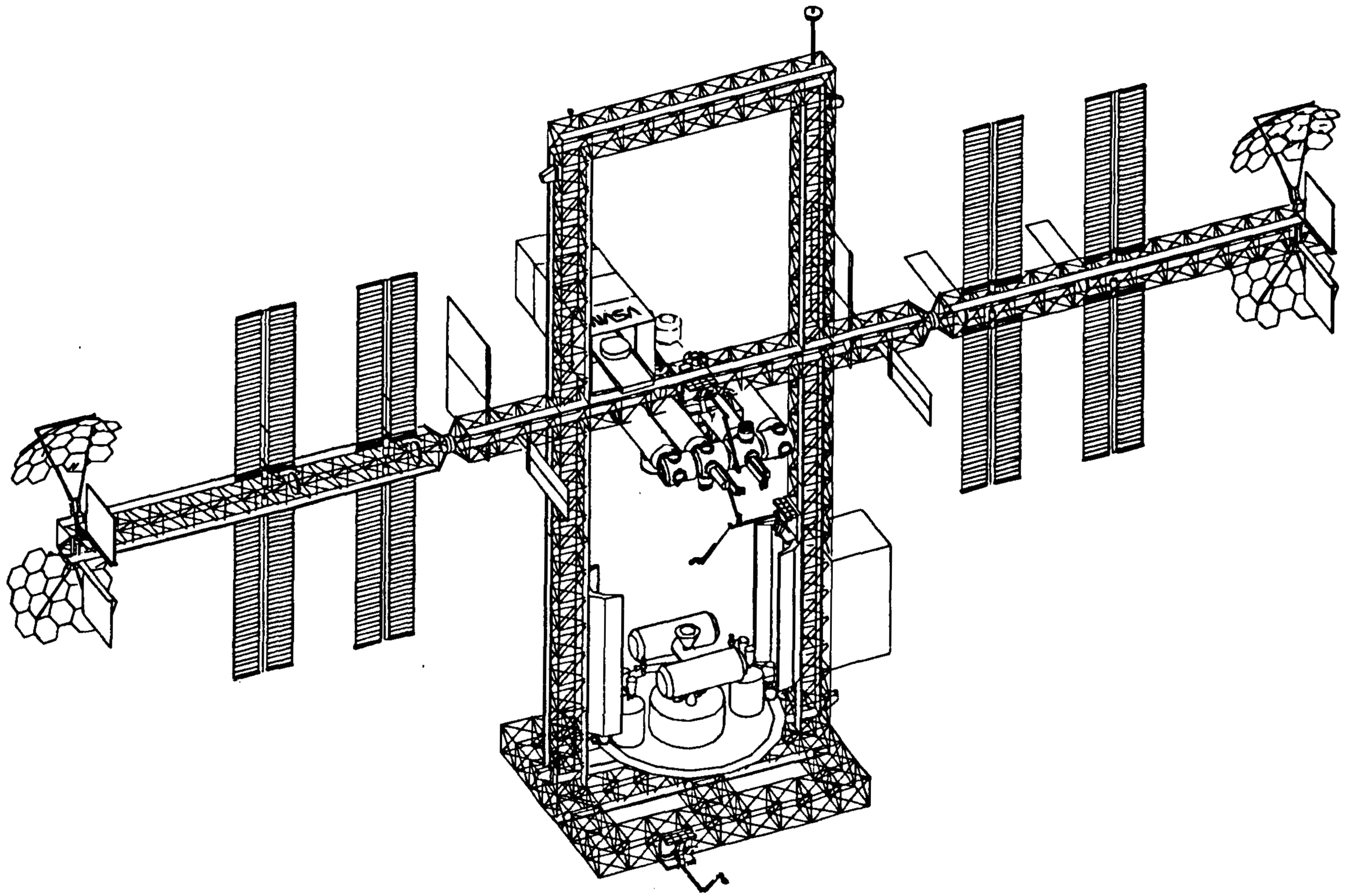
MERC Additions to Space Station Freedom



MERC WITH MPV

In the months prior to the launch of the second flight in the Mars evolution scenario several flights from Earth to low-Earth-orbit carry the components of the MPV to the MERC and the vehicle is constructed and verified on the assembly platform

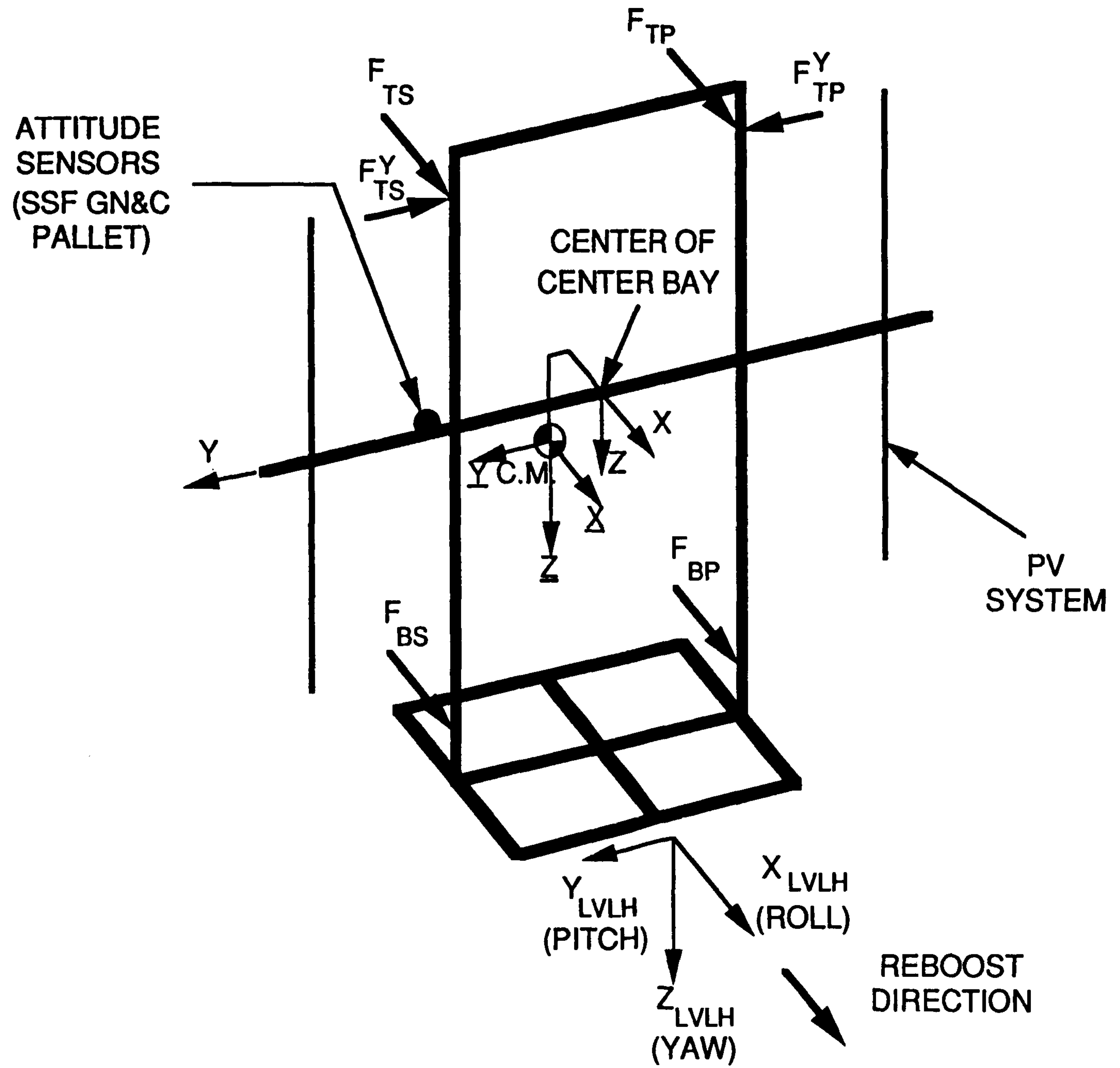
Mars Evolution Reference Configuration (MERC) with Mars Piloted Vehicle (MPV)



Locations of RCS Jets, Sensors, and Center of Mass

Three different coordinate systems are employed to characterize the geometry, dynamics, and orientation and location on orbit of the station. As shown in the figure, the geometrical coordinate system (X-Y-Z) has its origin at the center of the center truss bay. A body-fixed coordinate system ($\underline{X}$-$\underline{Y}$-$\underline{Z}$) at the center of mass with axes parallel to the geometrical coordinate system is used to describe the dynamics and the orientation of the station with respect to the local vertical, local horizontal (LVLH) coordinate system. The LVLH coordinate system is used to describe the position of the station on orbit with respect to an earth-fixed inertial coordinate system. The LVLH system is defined as follows: X_{LVLH} is parallel to the flight direction and coincides with the $\underline{X}$ axis, Z_{LVLH} is directed toward the center of the earth, and Y_{LVLH} is normal to the orbit plane composing a right handed coordinate system. Attitude control for the MERC is provided by a combination of control moment gyros and a hydrogen-oxygen reaction control system (RCS). The gyros are located outboard of the starboard keel on the guidance, navigation, and control (GN&C) pallet as shown in the figure. The four clusters of on/off type RCS thrusters, used for control moment gyro spin-up and desaturation, and altitude reboost, are located on the upper and lower keels and provide a total of 200 lbf thrust in the flight direction.

Locations of RCS Jets, Sensors, and Center of Mass

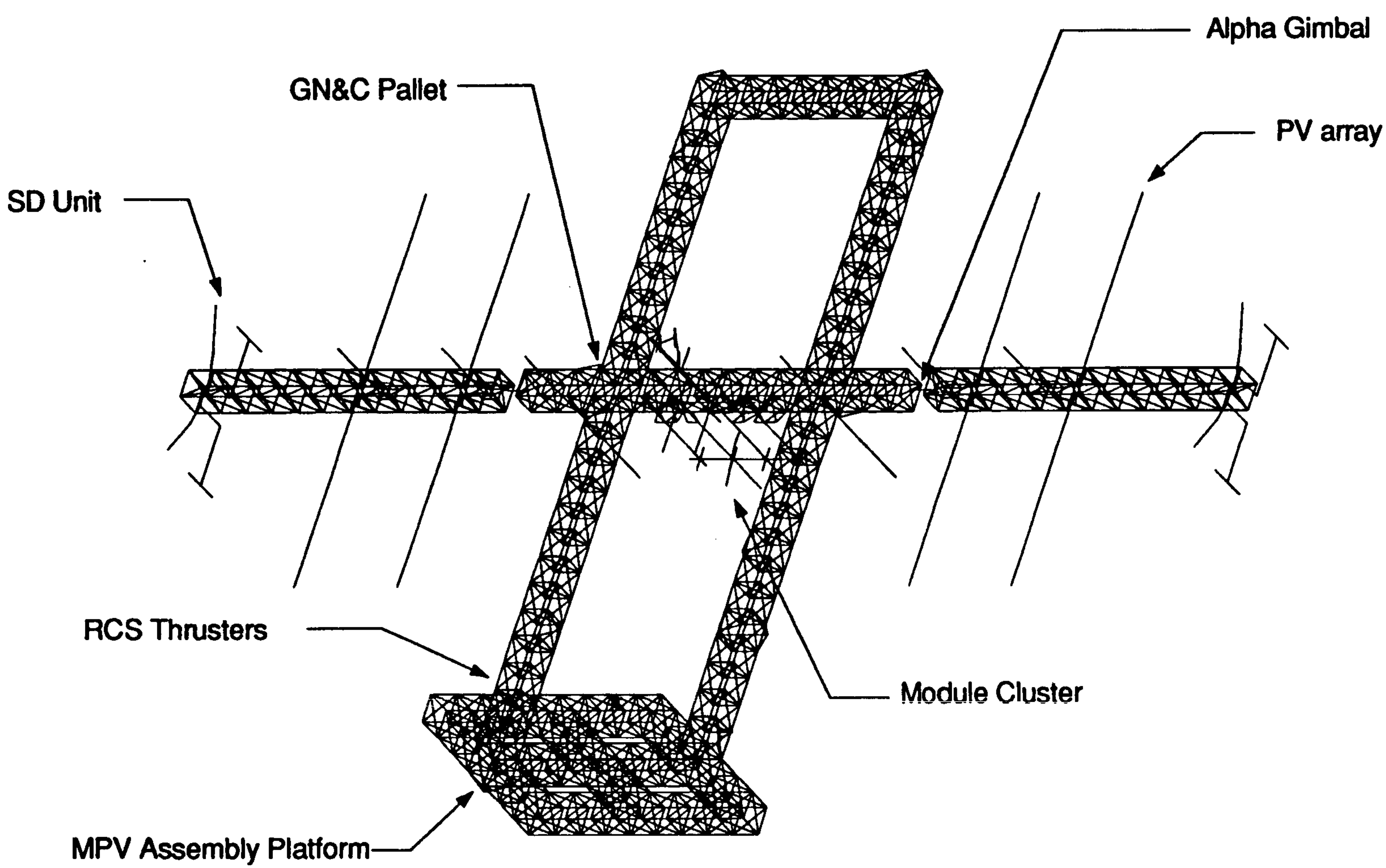


Structural Model

Detailed finite element models of the MERC and the MERC with MPV were developed. The MERC finite element model is shown in the figure. These models were based on a recent NASA baseline structural model of SSF. The truss members are aluminum coated graphite-epoxy tubes with a 2.0 inch outside diameter, a wall thickness of 0.067 inches, a modulus of elasticity of 13.77×10^6 psi, and a material density of 4.05×10^4 $lbf\text{-}s^2/in^4$. These members are represented by beam elements. Joint effect stiffness reduction is accounted for by modulus reduction. The pressurized modules are located on the positive z side of the center of the transverse boom. The modules are modeled as beam elements with structural and non-structural mass distributions. The local module mass inertias are represented by concentrated masses. The module interconnects are represented by translational and rotational springs which model the properties of the module berthing mechanisms. The pressurized module cluster is connected to the transverse boom by a series of truss tube members, utilizing rigid-link offsets from the elastic centerline of the modules. The alpha gimbals, which provide solar vector tracking, are located symmetrically about the z axis on the transverse boom. The gimbals are modeled as beam elements using lineal mass distribution (equal mass per unit length). The central station thermal radiators and PV systems are located symmetrically about the z axis on the port and starboard transverse boom. These components are modeled with beam elements using lineal mass distribution, and a bending stiffness tuned for a first bending natural frequency of 0.15 Hz for the radiators and 0.10 Hz for the PV system assuming a clamped-free boundary condition. The solar dynamic units are located on the positive and negative z faces at the outer edges of the port and starboard transverse boom. The units are modeled as rigid elements with discrete mass representations of the receiver, collector, and deployment mechanisms.

Various other structures, which include RCS, GN&C pallet, MPV, trans-Mars injection stage hangar, shuttle derived vehicle (SDV) pallets, and communications antennas, are represented as offset masses with inertia matrices about their centers of mass. Other non-structural components (utility trays, thermal control system, joint nodal clusters, and RCS tank farms) are represented by concentrated masses applied at the appropriate model nodes. The MERC finite element model has 2420 beam elements, 434 concentrated mass elements, 57 rigid elements, 1000 nodes, and approximately 5800 dynamic degrees of freedom. The addition of the MPV to the MERC model adds two concentrated mass elements, two rigid elements, and twelve dynamic degrees of freedom.

Mars Evolution Reference Configuration Finite Element Model



Rigid Body Properties of Finite Element Models

The mass characteristics and rigid body properties comparisons between the MERC, MERC with MPV, and SSF are shown in the Table. The mass of the MERC is 65 percent greater than the mass of SSF and its moments of inertia through the mass center are greater by approximately a factor of four. The mass increase of the MERC with MPV system over SSF is 112 percent and the moments of inertia about axes through the mass center increase by up to a factor of 12.

Rigid Body Properties of Finite Element Models

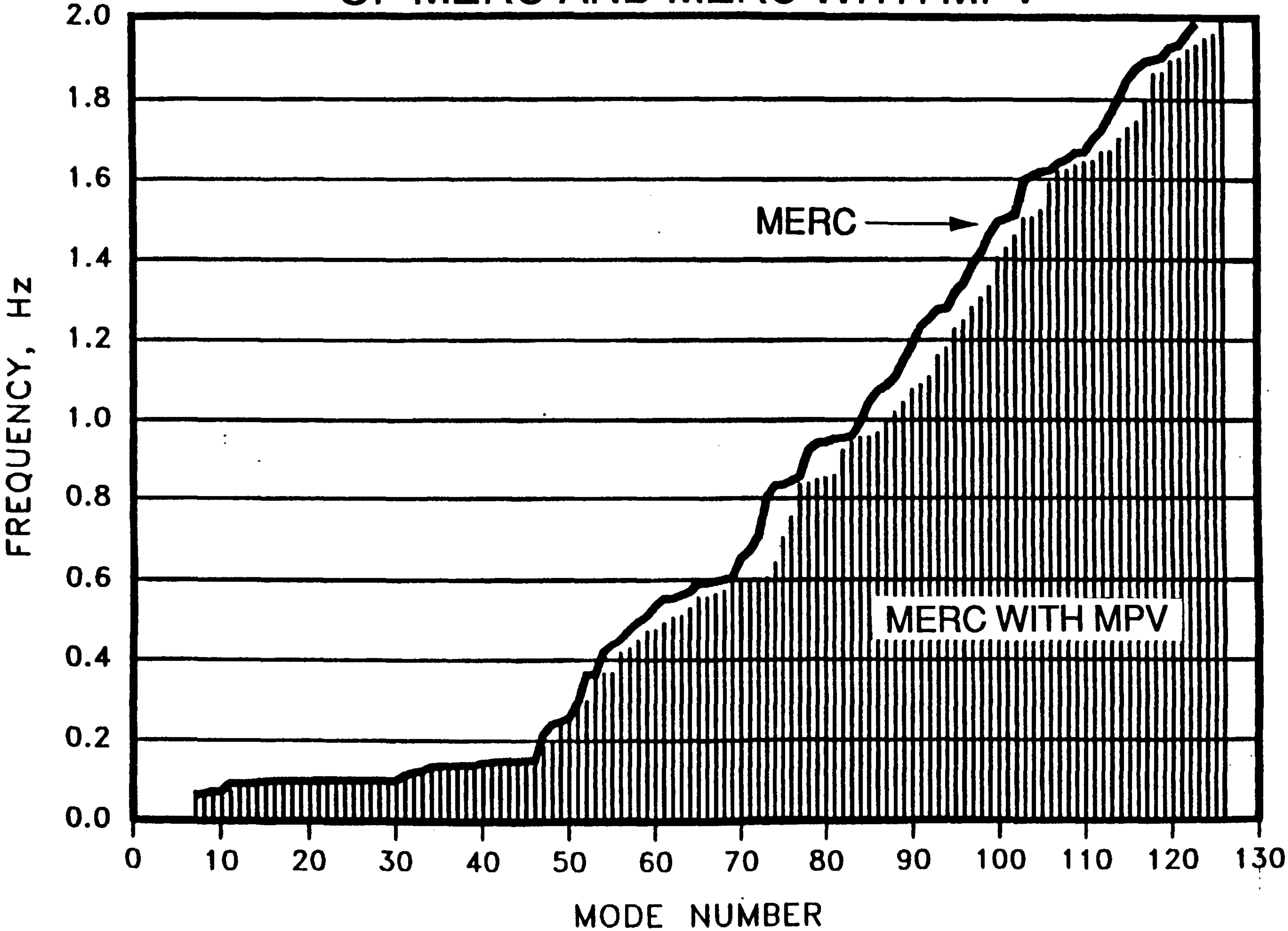
Configuration	Mass ($lbf\text{-}sec^2/in$) (Wt. on Earth, lbf)	Center of Mass (in) *			Moment of Inertia ($10^6 lbf\text{-}sec^2\text{-}in$) **			Product of Inertia ($10^6 lbf\text{-}sec^2\text{-}in$) **		
		X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
SSF	1,548 (598,000)	-78.7	25.1	132.6	1132	299	1214	6.0	-8.3	-9.7
MERC	2,552 (986,000)	-44.6	10.3	270.9	4801	1302	4045	23.5	-40.5	73.1
MERC with MPV	3,282 (1,268,000)	-39.4	-16.4	714.7	7202	3615	4182	18.7	-82.7	177.7

*Measured from the center of center bay. ** About the center of mass.

Structural Analysis

The finite element code MSC/NASTRAN, with the Lanczos method of eigenvalue extraction, was used to obtain the undamped natural frequencies of the MERC and the MERC with MPV below 2.0 Hz. The distributions of natural frequencies for the MERC and the MERC with MPV are shown in the figure. The attachment of the MPV to the MERC system adds three natural frequencies below 2.0 Hz and causes a general lowering of most frequencies above 0.25 Hz.

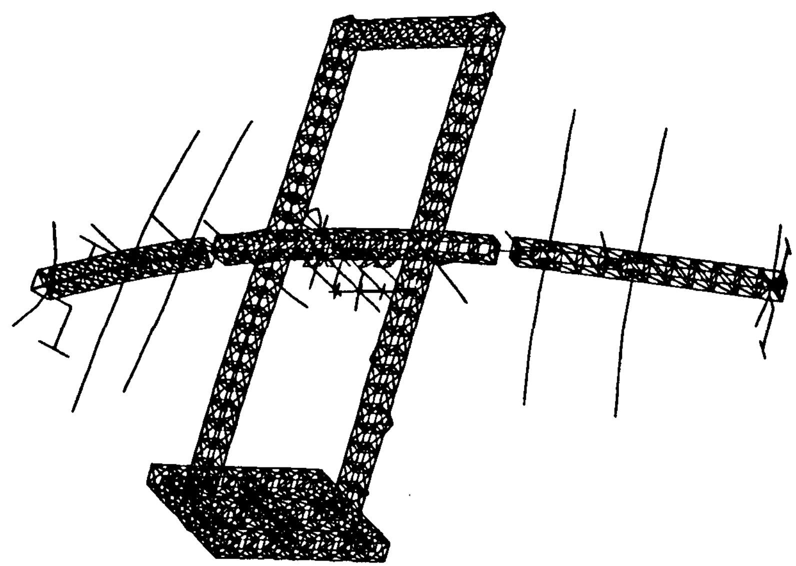
UNDAMPED NATURAL FREQUENCY COMPARISON OF MERC AND MERC WITH MPV



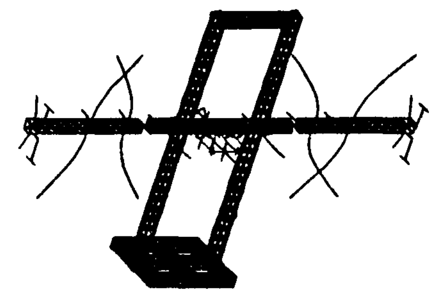
Undamped Natural Modes

The fundamental modes for both configurations (first flexible mode) occur at 0.064 Hz. The MERC with MPV fundamental mode is shown in the figure. An example of an appendage mode, in this case MERC photovoltaic array first bending, is also shown. The first occurrence of MPV assembly platform bending of the MERC with MPV system occurs at 0.36 Hz and is shown. In general the modes show a complex motion with strong coupling of the truss structure with various power, radiator, and payload components. The majority of the modes exhibit similar behavior in that the module cluster region, which has the bulk of the mass, acts as a node point for most modes and the stiff MPV assembly platform moves as a rigid body.

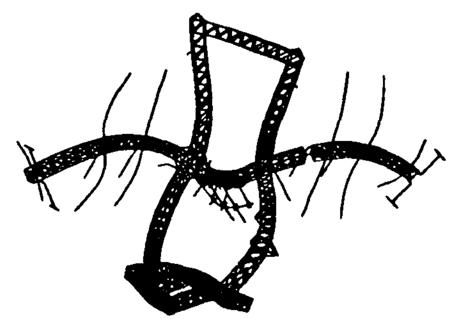
Typical Modes of the MERC and the MERC with MPV



MERC with MPV Fundamental Framework Mode Shape at 0.064 Hz



MERC Appendage Mode Shape at 0.099 Hz



MPV Assembly Platform Bending Mode Shape at 0.36 Hz

Lowest Frequency Occurrence of Component Modes

A comparison of component mode occurrences between MERC, MERC with MPV, and SSF is shown in the table. The undamped frequencies of the major truss framework modes are significantly reduced with the addition of the MPV.

Lowest Frequency Occurrence of Component Modes

Mode Shape	SSF Frequency (Hz)	MERC Frequency (Hz)	MERC/MPV Frequency (Hz)
PV Bending	0.090	0.099	0.095
Transverse Boom Bending	0.144	0.064	0.064
Lower Keel Bending	N/A	0.155	0.111
Lower Keel Torsion	N/A	0.219	0.103
MPV Assembly Platform Bending	N/A	0.672	0.362

Reboost Analysis

To reboost the MERC and the MERC with MPV, the RCS composed of four clusters of jets, located on the dual keels, fires its jets in the negative X_{LVLH} direction to accelerate the station in the flight direction. Since the jets are not located the same distance from the center of mass, the station will begin to yaw about the Z_{LVLH} axis and pitch about the Y_{LVLH} axis. Inertia coupling will also cause a roll motion about the X_{LVLH} axis. For the current study the station is required to maintain a rigid body flight attitude to within three degrees of the nominal flight path, i.e. about the LVLH axes. The attitude and attitude rate are sensed at the GN&C pallet. An error signal, composed of the measured attitude summed with the measured attitude rate, is used with a Schmitt trigger to off- or on-modulate the jets at the appropriate locations to control the attitude. A 50 lbf RCS jet force is used in a given direction at each RCS cluster. It is assumed that the station is assembled in a 220 nautical mile (NM) circular orbit. Altitude changes due to RCS jet firings for reboost in one orbit were studied. Orbital mechanics are incorporated to compute the orbit trajectory subject to time varying jet firings for the attitude control during reboost.

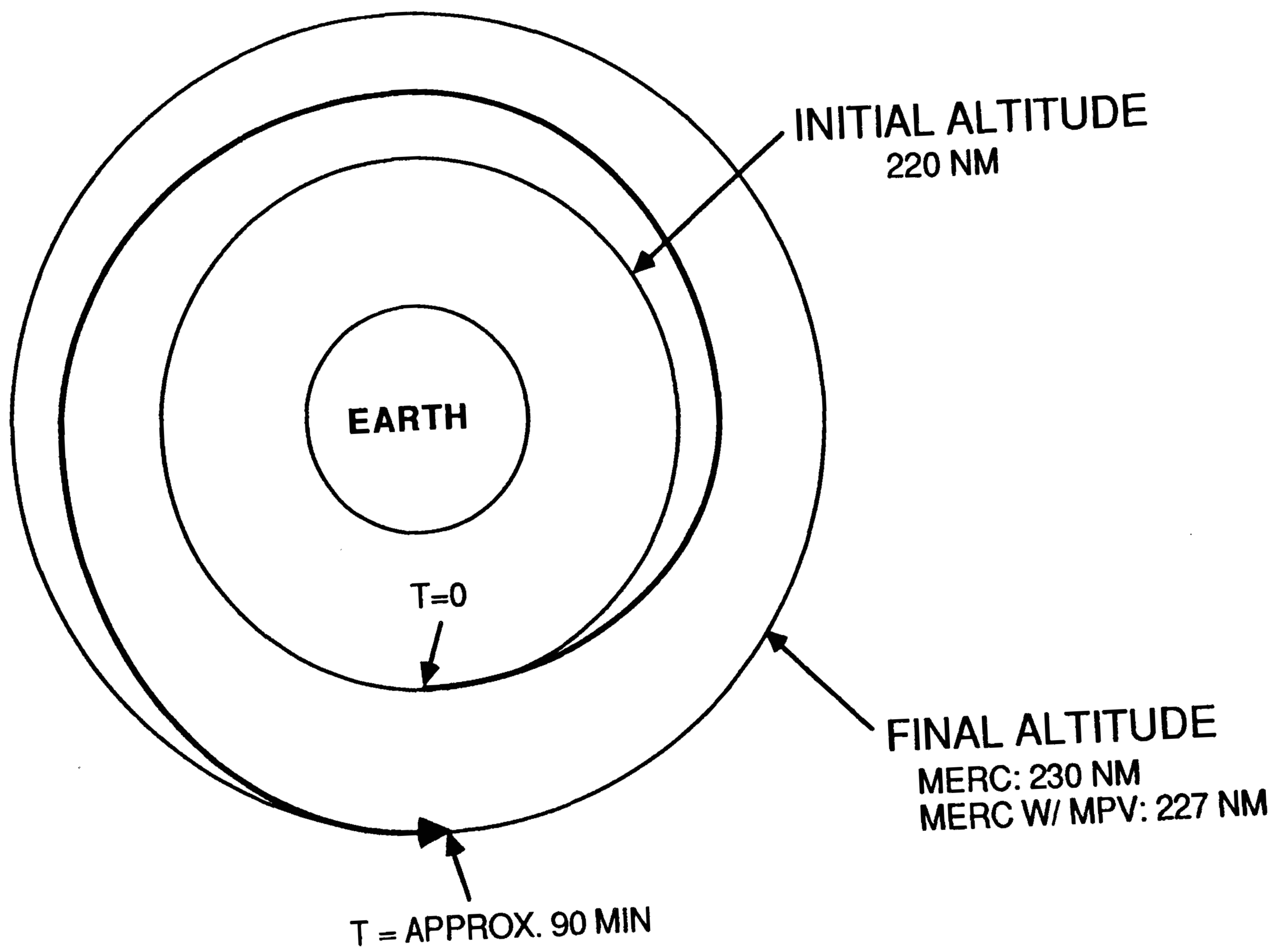
The dynamic characteristics of the MERC and the MERC with MPV are represented as a combination of rigid body and flexible structural dynamics. In order to obtain the equations of motion for the rigid body dynamics, a few assumptions are made. Environmental torques generated by atmospheric drag, solar radiation, and gravitational gradient are assumed to be negligible compared to torques generated by RCS firings during the reboost maneuver. Also, since the attitude change maintained is small, the orientation of the station is represented by a time integral of angular rate. Flexible structural dynamics are modeled by incorporating all flexible modes below 2 Hz. One-half percent of critical damping is assumed for modal damping for each mode. Based on laboratory tests of similar structures, the damping levels assumed are probably lower than the actual damping which will occur so that computed response levels at the sensor location should be conservative.

Reboost Assumptions

The study of a reboost maneuver of a Mars reference configuration is based on the following assumptions:

- RCS jet force magnitude of 50 lb at each RCS pod
- Thruster selection based on an attempt to minimize limit cycle rigid body frequencies to prevent excessive controls/structure interactions
- Rotation limits about each axis assumed to be $\pm$ 3 degrees without rotation rate limits
- The environmental torques (drag, gravity gradient, solar radiation pressure) assumed negligible compared to the torques generated by RCS firings during reboost
- Pitch, and yaw attitudes are controlled by off-modulation of X-axis jets
- Roll attitude controlled by on-modulation of Y-axis jets

REBOOST ANALYSIS



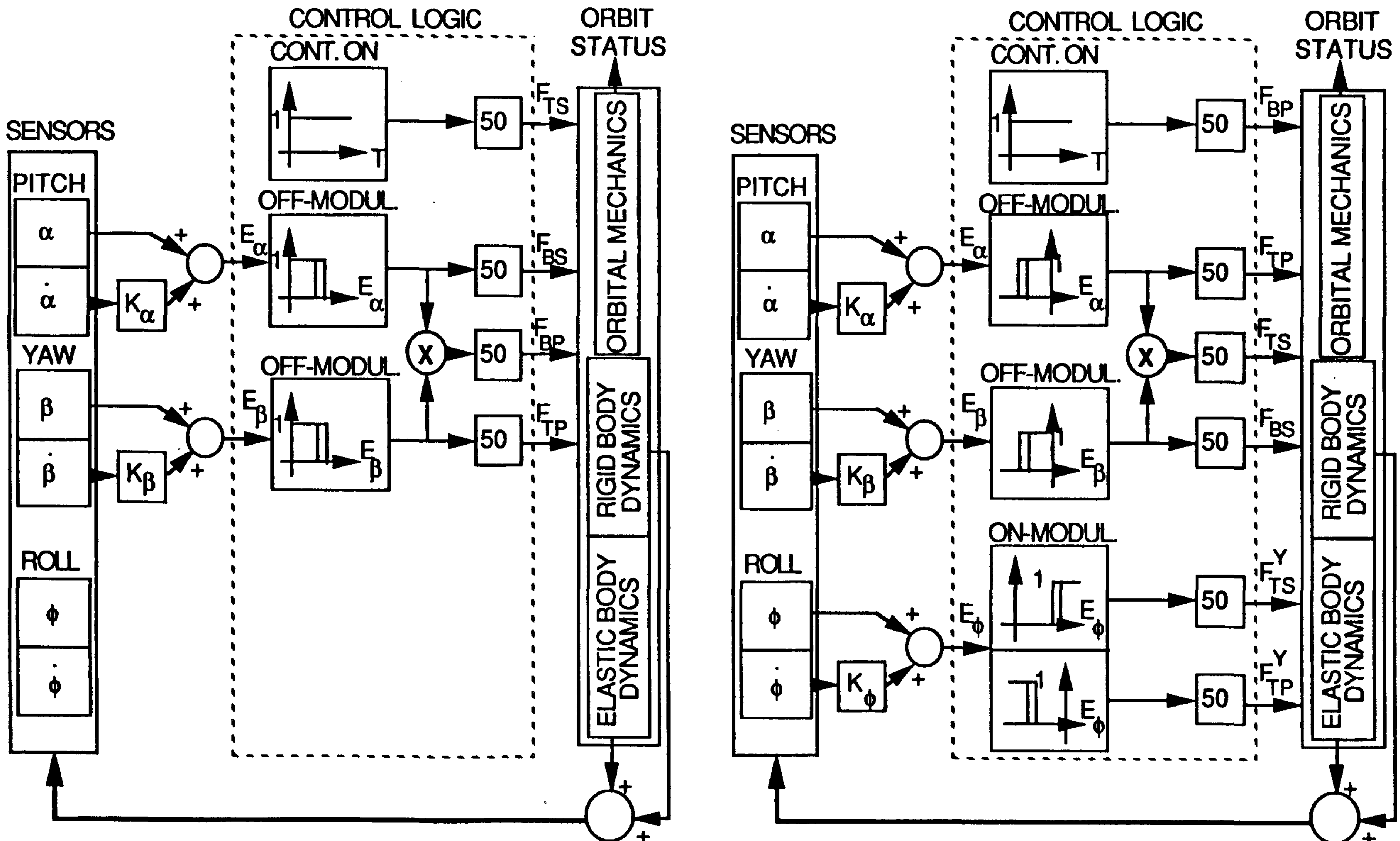
Attitude Control System

Closed-loop attitude control using the RCS jets is performed in order to maintain the attitude of the station within $\pm$ 3 degrees. Schematic diagrams of the closed-loop attitude control systems are shown in the figure for the MERC and the MERC with MPV, respectively. The sensors located at the GN&C pallet measure the total attitude and the attitude rate about each axis. This measured motion is the sum of rigid body motion and flexible structural responses at the sensor location. A proportional-derivative feedback control is employed. The error signal drives the Schmitt trigger logic to produce an on-off modulation of the RCS jets.

Since there were significant changes in the inertia properties and center of mass locations, due to assembling the MPV on the MERC , the MERC and the MERC with MPV require different attitude control logics. The changes in the control logic involve not only the adjustment of the control parameters such as deadband and hysteresis but also the complete reorganization of the firing sequences. Therefore, control systems using RCS jets for the MERC should be designed to accommodate control logic changes as the MPV is assembled on the MERC.

When the error exceeds the deadband plus hysteresis, the jet is turned off until the error becomes smaller than the deadband. This modulation creates an eventual limit cycling of jet firings. The deadband and the hysteresis are designed so as to keep the attitude excursion within the required bounds and to reduce the frequency of limit cycling without losing stability of the attitude control system. As the separation between the limit cycle frequency and the fundamental frequency increases, the elastic response caused by the jet firing modulation decreases. Also, the hysteresis is adjusted so that the flexible component of the error signal will not cause an RCS jet chattering instability when the error signal approaches the boundary of the deadband. An iterative design procedure is employed to select control parameters which satisfies the design objectives.

Block Diagram of Closed Loop Attitude Control During Reboost



(a) MERC

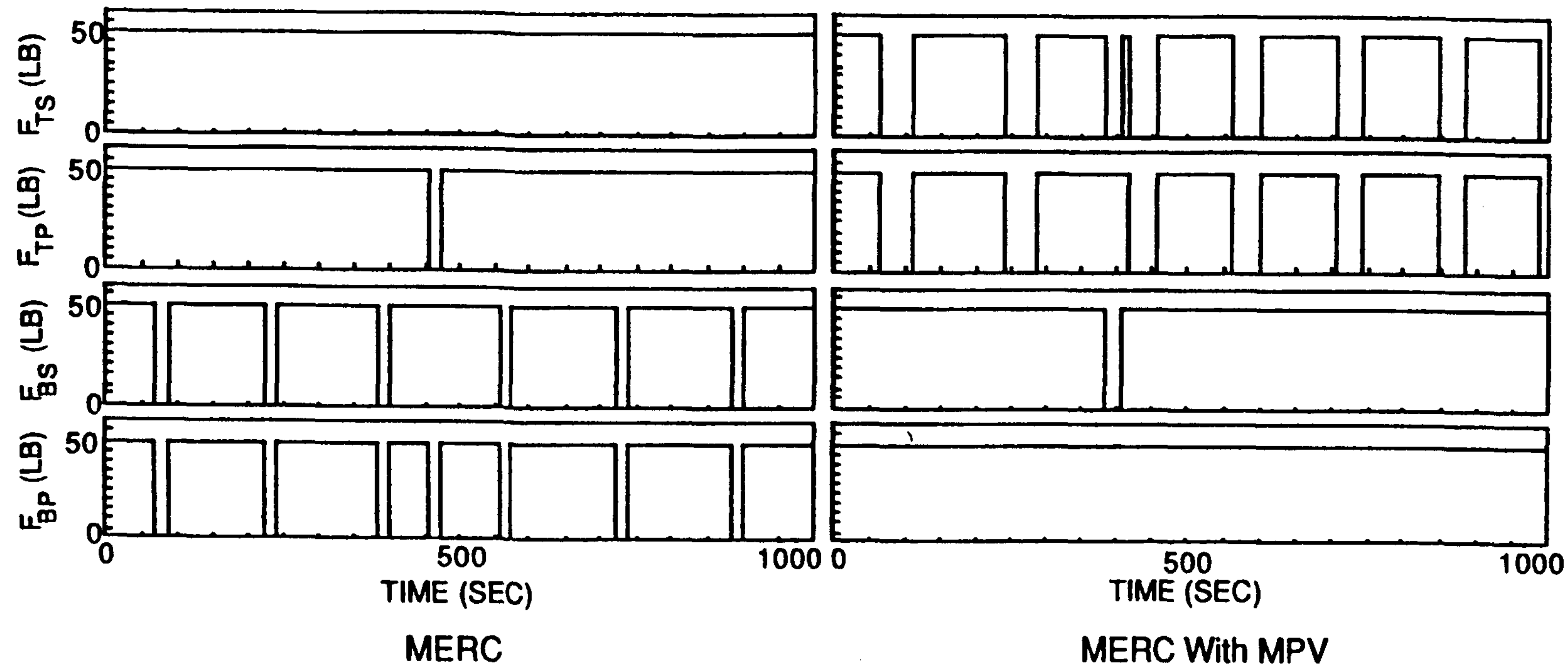
(b) MERC with MPV

Reboost Results

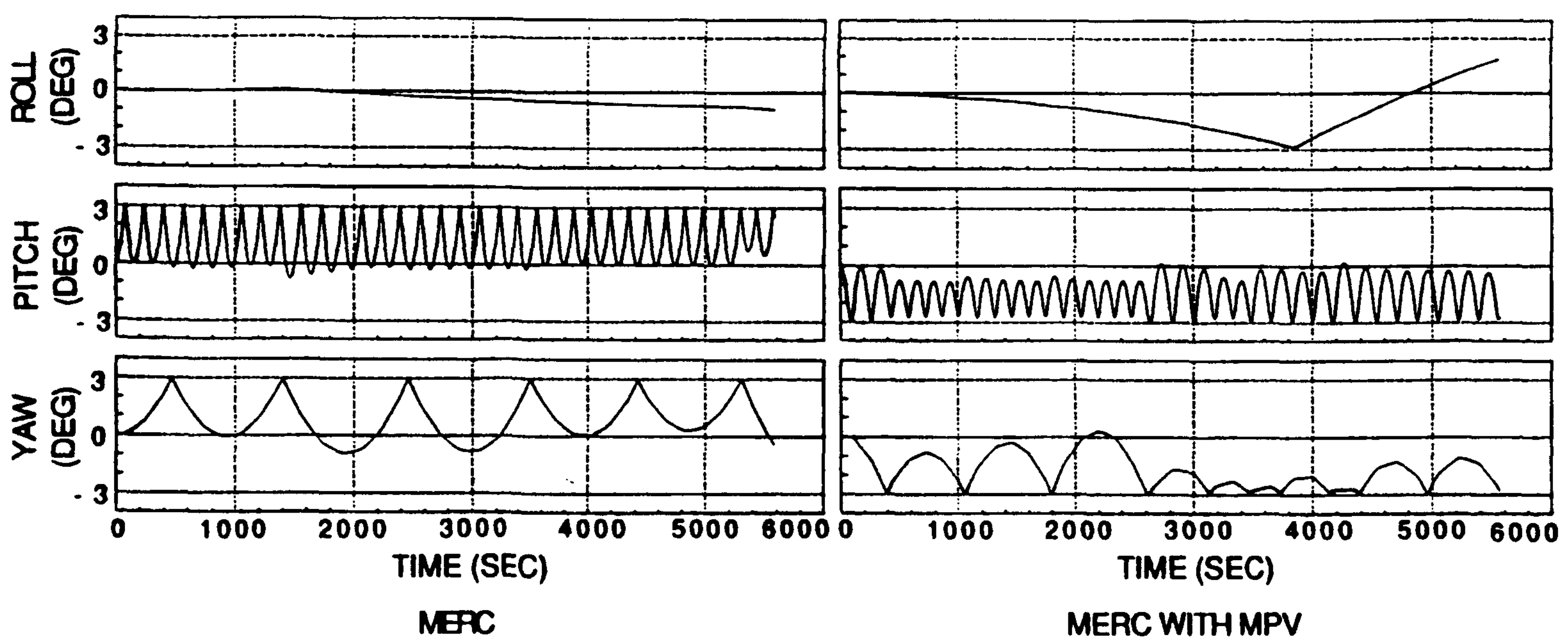
The resultant RCS firing sequences for the first 1000 seconds of the reboost maneuver of the MERC and the MERC with MPV are shown in the figure. To prevent a chattering instability, which could be caused by elastic rotation in the vicinity of the sensors, the hysteresis of the Schmitt trigger was made as large as possible while maintaining rigid body attitude control stability. Although attitude rate is not controlled, the magnitude of the rate is maintained small and never exceeds 0.09 deg/sec and 0.094 deg/sec about each axis for the MERC and the MERC with MPV, respectively. The approximate limit cycle frequencies of 0.0010 Hz and 0.0018 Hz in the yaw axis and 0.0062 Hz and 0.0063 Hz in the pitch axis for the MERC and the MERC with MPV, respectively, are well below the fundamental structural frequency of the MERC and the MERC with MPV which is 0.064 Hz. With this separation of frequencies, the dynamic loadings due to jet cycling should not cause excessive structural response during the reboost.

Reboost Results

RCS Jet Firings During the First 1000 Sec Reboost



Total Error at the Sensor Location



Dynamic Response

The elastic dynamic behavior of certain critical points of the MERC and the MERC with MPV during reboost are summarized in the table. These results indicate that the MERC with MPV is more responsive in certain areas than the MERC, to the reboost forcing function. There are several factors which lead to this result. The responses are driven by totally different reboost pulses, due to configurational mass distribution differences. The primary MERC reboost pulse is from the lower RCS jets and excites the lower regions of the station to a greater extent than do the MERC with MPV system RCS pulses. The primary MERC with MPV RCS pulses are from the upper jets and excite the transverse boom area components to a greater extent than the MERC RCS pulses.

Maximum Displacements and Accelerations at Critical Points

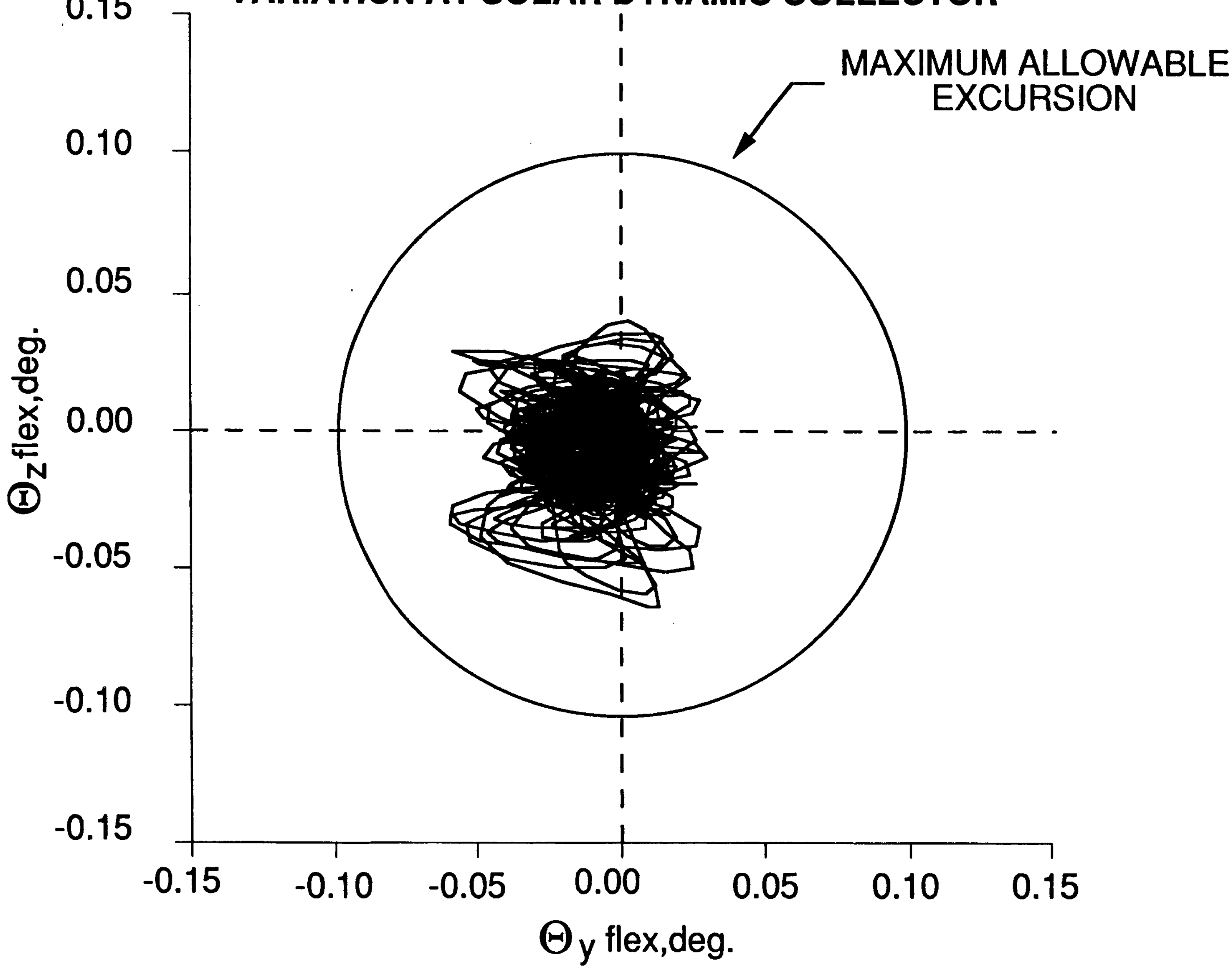
Location	MERC		MERC with MPV	
	Displacement (inches)	Acceleration (milli-G's)	Displacement (inches)	Acceleration (milli-G's)
GN&C Pallet	0.24	0.89	0.34.	0.70
SD Collector	0.88	1.75	2.26	2.14
PV base	0.37	1.49	0.96	1.05
PV tip	1.90	2.48	4.97	6.47
Hab Center	0.19	0.32	0.28	0.36
MPV Assembly Platform	1.05	2.60	0.48	1.44

Elastic Response at the Solar Dynamic Power System

An area of particular concern is the elastic rotation local to the SD systems at the port and starboard tips of the transverse boom. The SD system uses a concentrator to focus solar radiation energy on a receiver assembly which increases the pressure of a gas working fluid. The fluid drives a turbine connected to an electrical alternator and compressor. The concentrator requires a $\pm$ 0.1 degree solar vector pointing accuracy during orbital daylight. A combination of alpha and beta joint rotational control is provided to accomplish this pointing accuracy during nominal orbital operations. Since the station is allowed a $\pm$ 3.0 degree rigid body rotation during reboost, a local SD pointing control system is used to maintain pointing. The low frequency rigid body excursions from the LVLH axes ($\pm$ 3 degrees at 0.006 Hz) for the MERC and the MERC with MPV system are easily controllable and should present no pointing problems. The higher frequency local elastic motions of the SD systems were investigated to determine the extent of elastic motion which must be countered by active control. As a measure of elastic motion, plots of the flexible component of sun line variation in the YZ plane over the time of the reboost maneuver were generated. The MERC with MPV system result, shown in the figure, exhibited greater motion than the MERC configuration since the top RCS jets located closer to the SD were cycled to control attitude. The local elastic motion of the SD location never exceeded the 0.1 degree requirement and should present no control problems.

Results indicate no excessive displacements or accelerations at the critical points investigated. These results are based on the current mass distributions and elastic representations and are highly dependent on the NASA baseline alpha joint stiffness used in the structural modeling. This stiffness is subject to change as the design of SSF approaches maturity.

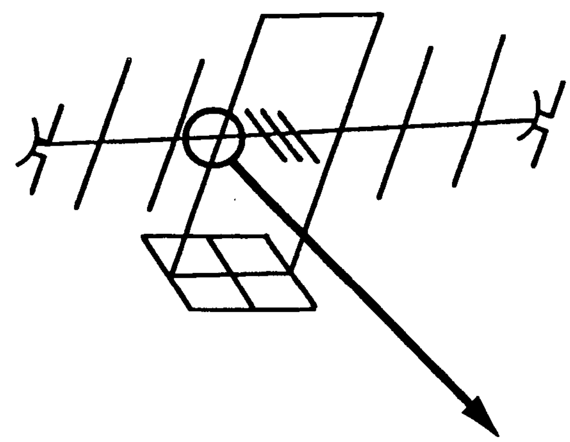
FLEXIBLE COMPONENT OF SUN LINE VARIATION AT SOLAR DYNAMIC COLLECTOR

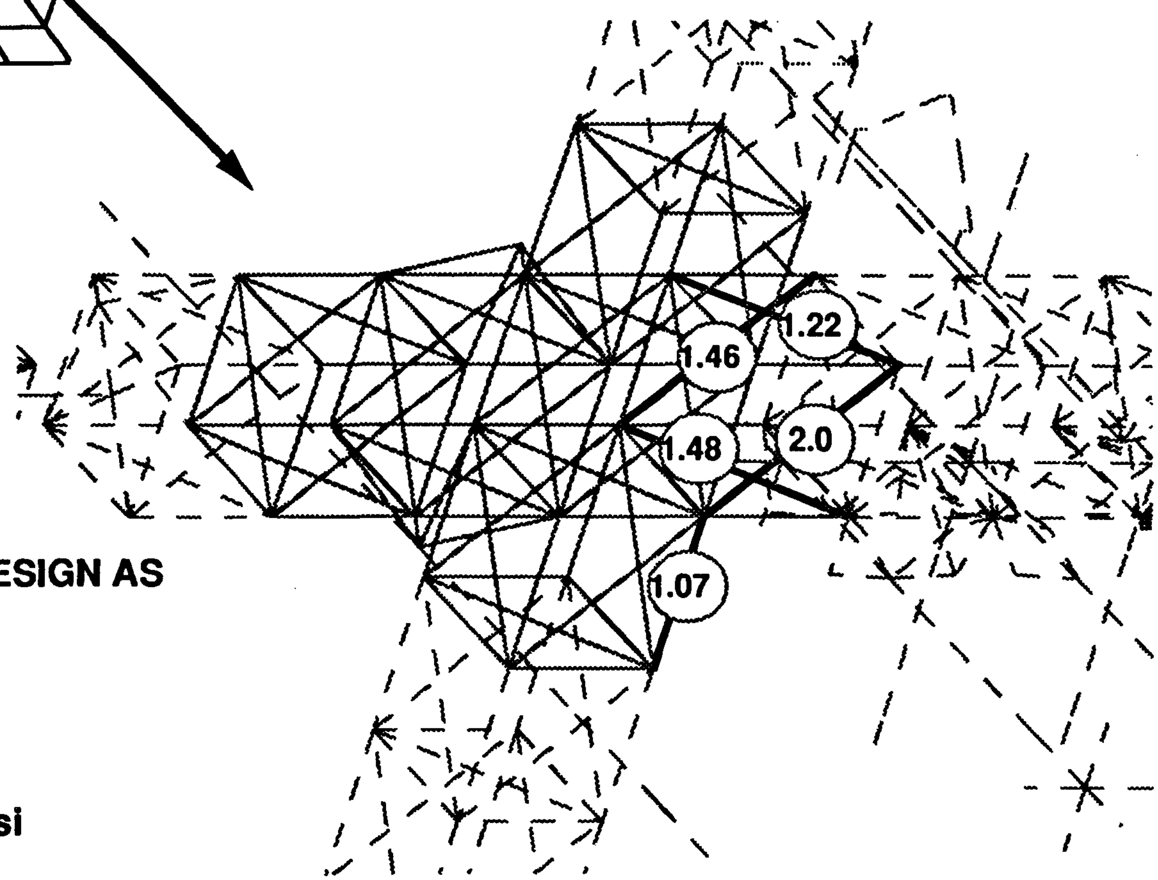


Elements at Stbd Keel-Boom Interface Which Require Stiffening to Prevent Buckling During Reboost

A transient analysis was performed to calculate member loads at selected critical locations during a reboost maneuver. Critical buckling loads were calculated for longerons, battens and diagonals, and compared to the maximum compressive axial force in the selected truss members. Assuming a safety factor of 1.5, four diagonals and one longeron at the starboard keel-boom interface should be stiffened to prevent buckling during the reboost. One method of stiffening the tubes would be to increase the tube wall thickness from the nominal 0.067 inches to 0.153 inches or increase the thickness a lessor amount but increase the percent of axial fibers in the composite layup. The outside diameter must remain at 2 inches since that is the maximum diameter which allows for comfortable handling by an astronaut in a space suit.

ELEMENTS AT STBD KEEL-BOOM INTERFACE WHICH NEED STIFFENING TO PREVENT BUCKLING DURING REBOOST





ASSUME TUBE DESIGN AS

D = 2 in

t = 0.067 in

E = 13.7E6 psi

Safety Factor = 1.5

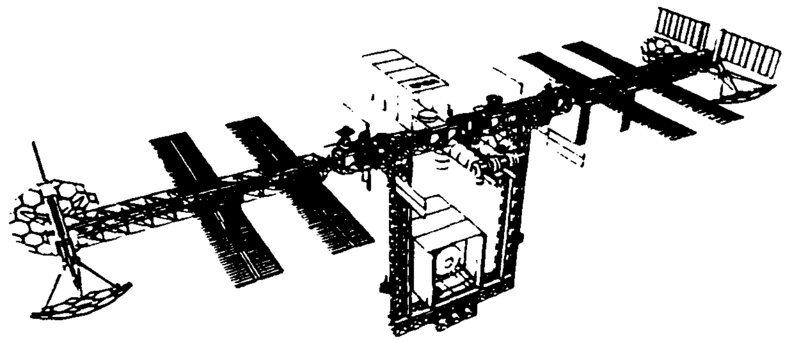
DYNAMIC CHARACTERISTICS OF THE LUNAR TRANSPORTATION NODE CONFIGURATION

A preliminary study was made of the dynamics of an evolutionary concept of Space Station Freedom consistent with use of the spacecraft as a transportation node for a manned Lunar mission. In this concept, lower keels are added to the assembly complete configuration.

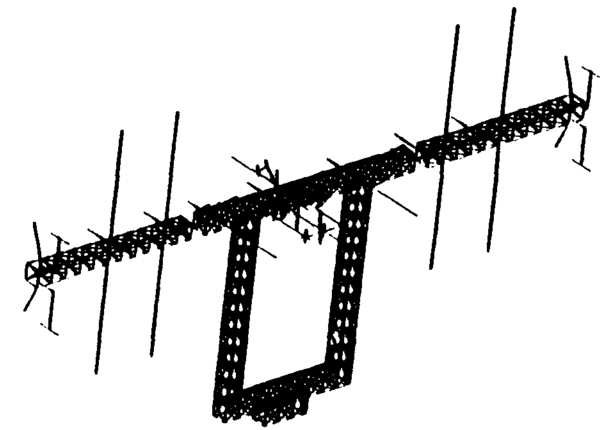
The finite-element model of the Lunar Transportation Node, which was developed from the Level II finite-element model of the Assembly Complete configuration, contains almost twice as much mass as the Assembly Complete model. Most of the increased mass is due to the addition of the solar dynamic power system and the Lunar Assembly Hanger and Lunar Transfer Vehicle (LTV). Addition of the mass of the Lunar Assembly Hanger and LTV, which accounts for 35 percent of the total station mass, causes the center of gravity of the station to shift approximately three bay lengths further away from the centerline of the transverse boom.

The eigenvalue analysis of the model of the structure yielded 113 flexible modes below 2 Hz. The fundamental frequency of 0.07 Hz corresponding to a transverse boom bending mode is 50 percent lower than the comparable Space Station Freedom first transverse boom bending mode due to the added masses of the solar dynamic systems.

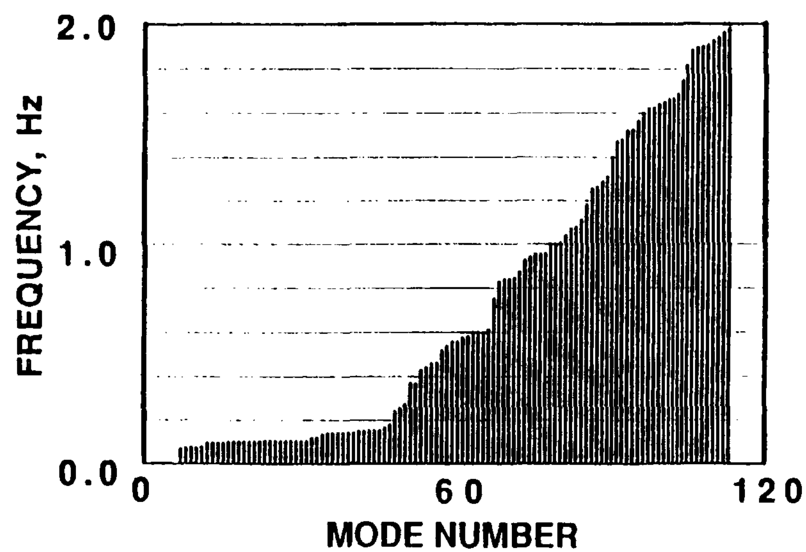
DYNAMIC CHARACTERISTICS OF THE LUNAR TRANSPORTATION NODE CONFIGURATION



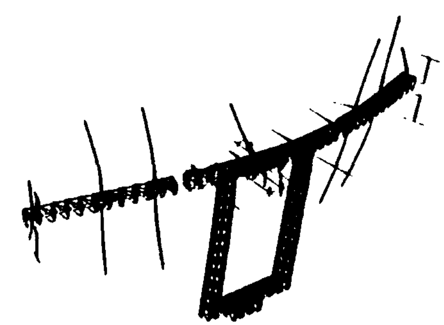
LUNAR TRANSPORTATION NODE CONFIGURATION



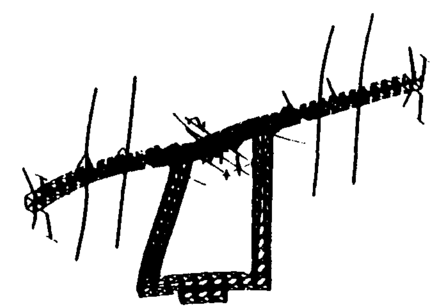
FINITE ELEMENT MODEL



FREQUENCY DISTRIBUTION



FUNDAMENTAL (0.07 Hz)



KEEL BENDING (0.51 Hz)

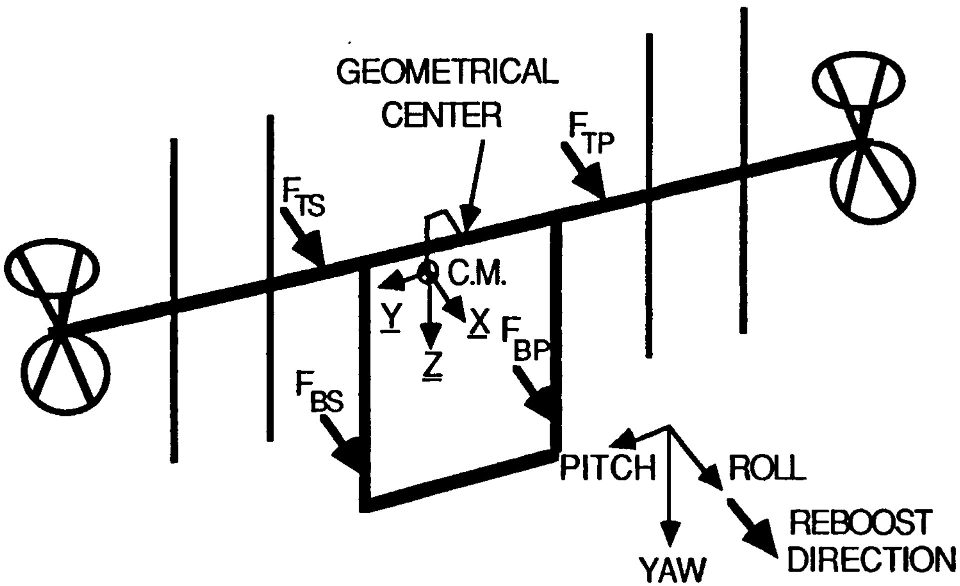
TYPICAL MODES

Reboost Excitation

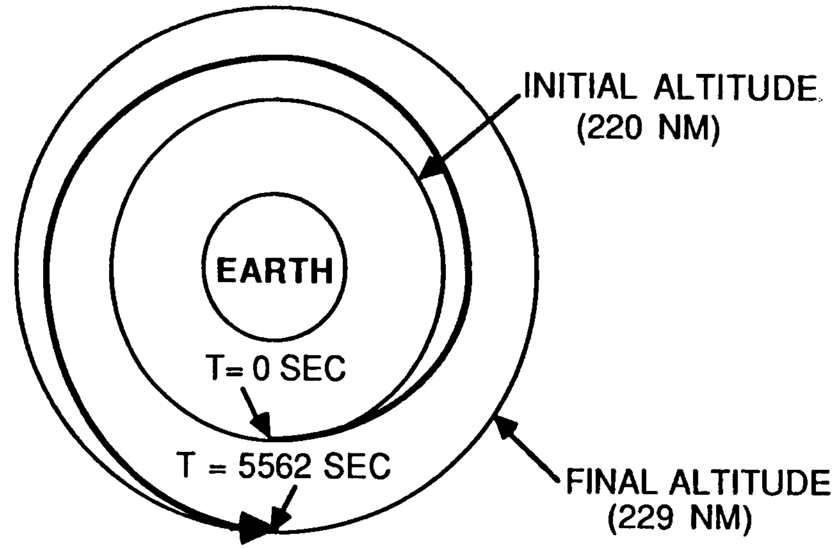
To reboost the Lunar transportation node, a Reaction Control System (RCS) composed of four clusters of jets, located on the transverse boom and the lower keels as shown in the figure, fires its jets to accelerate the station in the reboost direction. Since the jets are not located at the same distance from the center of mass, the station will begin to yaw about the $\underline{Z}$ axis and pitch about the $\underline{Y}$ axis. For the current study the station is required to maintain a rigid body flight attitude to within $\pm$ 3 degrees of the nominal flight path. Closed-loop attitude control using the RCS jets is performed in order to maintain the attitude of the station. An error signal, composed of the rigid body attitude summed with the rigid body attitude rate, is used with a Schmitt trigger to off-modulate the jets at the appropriate locations to control the attitude. A 50 lbf RCS jet is used in a given direction at each RCS cluster.

The resultant RCS firing sequences and the rigid body pitch and yaw attitude for the first 1000 seconds of the reboost maneuver are shown in the figure. Orbital mechanics were incorporated to compute the orbit trajectory subject to time varying jet firings for the attitude control during reboost. Assuming that the station is assembled in a circular orbit at 220 nautical miles (NM), approximately 9 NM altitude is picked up by reboost RCS jet firings in one orbit.

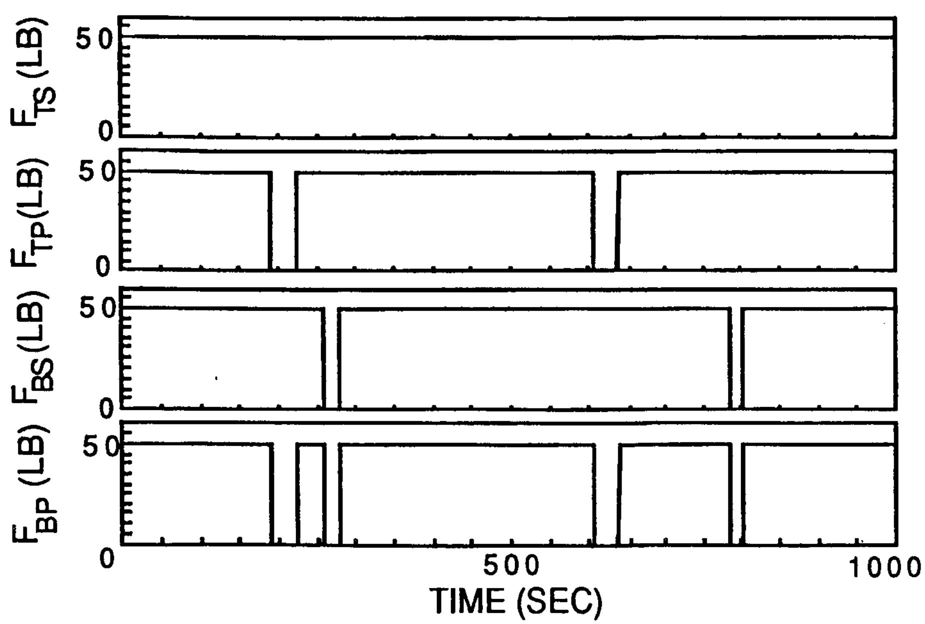
EXCITATION DURING REBOOST OF LUNAR TRANSPOTATION NODE



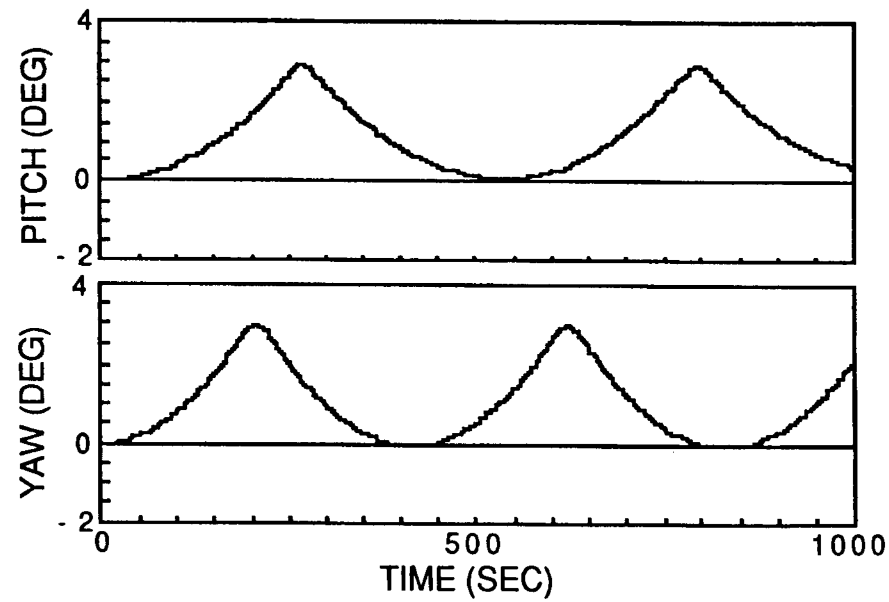
LOCATIONS OF RCS JETS AND C.M.



ORBIT ALTITUDE



RCS FIRINGS



RIGID BODY ATTITUDE

STRUCTURAL RESPONSE TO REBOOST

The elastic dynamic behaviour of certain critical points of the lunar transportation node is summarized below. The loads used in this study are based on the off-modulated Reaction Control System jet firings used for attitude control while reboosting the station from its assembly orbit. Preliminary investigation of buckling loads in the truss members at the interface between the transverse boom and the keels indicates that buckling failure (1.5 factor of safety) occurs in several of the truss batten/longerons. The baseline truss tubes modulus of elasticity, and wall thickness were 13.7×10^6 psi and 0.067 inches respectively. The buckling failure may be eliminated by increasing the truss tube stiffness either by increasing the tube wall thickness or the modulus of the material.

An area of particular interest is the elastic rotation local to the SD systems at the port and starboard tips of the transverse boom. The SD system concentrator requires a $\pm$ 0.1 degree solar vector pointing accuracy during orbital daylight. A combination of alpha and beta joint rotational control is provided to accomplish this pointing during nominal orbital operations. The higher frequency local elastic motions of the SD systems were investigated to determine the extent of elastic motion which must be countered by active control. As a measure of elastic motion, a plot of the flexible component of sun line variation in the YZ plane over the time of the reboost maneuver (shown in the figure) was generated. The local elastic motion of the SD location never exceeded the 0.1 degree requirement and should present no control problems. These results are highly dependent on the NASA baseline alpha joint stiffness used in the structural modeling. This stiffness is subject to change as the design of SSF approaches maturity.

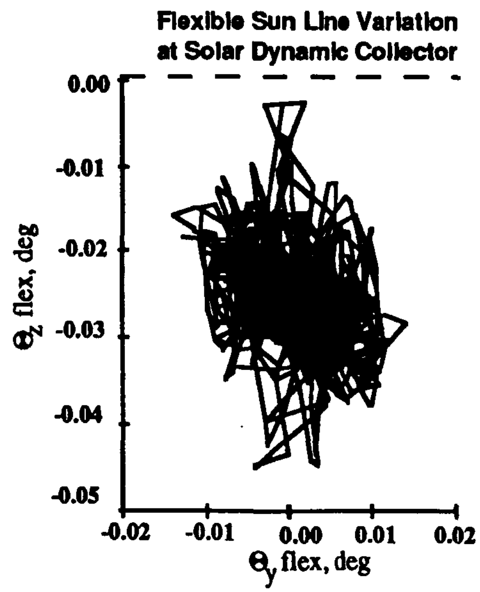
Results at the remaining critical points indicate no excessive displacements or accelerations.

Structural Response To Reboost

LOADS

- o Buckling loads in truss members were investigated at interface between Boom and Keels ($E = 13.7 \times 10^6$ psi, 1.5 safety factor) :
  - Max. load experienced in truss diagonal - **(1.5)** x **P/P_{cr}** = 0.29
  - Max. load experienced in truss batten/longeron - **(1.5)** x **P/P_{cr}** = **1.19** **(Buckling Failure)**
  - Structure at interface between Booms and Keels will have to be stiffened.

RESPONSE



Location	Disp. (Inches) X	Y	Z
Tip of PV	2.40	1.03	0.29
Base of PV	0.96	0.09	0.29
SD Collector	1.66	0.44	0.54
Center of Hab. Module	0.25	0.13	0.09
Center of Lab. Module	0.30	0.12	0.07
Vehicle Attachment	0.04	0.14	0.13

- o Peak accel. at modules = 621 μG (Lab.)

- o No pointing problems at the SD collector or excessive displacement or acceleration occurred during reboost.

ATTITUDE CONTROL OF LUNAR TRANSPORTATION NODE CONFIGURATION

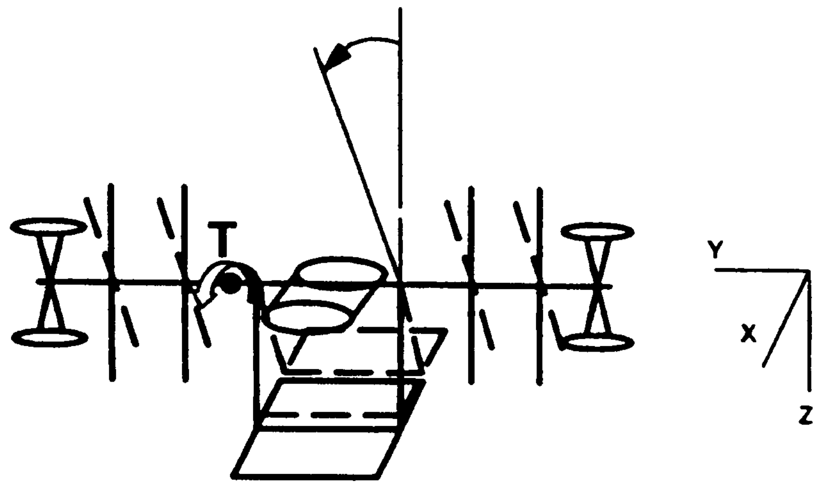
A simple, rigid body, attitude control system was designed for the Lunar Mission Node using control moment gyros (CMG) and based on a proportional plus differential (PD) feedback control law. The same control performance characteristics (i.e. 70.7% closed-loop system damping and 0.01 Hz bandwith frequency) were used as baselined for the space station Freedom. A second order Butterworth compensator designed for the Space Station Freedom assembly complete configuration (of 0.032 Hz break frequency) was included in the control loop for response simulation purposes.

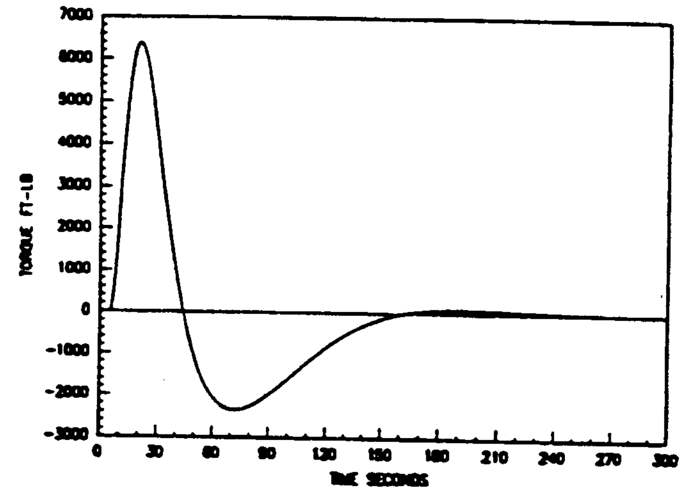
The figure shows the maximum control torque and the corresponding number of CMG's required to control the attitude of the Lunar Mission Node with the same control performance characteristics as the space station and for a one degree commanded attitude change about each axis.

The number of CMG's required to perform a 1 degree attitude change about a given axis is up to 10 times greater than the number on S.S. Freedom for the same response performance. A practical approach would be to reduce response performance requirements rather than to install a large number of CMG's.

PRELIMINARY STUDY

CMG MAXIMUM TORQUE IN FT–LB AND NUMBER OF CMG'S TO CONTROL ATTITUDE OF LUNAR MISSION NODE WITH SAME CONTROL PERFORMANCE CHARACTERISTICS AS S.S. FREEDOM

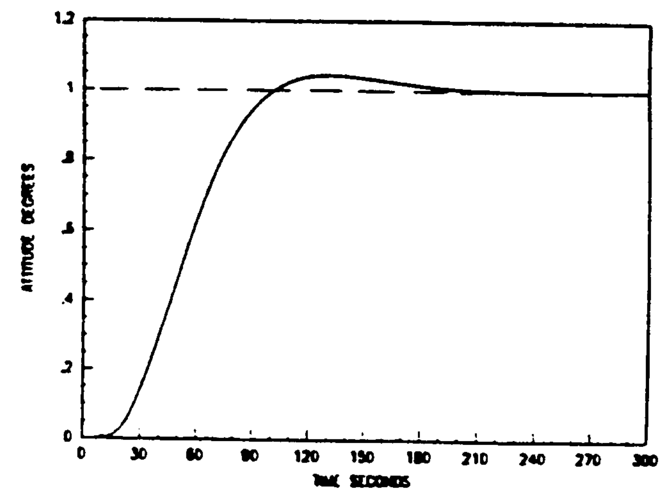




Control torque time history about X axis

COMMANDED ONE DEGREE ATTITUDE CHANGE ABOUT EACH AXIS

	TORQUE MAGNITUDE	NO. OF CMG'S
Tx	6400	32
Ty	2800	14
Tz	4210	22



Attitude response time history

ZNM 9/15/89 LUNAR

Concluding Remarks

A concept for a manned mission to Mars uses an evolutionary version of Space Station Freedom as a transportation node. This modified station with a Mars piloted vehicle installed has more than twice the mass of Space Station Freedom and up to a twelvefold increase in the moments of inertia. The lowest framework frequency of the modified station both with and without the Mars piloted vehicle is more than 50 percent below the lowest framework mode of the Space Station Freedom configuration. The low frequency modes have a complex motion with a strong coupling of the truss structure with the various power, radiator, and payload components. All modes exhibit similar behavior, in that the region of the modules, which has the bulk of the mass, acts as a node point for most modes and the region of the stiff Mars piloted vehicle assembly platform moves as a rigid body.

To reboost the station, a reaction control system composed of four clusters of jets, located on the dual keels fires its jets opposite to the flight direction. The jets are off-modulated at the appropriate locations to control the pitch and yaw attitude. The added mass, change in location of the center of mass and increase in inertia caused by the addition of the Mars piloted vehicle to the evolutionary station lowered the global keel frequencies significantly changing the character of the response of the station and required an adaptability in the jet firing logic for attitude control. The off-modulation pulsing of jets provided sufficient control to maintain station attitude to within three degrees yaw and pitch during the reboost maneuver. Study results indicate that there is sufficient separation between the reboost jet firing limit cycle and the fundamental frequency of the station to prevent excessive structural response to reboost loads. The attitude control is not significantly influenced by the elastic dynamic response at the sensor during the reboost maneuver.

One particular area of concern, the elastic rotation local to the solar dynamic systems at the tip of the transverse boom was investigated to determine the extent of the motion which must be countered by an active control system. The local elastic rotation at the solar dynamic system location never exceeded the 0.1 degree pointing requirement and should therefore present no control problems. These results are based on the current mass distribution and elastic model representation and are highly dependent on the NASA baseline stiffness of the alpha joint used in the structural modeling. This stiffness is subject to change as the design of Space Station Freedom matures.

CONCLUDING REMARKS

- LOWEST TRANSVERSE BEAM FREQUENCY REDUCED 55% WITH INSTALLATION OF SD SYSTEM.

- JET PULSING DURING REBOOST CAUSED NO SERIOUS ELASTIC DYNAMIC RESPONSES.

- THE CURRENT BASELINE TUBE DESIGN IS NOT STIFF ENOUGH TO PREVENT BUCKLING OF TRUSS MEMBERS DURING REBOOST.

- OFF-MODULATION PULSING OF JETS PROVIDES SUFFICIENT CONTROL TO MAINTAIN ATTITUDE DURING REBOOST.

- LARGE VARIATIONS IN MASS AND STIFFNESS PARAMETERS DURING STATION OPERATIONS REQUIRES:
    - UP-TO-DATE KNOWLEDGE OF MASS CHARACTERISTICS
    - HIGHLY ADAPTIVE CONTROL SYSTEMS.
    - ROBUST CONTROL SYSTEMS

- CONTROL PERFORMANCE REQUIREMENTS FOR EVOLUTIONARY CONFIGURATIONS MIGHT HAVE TO BE RELAXED BECAUSE OF PRACTICAL LIMITATIONS IN AVAILABLE CONTROL AUTHORITY.

Environmental Control and Life Support System Evolution

Paul Wieland
Life Support Branch/ED62

Environmental Control And Life Support System Evolution

I. Introduction: Space Station *Freedom* Evolution Impact on the ECLSS

The Space Station *Freedom* Environmental Control and Life Support System (ECLSS) will have to accommodate the changes to *Freedom* as it evolves over the design life of 30 years or more. Requirements will change as pressurized modules are added, crew numbers increase, and as the tasks to be performed change. This evolution will result in different demands on the ECLSS and the ECLSS will have to adapt. Technologies other than the baselined ones may be better able to perform the various tasks and technological advances will result in improved life support hardware having better performance, increased reliability, reduced power consumption, weight, and volume, greater autonomy, and fewer resupply requirements. A preliminary study was performed to look at alternative technologies for life support and evaluate them for their integration requirements, focusing on the fluid line interface requirements. (A follow–on study will expand greatly on the scope of this preliminary study.) The integration requirements of the alternative technologies may be different from those of the baselined technologies. If this is the case, then by designing the initial space station to have the necessary fluid lines, etc. required by the selected alternative technologies then the task of replacing the baselined ones will be greatly simplified, thereby reducing the cost in on–orbit time as well as dollars.

Space Station *Freedom* Evolution Impact on the ECLSS

- Space Station *Freedom* will evolve over its 30 year or more lifetime, as pressurized modules are added, crew numbers increase, and as the tasks to be performed change.

- Requirements placed on the ECLSS will also change.

- During this time technological advances will lead to improved life support hardware which is better able to meet the new requirements.

- Replacing the initial hardware with the improved technologies will be simplified if the integration requirements of the improved technologies are built into the initial *Freedom* design.

- To better understand the integration requirements a preliminary study was performed to identify the fluid line interface requirements of the advanced technologies most likely to replace the initial technologies.

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Advanced ECLSS Technology:
Benefits and Integration Requirements

- Benefits of Advanced ECLSS Technologies:
  - Better performance
  - Increased reliability
  - Reduced power consumption, weight, and volume
  - Greater autonomy
  - Fewer resupply requirements
- Integration Requirements of Advanced ECLSS Technologies:
  - System–level integration needs
  - Fluid interface requirements
  - Electrical power requirements
  - Thermal control requirements
  - Control/data requirements
  - Resupply needs

II. Objectives of the Study

The objectives of the preliminary study were to provide answers to some basic questions:

(1) What requirements will be placed on the ECLSS in the future?
(2) How will these requirements differ from the initial *Freedom* ECLSS requirements?
(3) What constraints will affect the ECLSS?
(4) What technologies will be available to meet the future ECLSS requirements?
(5) What are the integration requirements of the alternative technologies?
(6) How do these integration requirements differ from those of the baselined ECLSS subsystems?
(7) What "scars" would facilitate transparent incorporation of the alternative technologies?

Objectives of the Study

The objectives of the preliminary study were to answer some basic questions:

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(2) How will these requirements differ from the initial *Freedom* ECLSS requirements?

(3) What constraints will affect the ECLSS?

(4) What technologies will be available to meet the future ECLSS requirements?

(5) What are the integration requirements of the alternative technologies?

(6) How do these integration requirements differ from those of the baselined ECLSS subsystems?

(7) What "scars" would facilitate transparent incorporation of the alternative technologies?

III. Approach Used

A two-part approach was used to identify the requirements placed on the future ECLSS and to identify and evaluate alternative technologies for their abilities to meet those needs.

A. Identification of Future ECLSS Requirements

The NASA documents which define the initial space station design and possible growth scenarios were reviewed for identification of the ECLSS requirements. These documents include: Space Station Program Definition and Requirements Document (PDRD) SSP 30000, Sec. 3; Space Station Mission Requirements Data Base (MRDB); the Space Station Systems Requirements Document, SS-SRD-0001, Sec. 3; MSFC Logistics System Evolution Study; and Growth Requirements for Multidiscipline Research and Development on the Evolutionary Space Station, NASA TM 101497.

From these documents groundrules and assumptions were derived and scenarios which are representative of the most likely evolution paths were identified. It was then possible to identify ECLSS associated constraints.

Two–Part Approach

- Identify Future ECLSS Requirements
  - Review of NASA documents defining the space station design and growth scenarios
  - Derive groundrules and assumptions affecting the ECLSS
  - Identify scenarios representative of the most likely evolution paths
  - Identify constraints associated with the ECLSS
- Identify and Evaluate Alternative Technologies
  - Define the ECLSS functions to be considered
  - Identify alternative technologies to perform those functions
  - Evaluate the integration requirements of the alternative technologies
  - Determine the "scars" needed to allow for easy replacement of the baseline technologies

1. Groundrules and Assumptions

The groundrules and assumptions used as a basis for the study are:

(1) The ECLSS will provide the capability to depressurize and repressurize all airlocks and hyperbaric airlocks, and will be responsible for makeup of gases lost during airlock operations.

(2) The ECLSS will be responsible for the supply of Extravehicular Mobility Unit (EMU) potable water, oxygen, and air, and for processing of the EMU CO_2, urine, and condensate water.

(3) The ECLSS will be responsible for animal habitat requirements [but the Process Materials Management System (PMMS) will be responsible for experiment (ultrapure) water].

(4) The ECLSS will be responsible for animal laboratory requirements [but the Fluid Management System (FMS) will be responsible for experiment makeup water].

(5) The ECLSS will grow by module, i.e., all full sized Lab and Hab modules will contain the same ECLSS equipment as the baseline.

(6) All pressurized elements (modules, resource nodes, airlocks, pocket labs, etc.) will contain Temperature and Humidity Control (THC) subsystems.

(7) Intermodule ventilation will use a series/parallel scheme, with the resource nodes serving as plenums for supplying air to the attached pressurized elements.

(8) EMU-type ECLSS support will be provided to all manned transfer vehicles.

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(8) EMU-type ECLSS support will be provided to all manned transfer vehicles.

2. Representative Evolution Scenarios and ECLSS Associated Constraints

Two evolution scenarios, the Multi-Discipline Research Scenario and the Transportation Node Scenario, were used as a basis for defining the requirements that will be placed on the ECLSS in the future. Constraints affecting the ECLSS could then also be identified.

a. Multi-Discipline Research Scenario

The Multi-Discipline Research Scenario provides: "pressurized volume, payload attach points, crew time, electrical power and other essential resources to a diverse user community in support of their scientific research, technology development and commercial endeavors in space." (NASA TM 101497)

For this scenario the number of connected pressurized modules could increase to as many as 6 Lab modules and 3 Hab modules, with the necessary nodes to connect them and up to 3 pocket labs in addition. The crew size could increase to as many as 24 or more, to operate the experiments and operate and maintain *Freedom*.

It is expected that some experiments may require large amounts of EVA time occasionally, for example, during setup or servicing.

Multi–Discipline Research Scenario

- The Multi–Discipline Research Scenario provides: "pressurized volume, payload attach points, crew time, electrical power and other essential resources to a diverse user community in support of their scientific research, technology development and commercial endeavors in space." (NASA TM 101497)
- Features Affecting the ECLSS:
  - Up to 6 Lab modules, 3 Hab modules, nodes, and 3 pocket labs
  - Crew size: 24 or more
  - Large amounts of EVA time occasionally (during experiment setup or servicing)

b. Transportation Node Scenario

The Transportation Node Scenario is less well defined at this time. For this scenario *Freedom* serves as a waypoint for missions beyond Low Earth Orbit (LEO). Tasks to be performed include servicing of transfer vehicles, assembly of large spacecraft, and processing of returned payloads.

Large amounts of EVA time on a regular basis are associated with using *Freedom* as a transportation node. Using the present airlock design, a two-person EVA transfer would involve up to 10% air loss by volume per cycle. For servicing of the Lunar Transfer Vehicle (LTV), which would require up to 40 hours per day, about 10 pounds of resupply air per day are required.

One scenario for the transportation node includes an isolated Hab module remote from the main cluster, with two nodes and an airlock, for use by four crew members dedicated to vehicle buildup and servicing tasks.

Transportation Node Scenario

- The Transportation Node Scenario is less well defined at this time. For this scenario *Freedom* would serve as a waypoint for missions beyond low Earth orbit. Tasks to be performed include servicing of transfer vehicles, assembly of large spacecraft, and processing of returned vehicles and payloads.

- Features Affecting the ECLSS:
  - Large amounts of EVA time on a regular basis (up to 40 hours per day for servicing of the Lunar Transfer Vehicle)
  - Increased resupply of lost air and water

c. ECLSS Associated Constraints

There are various constraints associated with different growth scenarios. Critical factors which affect the ECLSS include available power, crew time for maintenance, launch mass (for resupply needs), and requirement for two–failure tolerance. Safe haven considerations require that, in an emergency, a single ECLS subsystem group be capable of supporting eight people. Module growth patterns may be limited by the IMV system. Increases in crew size and the number of modules are to maintain a 4:1 crew to US module ratio or an 8:1 crew to US Hab module ratio.

Constraints Affecting the ECLSS

- Critical factors affecting the ECLSS include:
  - Available power
  - Crew time for maintenance
  - Launch mass for resupply
  - Requirement for two–failure tolerance
- Safe haven requirements
- Module growth
  - Growth patterns may be limited by the Intermodule Ventilation system
  - A ratio of 4:1 crew members to number of U. S. modules, or 8:1 crew to U. S. Hab modules, is to be maintained

B. Identification and Evaluation of Alternative Technologies

Alternative technologies for each ECLSS task were identified and those that could be developed to perform the ECLSS tasks were evaluated for their integration needs. The fluid line interface needs were then compared with those of the baseline ECLSS and the "scars" required to permit replacement subsystems with alternative subsystems were identified.

1. ECLSS Functions Considered

The ECLSS consists of several tasks, each consisting of one or more functions: Air Revitalization, Water Recovery and Management, Atmosphere Control and Supply, Temperature and Humidity Control, Fire Detection and Suppression, and Waste Management. The ECLSS functions considered in this study are: CO_2 removal, CO_2 reduction, O_2 generation, trace contaminant control, urine recovery, potable water recovery, hygiene water recovery, and waste management.

Space Station Evolution: Beyond the Baseline

NASA

ECLSS

Atmosphere Revitalization (AR)

- CO_2 Removal
- CO_2 Reduction
- O_2 Generation
- Contaminant Control and Monitoring

Atmosphere Control and Supply (ACS)

- O_2/N_2 Storage and Distribution
- Vent and Relief
- O_2/N_2 Pressure Control

Water Recovery and Management (WRM)

- Urine Processing
- Hygiene Water Processing
- Potable Water Processing
- Water Storage and Distribution
- Water Thermal Conditioning
- Water Quality Monitoring

Temperature and Humidity Control (THC)

- Air Temperature Control
- Humidity Control
- Ventilation
- Equipment Air Cooling
- Thermally Conditioned Storage
- Refrigerator/Freezer

Fire Detection and Suppression (FDS)

Waste Management (WM)

- Return Waste Storage
- Fecal Processing and Management

2. Identification of Alternative Technologies

Alternative technologies for the ECLSS tasks were identified by reviewing technical papers and reports (NASA and other) and through contacts with scientists and engineers working on ECLSS technology development.

3. Evaluation of the Integration Needs of Each Technology

After identifying the alternative technologies and developing a basic understanding of how each works or would work the next step was identification of the integration requirements, focusing on the fluid interface requirements.

4. Determination of the "Scars" Required for Each Technology

The fluid interface requirements of the new technologies were then compared with those of the baseline technologies and the ones not needed by the baseline technologies were identified. These then determine the required "scars."

Identification and Evaluation of Alternative Technologies

- Identification of Alternative Technologies
  - Literature search: review of technical papers and reports
  - Contacts with scientists and engineers working on ECLSS technology development
- Evaluation of the Integration Needs
  - Basic understanding of the alternative technologies
  - Identify the integration needs of each, focusing on the fluid interface requirements
- Determination of the Fluid Interface "Scars" Required
  - Compare the interfaces of the alternative and baseline technologies
  - The interfaces not required by the baseline technologies then determine what "scars" will be required

BASELINE ECLSS TECHNOLOGIES

The technologies baselined for the ECLSS functions are:

Function	Technology
CO_2 Removal	Four-Bed Molecular Sieve
CO_2 Reduction	Bosch Reactor
O_2 Generation	Static Feed Water Electrolysis
Potable Water Recovery	Multifiltration
Hygiene Water Recovery	Reverse Osmosis
Trace Contaminant Removal	Expendable Carbon Beds with Catalytic Oxidizer
Atmosphere Monitoring	Gas Chromatograph/Mass Spectrometer
Urine Recovery	Thermoelectric Integrated Membrane Evaporation System
Waste Management	Biodegradation Cup/Storage
Temperature and Humidity Control	Condensing Heat Exchanger
Fire Suppression	CO_2
Air Control and Supply	Cryogenic/High Pressure Storage

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Temperature and Humidity Control	Condensing Heat Exchanger
Fire Suppression	CO_2
Air Control and Supply	Cryogenic/High Pressure Storage

For the air revitalization and water recovery functions of the ECLSS, alternative technologies were evaluated and compared with the baseline technology. Comparisons were made based on estimated weight, power requirements, volume, maturity, safety, and resupply requirements. Fluid interface needs were also defined for each alternative. As an example, for CO_2 removal the Two-Bed Molecular Sieve, Electrochemical Depolarized Cell CO_2 Concentrator, Air Polarized Concentrator, Solid Amine Water Desorbed CO_2 Concentrator, and membranes were compared with the Four-Bed Molecular Sieve. Additional fluid interfaces are N_2 and H_2 for the EDC and APC, and hygiene water and a vent for the SAWD.

CO_2 REMOVAL

FLUID INTERFACES

TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Four-Bed Molecular Sieve	Cabin Air Liquid Coolant	Return Air CO_2, Liquid Coolant
Two-Bed Molecular Sieve	Cabin Air Liquid Coolant	Return Air CO_2, Liquid Coolant
EDC	Cabin Air, N_2 Purge Liquid Coolant, H_2	Return Air, H_2/CO_2, Liquid Coolant
SAWD	Cabin Air Hygiene Water	Return Air CO_2, Pressure Vent
APC	Cabin Air Liquid Coolant H_2, N_2 Purge	Return Air, H_2/CO_2, Liquid Coolant
Membranes	Cabin Air	Return Air CO_2

System impacts include larger capacity for the O_2 generator for the EDC and a larger THC to remove the moisture added by the SAWD.

CO_2 REMOVAL

TECHNOLOGY SPECIFICATIONS

	SPECIFICATIONS				SYSTEM IMPACTS		
TECHNOLOGY	WEIGHT (LBM)	AVG POWER (W)	VOLUME (FT^3)	HEAT REJ. (W)	WEIGHT (LBM)	POWER (W)	VOLUME (FT^3)
Four-Bed Molsieve	240	(Baseline) 1176	22.3	550	①	①	①
Two-Bed Molsieve	180	447	12.7	②	①	①	①
EDC	169	230	5.4	562	30	435 (Electrolysis and THC)	0.3
APC	190	413	6.1	②	30	435 (Electrolysis and THC)	0.3
SAWD	228	610	14.1	600	65	30 (THC and WRM)	4.0

① Negligible impact
② Undetermined parameter

PRELIMINARY IDENTIFICATION OF FLUID INTERFACE SCARS

After evaluating the alternative technologies and the fluid interface requirements of those considered to be the most likely replacements on Space Station *Freedom*, the fluid line scars required by subsystems based on these technologies were identified. For the prime candidates for the air revitalization and water recovery functions the identified scars are:

Function	Identified Scars
CO_2 Removal	none
CO_2 Reduction	none
O_2 Generation	interface with coolant loop and H_2 vent
Trace Contaminant Control	none
Urine Processing	cabin air line and liquid coolant line
Brine Processing	in: brine/rejection concentrates and air out: return air and potable water

By designing the Phase I Space Station *Freedom* to include the capability for these additional interfaces, the useful life of *Freedom* will be extended. Incorporating subsystems which use less power, require less volume, or have fewer resupply needs will provide benefits for either the multidisciplinary research scenario or the transportation node scenario resulting in a more productive Space Station *Freedom* program.

PRELIMINARY IDENTIFICATION OF FLUID INTERFACE SCARS

Fluid line scars have been identified for the technologies most likely to replace the baseline technologies:

Function	Identified Scars
CO_2 Removal	none
CO_2 Reduction	none
O_2 Generation	interface with coolant loop and H_2 vent
Trace Contaminant Control	none
Urine Processing	cabin air line and liquid coolant line
Brine Processing	in: brine/rejection concentrates and air out: return air and potable water

IV. Results

A. Database of the Alternative Technologies

A database was created, and computerized, with descriptions of the alternative technologies and the references where the information was obtained. This database will be expanded as more information becomes available.

B. Types of "Scars" Identified

The "scar" requirements for the alternative technologies fall into three general levels: (1) intrarack, (2) interrack (rack interface plate), and (3) module or cluster level. It is assumed that replacement of the ECLSS hardware would occur at the rack level, therefore "scars" at the intrarack level can be ignored. At the interrack or rack interface plate level there may be a need to add extra fluid lines (for example, to provide cooling water not originally needed) or to oversize the tubing or ducting to accommodate a higher flow rate than initially required. On the module or cluster level, additional ECLSS resupply tanks or an additional tank farm (with associated valves, pressure regulators, instrumentation, etc.) may be needed in order to meet the requirements of high levels of EVA and airlock usage.

C. Issues and Areas for Further Study

The results of the preliminary study identified several issues and areas to be studied further. More definitive data is needed on the Transportation Node Scenario to adequately determine the requirements and constraints on the ECLSS. Additional Intermodule Ventilation (IMV) analyses are needed in order to evaluate the effects of adding modules in various configurations. The effects of various crew distributions on the pCO_2 and pO_2 levels is also needed. Safe haven requirements may change as *Freedom* evolves and this needs to be evaluated further.

D. Scope of the Follow-on Study

The follow-on study will greatly expand the scope of the preliminary study in several ways:

(1) Computer models of the alternative technologies will be developed and incorporated into existing analysis tools,
(2) A prioritized list of the potential technologies will be developed and a more thorough assessment of the software control "hooks" and hardware "scars" performed,
(3) A comparative analysis will be performed against the baseline system, and
(4) Cost/benefit trade studies will be performed to identify the best candidates to replace the baseline technologies.

Results

- Database of Alternative Technologies

- Three Levels of "Scars" Identified
  - Intrarack
  - Interrack
  - Module or cluster

- Issues and Areas for Further Study
  - More definition of the Transportation Node Scenario is needed
  - Additional analyses of Intermodule Ventilation are needed to evaluate the effects of adding modules in various patterns
  - Additional analysis of the effects of crew distribution is needed
  - Possible changes to Safe Haven requirements as *Freedom* evolves need to be evaluated

- Expanded Scope of the Follow-on Study
  - Computer models of the alternative technologies will be developed and incorporated into existing analysis tools,
  - A prioritized list of the potential technologies will be developed and a more thorough assessment of the software control "hooks" and hardware "scars" performed,
  - A comparative analysis will be performed against the baseline system, and
  - Cost/benefit trade studies will be performed to identify the best candidates to replace the baseline technologies.

FREEDOM

SPACE STATION FREEDOM

ELECTRIC POWER SYSTEM

SEI (Lunar Mars Mission) Accommodation Study

J. M. Friefeld
Rocketdyne

Rockwell International
Rocketdyne Division

20NW01/1

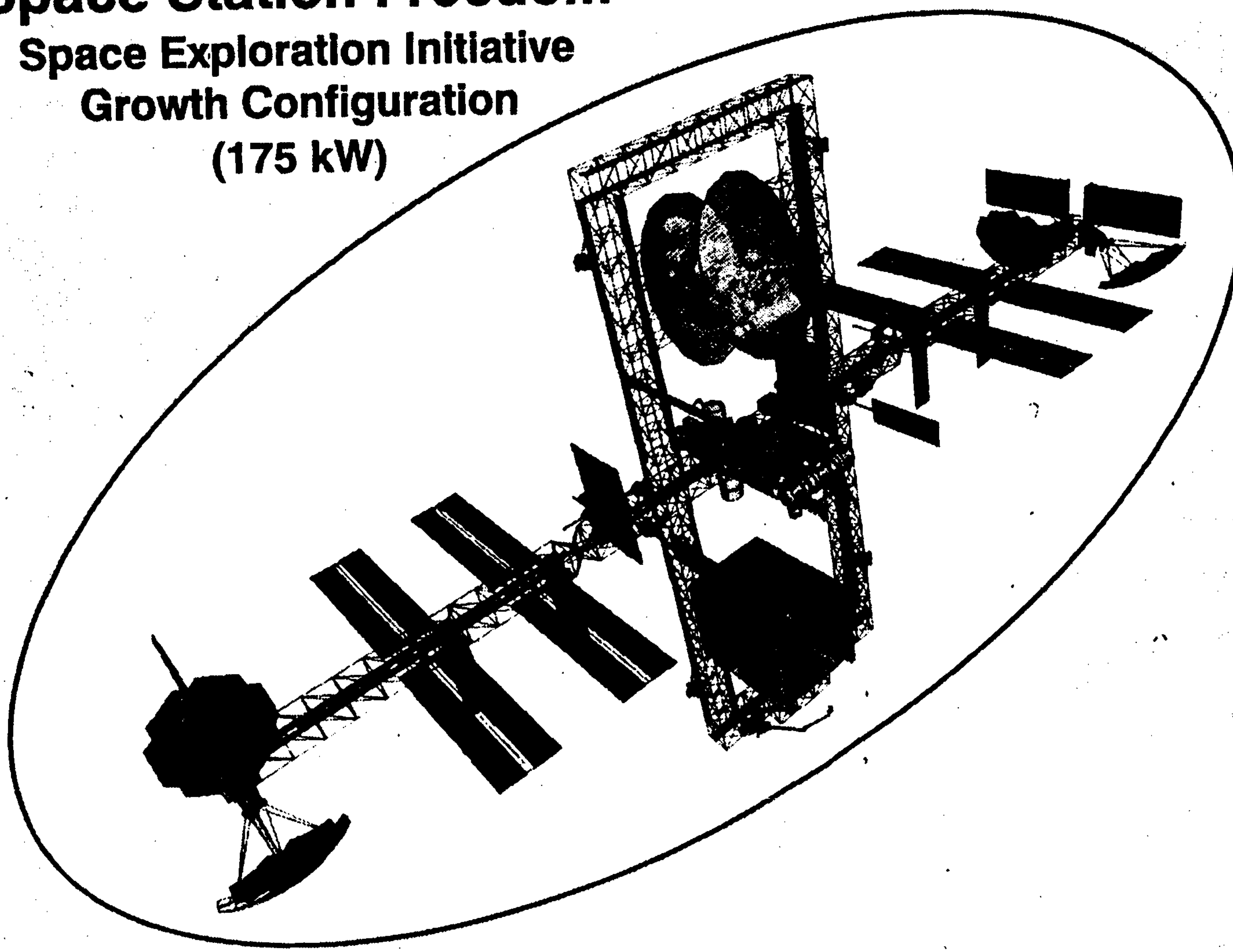
FREEDOM

LUNAR/MARS ACCOMMODATIONS
Overall Requirements

- Support SSF Buildup
- Structure
  - First Node Event (1999) - Lower Keel/Boom & Transverse Boom Extensions
  - Lunar/Mars Mission Node (2013) - Upper Keel/Boom & MTV Support Structure
- Elements
  - Hab Module - 2000
  - Hab Module - 2013
- Airlocks/Resource Nodes
  - Support to Lunar/Mars Mission - Additions in 2000 and 2013
- Power Requirements
  - First Node Event (1999) - 110 kW
  - Lunar Mission Node 1 (2000) - 146 kW
  - Lunar Mission Nodes 2 (2003) - 156 kW
  - Lunar/Mars Node (2013) - 191 kW

Space Station Freedom

Space Exploration Initiative Growth Configuration (175 kW)



FREEDOM

SSF POWER GROWTH CONSIDERATIONS

- Power Generation Capacity Accommodated by Addition of 25 kw Solar Dynamic Power Modules

- Added Primary Power Distribution May be by DC (as in Assembly Complete Station) or with AC for Additional Capability

- Other Issues:
  - Controls
  - Alpha Gimbal
  - Primary Distribution Architecture

- Preliminary Study Performed Under IR&D in October-November 1989 Timeframe to Assess Issues

POWER GENERATION SUMMARY

- Current SD Power Module Capability (25 kw) May be Marginal if DC Distribution is Used
- Upsizing Module to Give 25 kw With DC Causes 700 lb. Mass Penalty - Possible Impact on NSTS Packaging
- Current Design Effort Under Contract - Effort Provides for Reoptimizing NSTS Packaging Considerations

PRIMARY POWER DISTRIBUTION OPTIONS

- DC - Add Separate DC System to Distribute Power to New Modules
  - No New Hardware Designs
  - High i^2R Loss in Cable Runs or Increase Weight

- AC - Add AC System to Distribute SD Power (1200 Hz)
  - Three Phase System - More Sensors and Switches
  - Fault Currents Easier to Handle
  - New Hardware (AC Main Bus Switch, AC-DC Converters, Cables)

Hybrid - Same Features as Above
  - Can Scar All SSF Elements for Future Power
  - PV/SD Cross Strap at Main Bus Switch

POWER DISTRIBUTION OPTION COMPARISON

	AC	DC	Hybrid (AC)	Hybrid (DC)
Distribution Voltage	220 Vac	160 Vdc	220 Vac	160 Vdc
User Voltage	120 Vdc	120 Vdc	120 Vdc	120 Vdc
Added Power Available to R&D Elements	No	No	Yes	Yes
Added Orbital Replacement Units (ORU)	50	50	54	50
New ORU Designs	3	0	3	0
ORU Weight (Lb) - Preliminary Estimate	8000	8400	8500	8400
Cable Weight (Lb) - Preliminary Estimate	1800	7000	1800	7000

FREEDOM

OTHER POWER GROWTH ISSUES

SUMMARY

- Current Mil STD-1553B Data Bus May be Limited Due to Added Data and Length Limits - Recommend Consideration of 1EEE802.4

- Alpha Gimbal Scarring Should be Performed Based on SEI Considerations

- Grounding Impact is Nil (Same for AC and DC)

- Current Star Distribution is Appropriate for Growth SSF

FREEDOM

SSF ELECTRICAL POWER SYSTEM

SEI MISSION ACCOMMODATION STUDY SUMMARY

- Current SSF Approach is Generally Compatible With Overall Requirements
  - Existing SD Modules
  - DC Primary Distribution
  - Star Architecture

- Other Approaches Can Better Match SEI Requirements
  - AC Primary Distribution
  - High Speed Data Bus

- Alpha Gimbal Scarring Should Be Given Immediate Attention

SESSION VII
OPERATIONS EVOLUTION

Session Chair:
Ms. Karen Brender
NASA Langley Research Center

SESSION VII - INTRODUCTORY REMARKS

OPERATIONS ANALYSIS FOR EVOLUTION STATION CONCEPTS

Karen D. Brender, Manager
Evolutionary Definition Office
Langley Research Center

FY89 STUDIES ON OPERATIONS FOR STATION EVOLUTION

- REQUIREMENTS DRIVEN BY SOLAR SYSTEM EXPLORATION MISSION SCENARIOS
- CONCENTRATION ON ON-ORBIT OPERATIONS IN LEO TO SUPPORT EXPLORATION
- INITIAL DATA SOURCES WERE PREVIOUS MISSION OPERATIONS (APOLLO, SKYLAB, SPACELAB, STS) AND GROUND OPERATIONS DATA
- REQUIRED EXPERTISE IN ON-ORBIT OPERATIONS, GROUND OPERATIONS LOGISTICS, AUTOMATION, ROBOTICS AND OTHER APPLICABLE AREAS
- MAJOR START ON OPERATIONS DATA BASES FOR STATION EVOLUTION
- REQUIRED PARTICIPATION FROM MOST NASA CENTERS AND THE JET PROPULSION LABORATORY

1989 HUMAN EXPLORATION INITIATIVE STUDIES

- ANALYSIS OF FY89 CASE STUDIES HAS PROVIDED A LARGE STATION OPERATIONS DATA BASE APPLICABLE TO THE LUNAR/MARS MISSIONS
  - ON-ORBIT VEHICLE ASSEMBLY/PROCESSING TASK DEFINITION AND ANALYSIS
  - ROBOT AND EVA TASK PRIMITIVES FOR ON-ORBIT OPERATIONS
  - TRAJECTORY/DEPLOYMENT STUDIES FOR LAUNCHING SPACECRAFT FROM LEO
  - SELECTION OF PRIME AREAS FOR AUTOMATION AND ROBOTICS
  - REQUIREMENTS FOR OPERATIONS ANALYSIS TOOLS AND DATA BASES

FY90 STUDIES ON OPERATIONS FOR STATION EVOLUTION

- APPLICATION OF FY89 RESULTS TO THE HUMAN EXPLORATION INITIATIVE MISSION SCENARIOS
- FACTOR IN OPERATIONS FOR STATION DRIVEN TASKS AND FOR RESEARCH AND DEVELOPMENT
- CONTINUE REFINEMENT OF TASK BREAKDOWN AND APPLICATIONS OF A&R
- CONTINUED REQUIREMENT FOR EXPERTISE IN ON-ORBIT OPERATIONS, GROUND OPERATIONS, LOGISTICS, AUTOMATION, ROBOTICS ETC. . .
- COMPLETE OPERATIONS DATA BASES AND START CONSTRUCTION OF AUTOMATED ANALYSIS TOOLS

SESSION VII

- OPERATIONS MODELING FOR SPACE STATION FREEDOM EVOLUTION (VEHICLE PROCESSING OPERATIONS DATA BASE)
- ON-ORBIT ASSEMBLY AND SERVICING TASK DEFINITION
- ADVANCED ROBOTICS FOR IN-SPACE VEHICLE PROCESSING
- ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING
- SPACE VEHICLE DEPLOYMENT FROM STATION
- GRAPHICAL ANALYSIS OF MARS VEHICLE ASSEMBLY

OPERATIONS MODELING FOR SSF EVOLUTION

SPACE STATION EVOLUTION

Beyond the Baseline

South Shore Harbour Resort and Conference Center

League City, Texas

Feb 8, 1990

George G. Ganoe
Evolutionary Definition Office
Langley Research Center

Background

The operations required to support the on-orbit Space Station Freedom activities planned or being studied will be complex. Operational capability to perform tasks will be dependent on many factors such as manpower availability, logistics, other tasks being worked, and Space Station configuration. This effort uses information available about these and other factors to perform operations analysis for given missions and determine the feasibility of target configuration concepts to support those missions.

Studies have been conducted to determine processing requirements for a number of potential evolutionary missions on the Space Station Freedom. These studies have identified the need for growth of the Space Station in various ways. Some of the studies have dealt with the operational needs for the particular mission that they are concerned with, but none have looked at the total evolutionary operations requirement.

In order to pursue the subject of overall on-orbit operations to any appreciable level of detail, data bases of operational on-orbit tasks need to be compiled, and an analysis tool is needed to assist the analyst. A number of existing operations tools have been reviewed, and none have been found to satisfactorily perform the functions needed to analyze integrated operations requirements for the evolutionary Space Station Freedom. However, during the tool review, some existing applications were found to provide subsets of the required functionality, and these are being considered for incorporation into the analysis tool.

OPERATIONS MODELING FOR SSF EVOLUTION

Background

- In order to determine the feasibility of configuration concepts for evolution of the Space Station Freedom, analysis of on–board operations to accomplish the tasks to be carried out are required.
- Relevant supporting study activity in FY87 – FY89
  - KSC/MDAC Ground-to-Space Based Operations Task Definition Studies
  - LARC/CTA Ops Analysis Model Survey And Model Data Base Development Study
  - LARC/MDAC Multi-discipline Mission Accommodation Analysis
  - LARC/PRC Manned Mars And Lunar Base Missions Studies
  - KSC/MDAC Advanced Automation And Robotics For In-space Vehicle Processing
  - MSFC Space-based Transfer Vehicle Requirements And Accommodations
  - JSC EVA Systems Evolution Analysis
  - JPL Advanced Robotics for In-space Vehicle Processing
- Analyses of the on–board operations will draw on these studies but will require data bases of operational on–orbit tasks and an analysis tool(s) to assess operational capabilities of any given configuration

Vehicle Processing Operations Data base (VPOD)

One of the uses of the Space Station Freedom may be to perform the assembly and refurbishment of Planetary Exploration Space Transfer Vehicles. The Vehicle Processing Operations Data base (VPOD) is designed to provide a repository for the data that is being compiled relating to the on-orbit operations that will be required to accomplish those tasks. The VPOD can be used to derive estimates of requirements for; Crew Personnel, Equipment usage, Resource Requirements, and Required processing time. These estimates will then need to be integrated with all other operations that will be occurring at that time to determine overall Space Station operations requirements.

The VPOD has the capability to allow the vehicle processing operations to be specified to any desired level of detail. During the early phases of mission definition, when very little information is known about the mission, the VPOD can be used to provide preliminary estimates, and as more information is developed and entered into the data base, the estimates become more realistic.

VPOD three main tables of information relating to the operations required to assemble or refurbish a planetary vehicle on orbit. The first is the Events table which contains descriptions of the individual events needed and the Crew, Assemblies, Equipment, Resource, and Time requirements for performing the event. Next is the Assemblies table. This table contains the necessary information about the various pieces of the vehicle being worked on such as mass, dimensions, resource and test requirements. Finally the Equipment table contains a record of the various pieces of Orbital Support Equipment (OSE) needed to perform the various events.

The VPOD can be used to provide a base of information that will be used by an Operations Analysis and Simulation tool. Once the details of a vehicle assembly or refurbishment mission are specified in the VPOD, the analyst will be able to specify the mission by name, along with missions from a sibling data base for parallel Science efforts, and Space Station housekeeping and maintenance operations. The Analysis tool will then perform scheduling of all the required operations, and simulate their execution, keeping track of the resources used.

VPOD internal analysis can be used to generate summation reports and graphs showing mission specific information such as; Estimated Crew Time, OSE requirements, Station Resource requirements, and total required processing time.

VPOD can also be used to generate data files that can be used by other external tools such as spreadsheets, graphics generators, and word processors.

OPERATIONS MODELING FOR SSF EVOLUTION

Vehicle Processing Operations Data Base (VPOD)

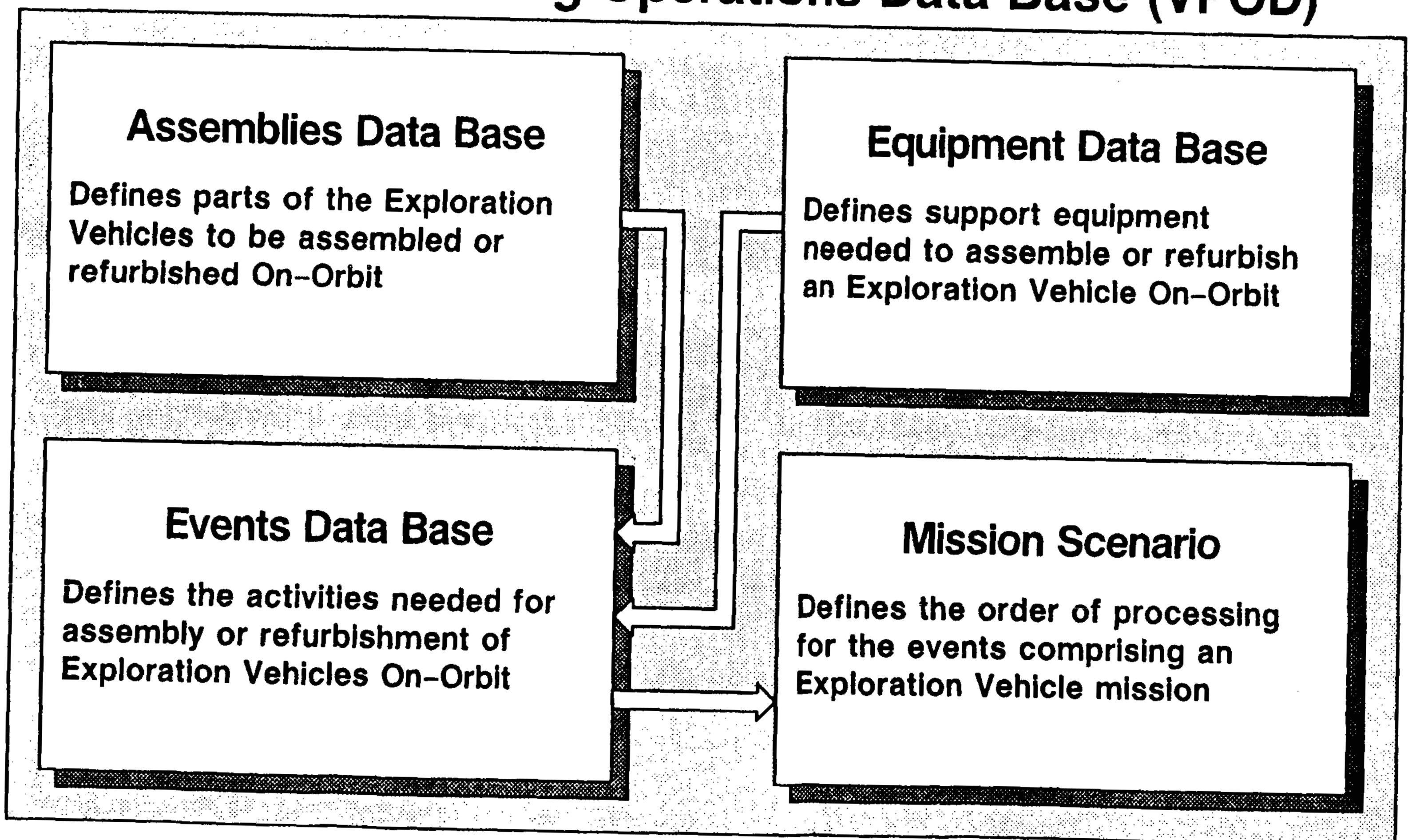
- Systematic, automated tool set to define operations tasks for on–orbit processing of planetary vehicles and derive estimates of
  - Crew personnel
  - Equipment usage
  - Resource requirements
  - Required processing time
- Model vehicle processing operations to any desired level of detail
- Contains generic events, assemblies, and equipment
- Base of information for use by other mission analysis tools
- Generate summation Reports and Graphs
- Generate data files to be used by other tools

Vehicle Processing Operations Data base (VPOD)

This chart shows a functional flow diagram for the VPOD. The Assemblies Data Base, and The Equipment Data Base are both used by the Events Data Base. The Assemblies Data Base contains descriptive records of the various parts of a vehicle that must be assembled or refurbished. The Equipment Data Base contains a list of the various OSE that is needed to perform the Events that put the assemblies together. The Events Data Base describes the individual operations required to perform the mission. The Mission Scenario uses data from the Events Data Base and from the analyst to define the order of processing of events that comprise a Planetary Exploration Vehicle assembly or refurbishment.

OPERATIONS MODELING FOR SSF EVOLUTION

Vehicle Processing Operations Data Base (VPOD)



Vehicle Processing Operations Data base (VPOD)

The VPOD supports two user groups and two file types. The Data base manager can maintain the permanent data base files by updating the information in existing records, or incorporating data from Temporary data base files into the permanent data base. Write access to the permanent data base is controlled by the data base managers password.

The Mission Analyst can read information from the permanent data base files, create temporary data base files, and add or update information in his temporary data base files. The Mission Analyst can also create a mission scenario using the mission editor, and initiate the generation of the summary reports desired for a defined scenario. Data records in the temporary data base files can supersede the information in the permanent data base files. This is accomplished by searching the specified temporary data base files before proceeding with the search of the permanent data base for a piece of information needed by the mission scenario. If a record or set of records needed by the Mission Analyst from the permanent data base for a mission scenario is incorrect or must be changed, he can copy that record into his temporary data base file then make the updates required.

The VPOD user interface is designed for the operations analyst. No programming experience is needed to perform any of the functions. The user is presented with either a menu or help line on each of the information screens, and may receive further context sensitive help by using the help function key at any time.

OPERATIONS MODELING FOR SSF EVOLUTION

Vehicle Processing Operations Data Base (VPOD) continued

- Support Two user groups
  - Mission Analysts
  - Data Base Managers
- Support Two file types
  - Permanent data base file
  - Temporary data base files
- User Interface designed for Operations Analyst

Vehicle Processing Operations Data base (VPOD)

The VPOD user interface consists of six functional areas which are; the operations concept editor, the mission editor, the events editor, the equipment data base editor, the assemblies data base editor, and the report generator. The operations concept editor is used to update and modify a set of generic vehicle processing operations flows defined in Task Description Language (TDL) files. The resulting operations concept is used as a template for defining missions using the mission editor. The mission editor is used to define the logical sequence of events that are required to perform the operations needed for a vehicle processing mission. The events, assemblies, and equipment editors are used to create, modify, or delete records in the respective data base data base. The report generator is used to specify the mission to be reported, the specific reports desired, and the level of detail to be reported.

The reports available from VPOD consist of Waterfall charts showing the events sequence and overall timeline, Transition tables showing on-orbit crew crew skill and time requirements, tables of OSE and assemblies needed to perform the mission, and requirements for Space Station supplied resources such as power, communications, thermal, and fluids. A time ordered table of the materials needed can be generated to aid in determining Earth to Orbit Transportation manifesting.

OPERATIONS MODELING FOR SSF EVOLUTION

Vehicle Processing Operations Data Base (VPOD) continued

- User interface consists of six functional areas
  - Operations Concept editor
  - Mission editor
  - Events editor
  - Equipment data base editor
  - Assemblies data base editor
  - Report Generator.
- Outputs include
  - Waterfall charts
  - Mission Manifesting information
  - Resource Usage
  - Equipment and Assembly use
  - Crew Requirements

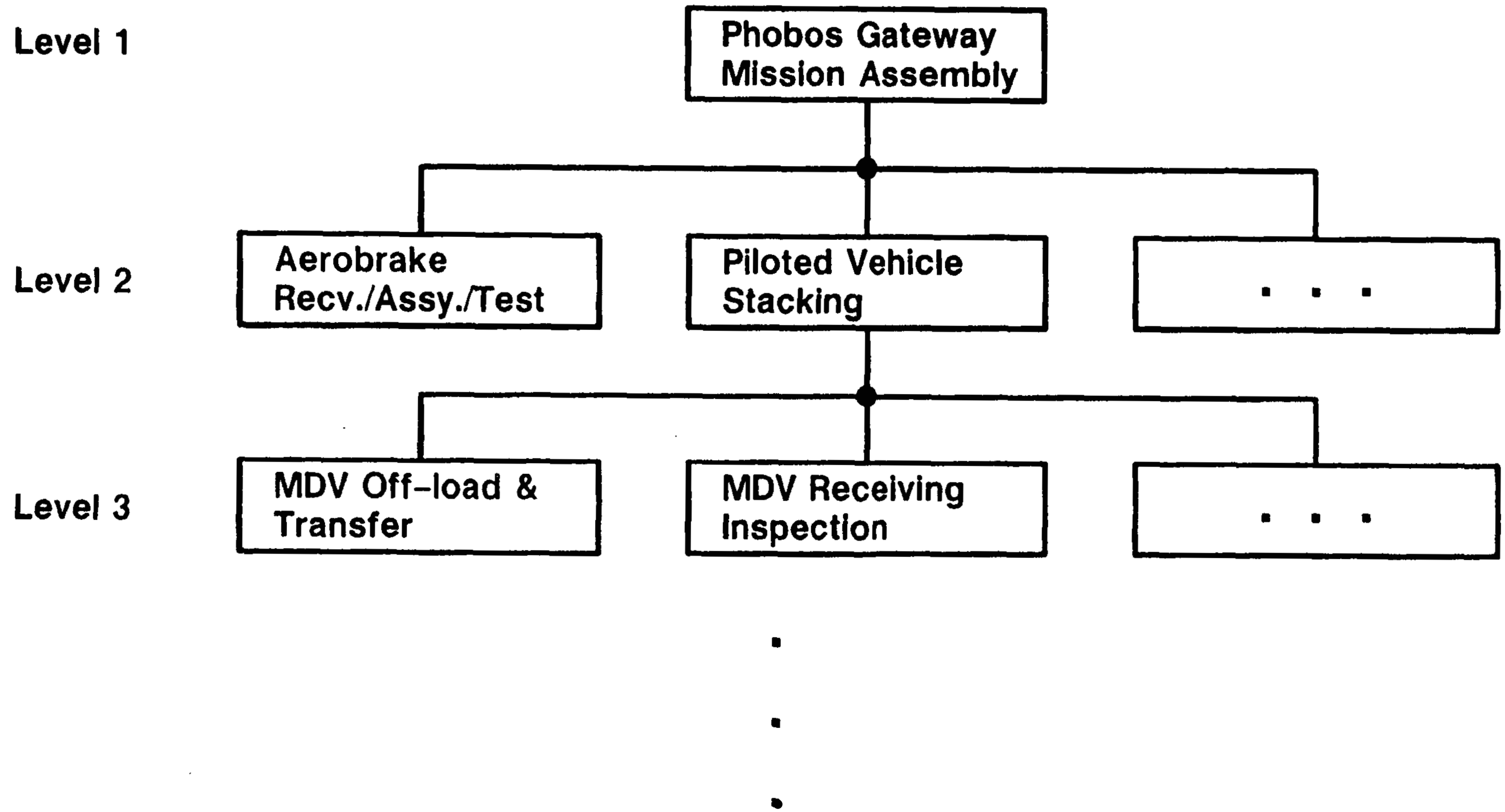
VPOD Events Hierarchy Example

The Events, Assemblies, and Equipment data bases in the VPOD are structured in a hierarchical manner. At the top level (level 1), events are defined as entire missions, an assembly would be the entire mission vehicle, and a level 1 Equipment record would represent a stand-alone piece of equipment. As the level increases, more detail about the element is available.

In this example, the on-orbit assembly of the Phobos Gateway Mission Vehicle is used to illustrate how the hierarchy works for events. The level one event is the entire vehicle assembly process. At the next level down, the major subsystems such as; Aerobrake receiving, assembly, and test, and Piloted vehicle stacking events are stored. The example then shows Piloted vehicle stacking detailed to the next level which consists of; Mars Descent Vehicle (MDV) off-load from the Earth to orbit launch vehicle and transfer to the Space Station assembly hanger, then MDV receiving inspection, and indicates that other operations follow at this level. These hierarchical levels can be taken to any desired level of detail (currently limited to about ten levels due to the size of the ID field).

OPERATIONS MODELING FOR SSF EVOLUTION

VPOD Events Hierarchy Example

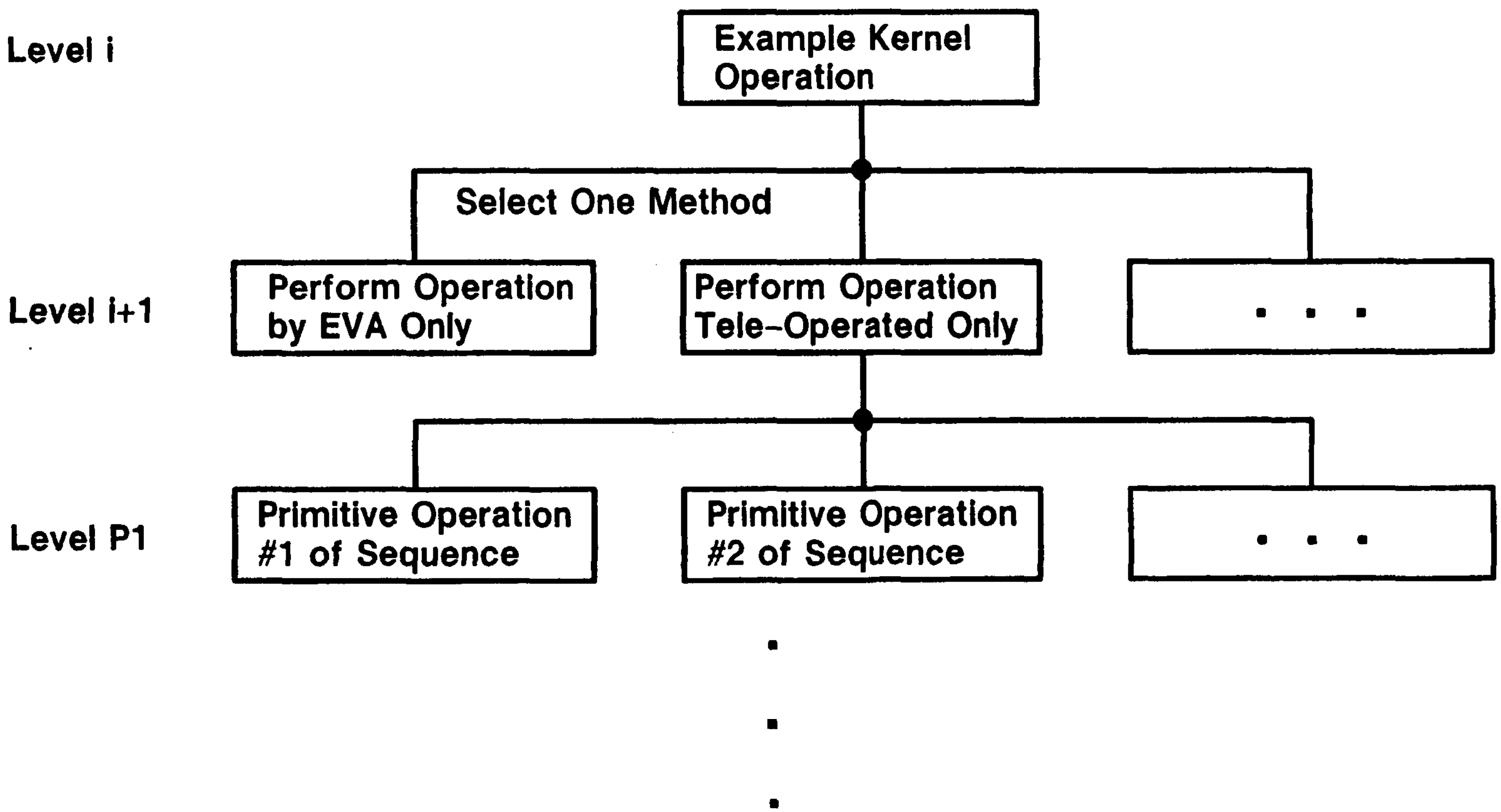


VPOD Events Hierarchy Example

This chart shows how the VPOD can support trade studies of EVA versus Tele–operated or Automated operations. At some level in the events hierarchy, a kernel operation is defined that may be performed by one of a number of methods. At the next level, all of the methods to be studied are defined, with any additional detail desired in successive levels below. Then when the mission analysis is performed the analyst will specify what the preferred type of operation is, and any exceptions that may be needed. By performing the analysis multiple times, and specifying a different preferred type of operation each time, compatible results for the different types of operations available can be generated.

OPERATIONS MODELING FOR SSF EVOLUTION

VPOD Events Hierarchy Example (Continued)



Advanced Analysis and Simulations Requirements

The main purpose of the VPOD is to act as a data repository for an Operations Analysis and Simulation tool that is currently in the requirements definition phase. This tool is needed to assist with the operations analysis that is needed to determine the feasibility of evolutionary Space Station Freedom configurations. These analysis will require the integration of operations that support Space Transfer Vehicle (STV) assembly and refurbishment, Scientific Research Projects, and New Technology Testing and Verification.

In order for the tool to support the integration of such a diverse set of operations needs, it will have to be able to interface to a number of different data bases. These data bases will consist of the VPOD which has been the subject of this report, a Science Missions Operations Data base (SMOD), a Space Station Housekeeping and Maintenance Operations Data base, and a Space Station Configurations Data base.

Multiple Space Station evolution concepts are being developed to support various types of missions. Using the Analysis and simulation tool, the user will select the mission to be evaluated, and the particular Space Station configuration that the mission is to be evaluated on, so that various evolution concepts may be evaluated to determine their capability to support the desired mission operations.

The analysis and simulation tool will also be able to support trade studies of manual versus Automation and Robotics (A&R) options for performing on-orbit operations at the Space Station. Targeted operations for the trade study can be analyzed using a variety of methods and the results can then be compared.

OPERATIONS MODELING FOR SSF EVOLUTION

Requirements Defined for Advanced Analysis and Simulation

- Tool for Operations Modeling and Analysis in Space (TOMAS)
- Integrate vehicle processing and Research Operations
- Interface to multiple data bases
- Support multiple Space Station Configurations
- Provide support for development of concepts for Space Station evolution
- Support study of both manual and A&R options for performing operations

Advanced Analysis and Simulations Requirements

The Advanced Analysis and Simulation tool will be a complex computer application, but the development can be minimized by using the proper commercially available programming tools. The data base requirements are being met using a standard data base language (Oracle SQL). The simulation portion of the application will be written using a standard simulation tool (CACI's Simscript II.5). The interface code required will be developed using the C programming language (Proposed ANSI Standard). C code will be used only as necessary to minimize the total programming effort.

By using the application development tools mentioned above, a high degree of portability between different computing environments can be achieved. The final application will be capable of being ported from the MS-DOS initial development environment to environments such as UNIX, VAX VMS, and IBM Mainframes.

All data sources used by the simulation will be traceable to their source. This is being accomplished by providing a traceability field in each record of the various data bases. Detailed analysis reports can then incorporate this information.

OPERATIONS MODELING FOR SSF EVOLUTION

Advanced Analysis and Simulation Requirements Continued

- Will be built using High Level System Development tools
  - Standard data base Language
  - Standard Simulation Language
  - Traditional programming languages used only as necessary
- Must be portable to multiple computing environments
  - MS-DOS
  - UNIX
  - VAX VMS
  - Mainframe
- Provide for data traceability

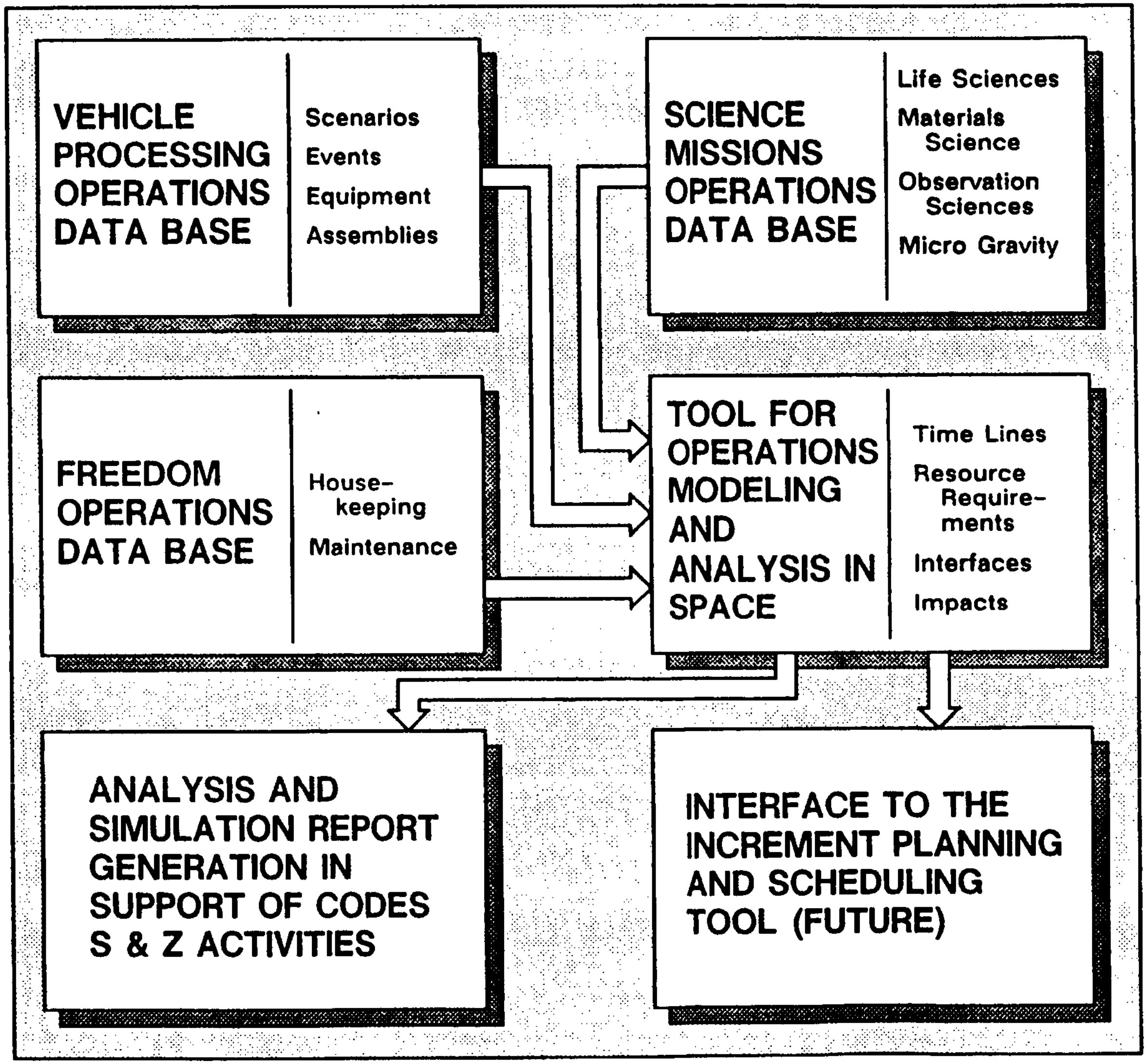
Advanced Analysis and Simulations Requirements

This chart shows the typical flow of operations data through the analysis tool. Required data from the individual data bases is collected by the analysis application. This data is then processed to provide the desired reports in support of the operations requirements for various NASA organizations. The Analysis outputs may also be useful as an input source for a Space Station Freedom Increment Planning and Scheduling Tool.

IN SPACE OPERATIONS MODELING FOR SSF

Preliminary version: Oct 1989
Final Version: April 1990

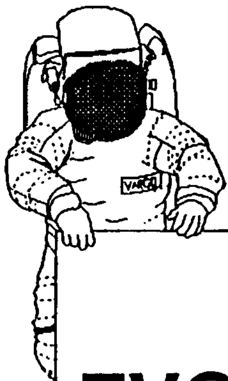
Preliminary version: Oct 1990
Final Version: April 1991

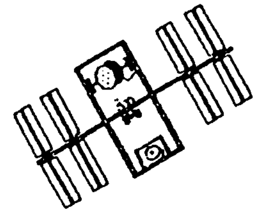


Preliminary version: May 1990
Final Version: Jan 1991

Preliminary version: Dec 1990
Final Version: Dec 1991

ON-ORBIT ASSEMBLY TASK DEFINITION STUDY





SPACE STATION EVOLUTION SYMPOSIUM

MCDONNELL DOUGLAS SPACE SYSTEMS COMPANY
KENNEDY SPACE CENTER

ADVANCED PRODUCT DEVELOPMENT

8 FEBRUARY 1990

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McDonnell Douglas Space Systems Company at Kennedy Space Center (MDSSC-KSC) has been tasked since November 1987 to provide support to the Space Station Evolution Working Group (EWG) based at NASA's Langley Research Center (LaRC). Work in the first year of this study included extensive data gathering and the development of study methodologies. The OEXP case studies as summarized in NASA Technical Memorandum 4075, Exploration Studies Technical Report FY 1988 Status, and NASA Document Z-2.1-002, Study Requirements Document FY 1989 Studies (SRD), define the mission scenarios and technical requirements which MSFC engineers and their contractors (Martin Marietta and Boeing) utilized in their design of exploration vehicles. LaRC selected case studies and vehicle designs upon which the study team performed processing analyses. An on-orbit SSF refurbishment crew of four dedicated to OEXP vehicle processing was baselined for all studies. In some instances, LaRC modified the vehicle designs, launch manifests, or mission scenarios provided by MSFC to obtain specific data from the processing analyses. The results from the following case studies analyzed during 1989 are provided in this report: Phobos Gateway On-Orbit Assembly and Launch, Lunar Evolution Vehicle On-Orbit Refurbishment, and Mars Mission Vehicle On-Orbit Assembly and Launch. In addition, a concept for facility accommodations at Space Station Freedom (SSF) was developed and support equipment to be provided at the facility was defined.

In support of the MSFC Launch/On-Orbit Processing (LOOP) study, LaRC asked us to assess ground and on-orbit processing impacts resulting from launching the OEXP vehicles on several different ETO launch vehicles.

Results developed by this study, including processing tasks and times, and personnel and equipment requirements, will be entered into the VPOD data base. VPOD will be used by LaRC to analyze future OEXP vehicles configurations, SSF facility and resource impacts, and life cycle cost predictions.

OBJECTIVES

- THE OBJECTIVES OF THE ON-ORBIT ASSEMBLY/SERVICING TASK DEFINITION STUDY ARE TO:
  - APPLY THE SPACE VEHICLE PROCESSING EXPERIENCE AND KNOWLEDGE RESIDENT AT KSC TO SSF ON-ORBIT PROCESSING (ASSEMBLY, TESTING, REFURBISHMENT, AND REFLIGHT),
  - DEVELOP GROUND AND ON-ORBIT PROCESSING TASK FLOWS BASED ON QUANTIFIABLE GROUND ANALOGIES,
  - IDENTIFY REQUIRED FACILITIES AND EQUIPMENT AND THE RESULTING SSF IMPACTS,
  - DETERMINE IMPACTS ON KSC FACILITIES TO ACCOMMODATE VEHICLE GROUND PROCESSING,
  - MAKE RECOMMENDATIONS CONCERNING VEHICLE AND FACILITY DESIGNS TO ENHANCE VEHICLE PROCESSING EFFICIENCY AND REDUCE OPERATIONAL COSTS,
  - INCORPORATE DATA GENERATED BY THIS STUDY INTO LaRC's VEHICLE PROCESSING OPERATIONS DATA BASE (VPOD).

A KSC data base of procedures and processing flows from Shuttle, Spacelab, Delta, Centaur, and Apollo/Saturn programs was used to determine the tasks, timelines, manpower, resources, and facilities necessary to process OEXP vehicles both on the ground at KSC and on orbit at Space Station Freedom. These ground assembly, refurbishment, test, checkout, and launch procedures contain schedules, manpower, and support equipment requirements. The most appropriate analogy was selected for each OEXP vehicle element and task from this KSC data base. Additionally, the study team conducted detailed technical interviews with the NASA and contractor systems engineers and technicians who are currently processing space vehicle flight hardware at KSC. Frequent telecons with the OEXP vehicle design engineers help determine system design details and processing requirements. Only those tasks which by necessity must be performed on-orbit due to the payload mass and volume restrictions of the ETO launch vehicle were incorporated. All other tasks were baselined for accomplishment on the ground prior to ETO launch. Once the tasks necessary to accomplish the mission were determined, they were organized into logical processing flows. Transition tables, the "building blocks" used to construct processing flows, were generated as accounting tools used to derive on-orbit times and manhours from the analogous ground tasks. Ground serial times are limited by personnel access to the hardware, whereas on-orbit serial times are determined by manpower and resource limitations. Labor intensive hands-on assembly task times have been adjusted to accommodate the limitation of using only two EVA crew members at a time. The Lunar/Mars flight crews were used to assist in stowing equipment during vehicle closeout. Transition tables also reference the KSC procedures used for analogy, which is either an Operations/Maintenance Instruction (OMI) for Shuttle/Spacelab, or a Launch Preparation Document (LPD) for the Delta Launch Vehicle.

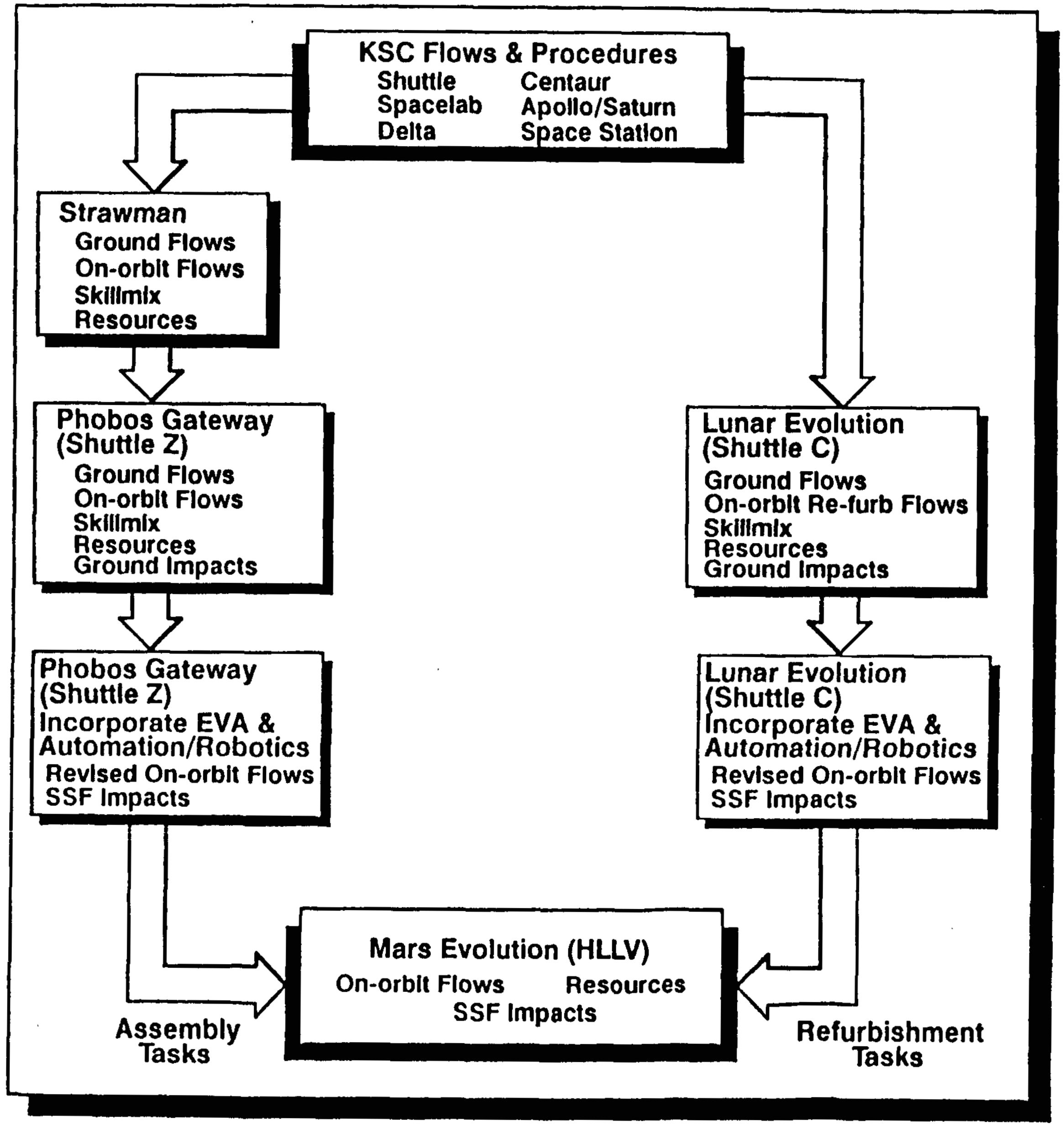
The study team developed a "Strawman" vehicle as a conceptual tool to assist in the transfer of KSC space vehicle processing experience to the performance of equivalent tasks on-orbit at SSF. This "Strawman" vehicle consisted of a crew module (similar to a Spacelab or Space Station pressurized module), a manned lander module, a four segment aerobrake, and two cryogenic propulsion stages (similar to the Centaur upper stage). A processing concept and flow to assemble, checkout, service, and launch this "Strawman" vehicle from KSC was developed from our data base. This imaginary vehicle was then transitioned to SSF for analogous on-orbit processing.

The Phobos Gateway vehicle was the first one selected by LaRC for analysis. This vehicle was compared to the "Strawman" vehicle for similarities, and the appropriate "Strawman" transition tables and assembly flows were transferred to the Phobos Gateway analysis. Where differences existed, the KSC data base was revisited for new analogies.

For the Lunar Evolution case study, LaRC directed that a *refurbishment/turnaround analysis* of the Lunar Piloted Vehicle (LPV) and Lunar Cargo Vehicles (LCV) at SSF be performed. The LPV and LCV designs were compared to the Shuttle and Spacelab, as they are the only space vehicles for which refurbishment data exist.

The Mars Mission Vehicle had a high degree of commonality with elements of the Phobos Gateway and Lunar Piloted Vehicles, and processing operations were derived from them. This Mars vehicle assembly flow was submitted to MDSSC-JSC for review and incorporation of accurate EVA/RMS operations times. Additional iterations to these flows to incorporate realistic EVA/RMS times and automation/robotics technology enhancements are planned.

Approach



KSC Flows & Procedures
Shuttle
Spacelab
Delta
Centaur
Apollo/Saturn
Space Station
Strawman
Ground Flows
On-orbit Flows
Skillmix
Resources
Phobos Gateway (Shuttle Z)
Ground Flows
On-orbit Flows
Skillmix
Resources
Ground Impacts
Phobos Gateway (Shuttle Z)
Incorporate EVA & Automation/Robotics
Revised On-orbit Flows
SSF Impacts
Lunar Evolution (Shuttle C)
Ground Flows
On-orbit Re-furb Flows
Skillmix
Resources
Ground Impacts
Lunar Evolution (Shuttle C)
Incorporate EVA & Automation/Robotics
Revised On-orbit Flows
SSF Impacts
Mars Evolution (HLLV)
On-orbit Flows
Resources
SSF Impacts
Assembly Tasks
Refurbishment Tasks

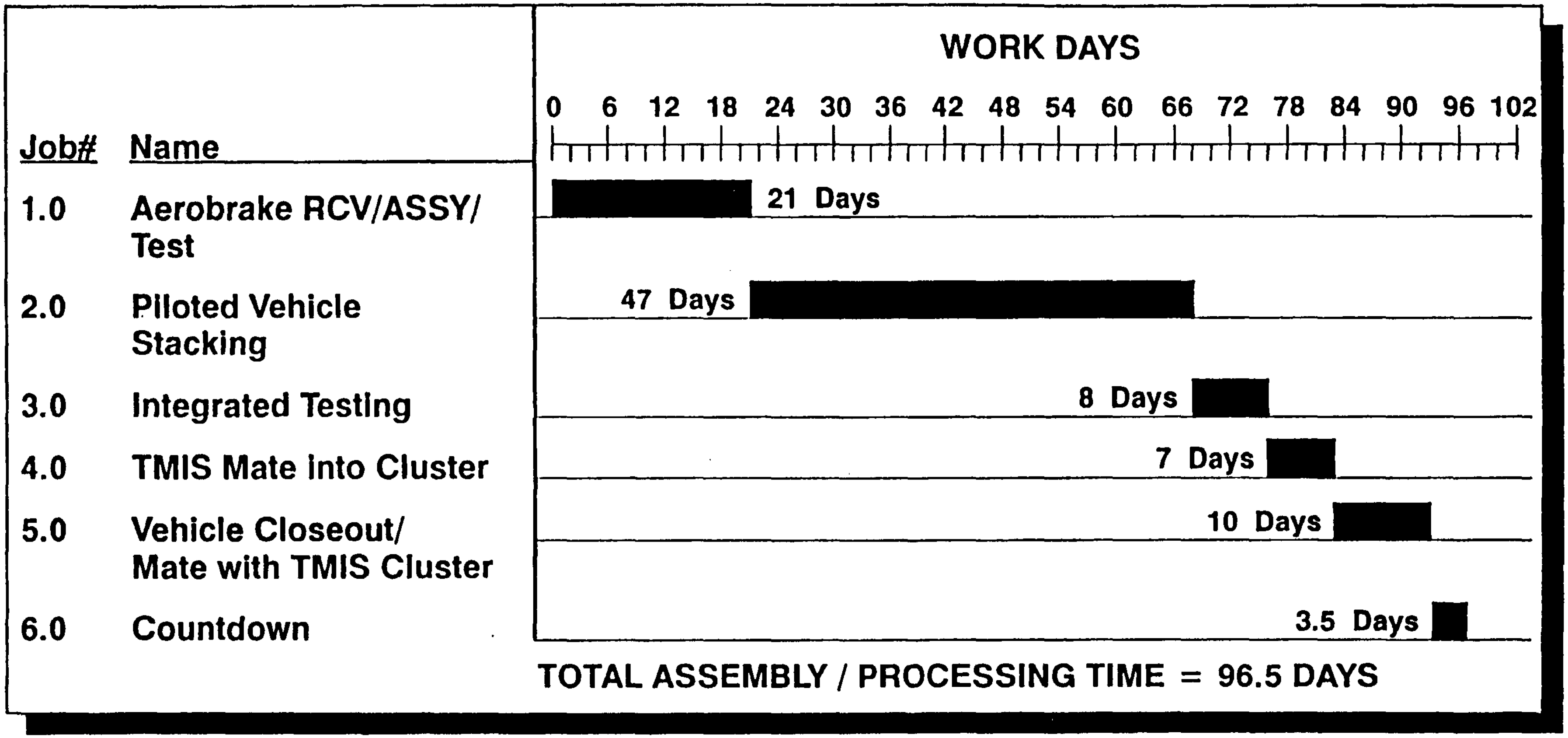
The Phobos Gateway vehicle analyzed was designed by Martin Marietta Aerospace. Three Shuttle-Z ETO vehicles launch the piloted vehicle components, which are assembled on a lower keel platform of SSF. All vehicle elements are delivered to SSF in time to support continuous assembly of the vehicle. All hypergolic propellant loading and ordnance installation occurs on the ground. The Trans-Mars Injection System (TMIS) stages and propellant are placed in LEO by three additional Shuttle-Z launches, and are clustered remotely at the co-orbiting Cryogenic Propellant Depot (CPD). An advanced Orbital Maneuvering Vehicle (OMV) brings the assembled piloted vehicle to the CPD for mating with the TMIS cluster, and for Trans-Earth Injection System (TEIS) cryogenic propellant loading. The fully integrated and fueled vehicle is then deployed for the trans-Mars injection burn. This launch manifesting was determined by LaRC.

The overall Phobos Gateway vehicle on-orbit processing flow is shown. Total assembly/processing time is 96.5 days (8 hours work shifts). Times shown are "KSC ground equivalent" times and do not incorporate EVA/RMS and automation or robotics enhancements.

KSC analogies used for Phobos Gateway processing, with rationale, include:

o Aerobrake assembly = Spacelab Instrument Pointing System installation (extensive crane, positioning, and bolting operations)
o Aerobrake Thermal Protection System (TPS) = Shuttle TPS (closeout panels with pre-installed thermal tiles)
o Mars Descent Vehicle (MDV) = Delta 2nd stage (hypergolic propellant propulsion stage) with aerobrake and Apollo rover
o Phobos Excursion Vehicle (PHEV) = Apollo Lunar Module, Spacelab pressurized module, and Delta 2nd stage (manned cabin with hypergolic propulsion)
o Trans Earth Injections System (TEIS) = Centaur and Delta 1st stage (cryogenic propulsion stage)
o Mars Orbit Operations System (MOOS) = Shuttle Orbital Maneuvering System (hypergolic propulsion pod including engines and tanks)
o Habitat module = Spacelab pressurized module (similar configuration, function, and life support systems)
o Reaction Control System (RCS) = Shuttle Orbital Maneuvering System (same as MOOS)
o Earth Capture Crew Vehicle (ECCV) = Apollo Command Module and PHEV (manned re-entry vehicle with hypergols and life support)
o Trans Mars Injection System (TMIS) = Centaur and Delta 1st stage (cryogenic propulsion stage).

Phobos Gateway
Overall On-orbit Processing Flow



The Lunar Piloted Vehicle and the Lunar Cargo Vehicle were designed by Martin Marietta. These vehicles are identical, except that the eight-man crew module is replaced on the LCV by an unmanned cargo element. The fully assembled and fueled vehicles are placed in LEO by a Shuttle-C ETO Launch Vehicle. The Space Shuttle orbiter is an ideal analogy since its flight crew systems, consumables, crew size, and mission duration are similar to the LPV. Some Shuttle tasks, such as hydraulic and auxiliary power unit servicing, have been deleted as the planned LPV does not utilize such systems and components.

Postflight deservicing begins when the LPV returns to the SSF from a Lunar mission. A self-diagnostic health check will be performed on all vehicle systems, and a visual inspection will be performed before the vehicle enters the SSF hangar. An advanced OMV will bring the vehicle within grappling range of one of the hangar's manipulator arms. After berthing in the hangar, the vehicle will be connected and switched to SSF facility power, life support, communications, and data system. The flight crew will egress, and residual propellants will be drained. Perishables, scientific results, and waste will be removed from the crew module. Inspections will be performed to document post-flight damage and vehicle condition.

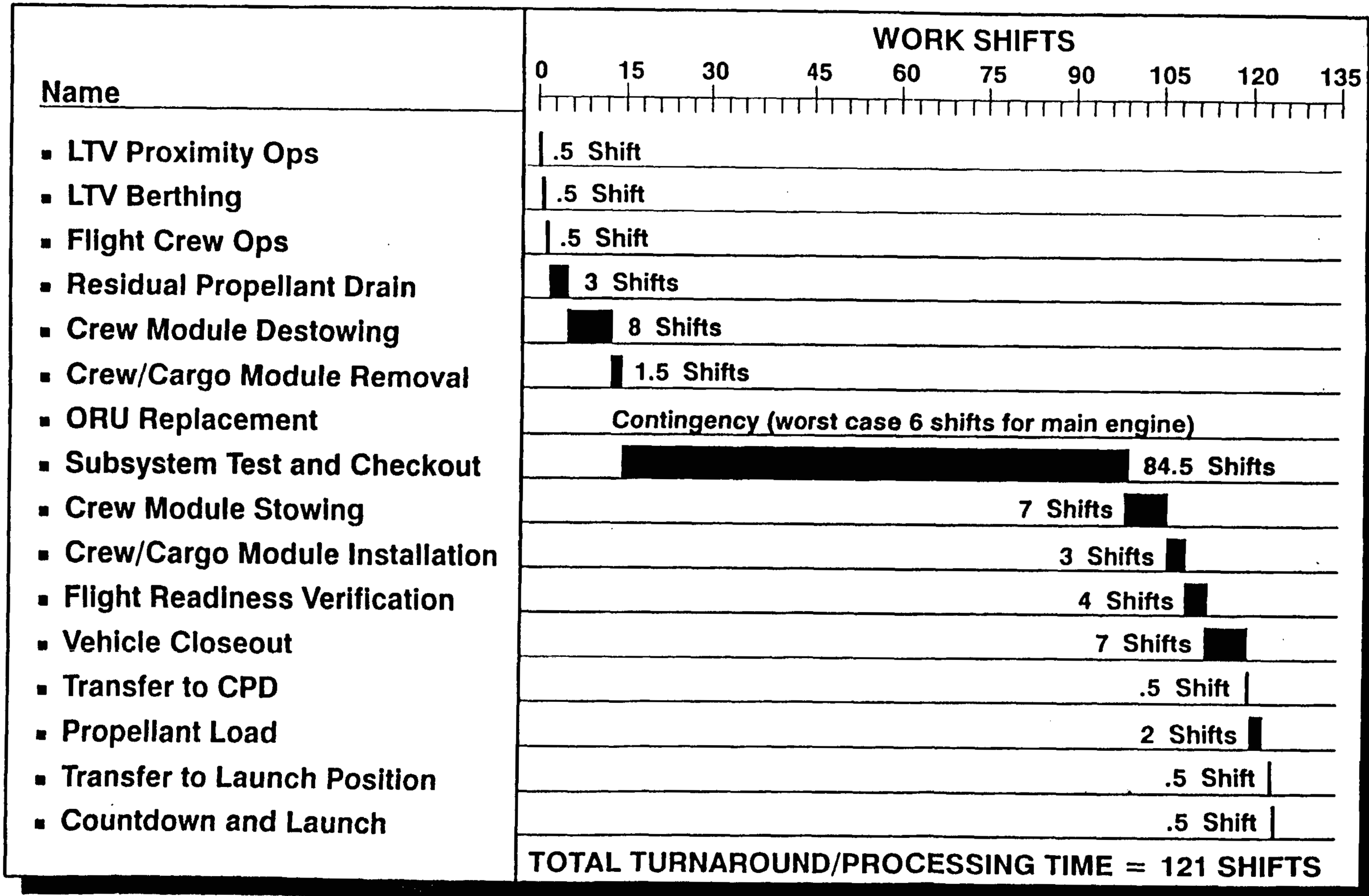
Refurbishment, retest, and closeout operations are then accomplished. Orbital Replacement Unit (ORU) tasks were based on similar Shuttle line replaceable unit (LRU) requirements. The aerobrake is replaced after every five missions. Thermal protection system (TPS) repair is performed "as needed" between aerobrake replacements. Shuttle TPS damage for a typical mission (less launch and landing damage) was used to estimate the number of tile and fabric repairs for each aerobrake use. Tile cavity damage is repaired using the fill-in/spray-on ablative repair kit developed by Martin Marietta for Shuttle in-space use. Refurbishment of the LPV/LCV propulsion system will consist of extensive post-flight inspections, followed by electrical checkout, engine servicing, and leak and functional checkout. The shuttle propulsion analogies used were the Space Shuttle Main Engine (SSME), External Tank (ET), Power Reactant Storage and Distribution (PRSD) tanks, and the Reaction Control System (RCS). Crew module refurbishment required 54.5 shifts. The crew module waste management system is serviceable (drain and flush) in place. LPV windows were chosen to be similar to the electrically heated Apollo/Skylab type windows, eliminating the extensive dissicant replacement operations on the Shuttle windows. Replacement of the crew consumables is done by changeout of lockers and prepacks. EVA suits will be exchanged on an "as-used" basis. Spacelab pressurized module installation and mate with the Shuttle orbiter (including associated electrical and fluid connections) was used as the analogy for mating either a cargo module or a crew module with the Lunar transfer vehicle.

Following ORU replacement and subsystem test and checkout, Integrated testing will be performed on the entire Lunar transfer vehicle. Included in this verification phase is flight software load, a countdown demonstration test, and a flight simulation test in which critical portions of the mission sequence are simulated to verify functional integrity of vehicle systems. During vehicle closeout, fluids and gases will be topped off, final crew equipment will be stowed, SSF umbilicals will be disconnected from the vehicle, and final inspection and closeout photography will be performed. Flight crew ingress will occur, and the vehicle will be powered up and switched to on- board system.

Cryogenic propellant depot (CPD) and launch operations begin with the docking of an advanced OMV to the vehicle, followed by transfer to the CPD. Shuttle External Tank propellant load and countdown was used as the analogy for this section of the ops concept.

The overall generic timeline for Lunar vehicle tunaround of 121 shifts incorporates parallel operations where feasible. (Non-parallel, serial operations resulted in a total turnaround time of 173.5 shifts). All Lunar vehicle processing times are "KSC ground equivalent" times and do not have EVA and automation enhancements yet incorporated.

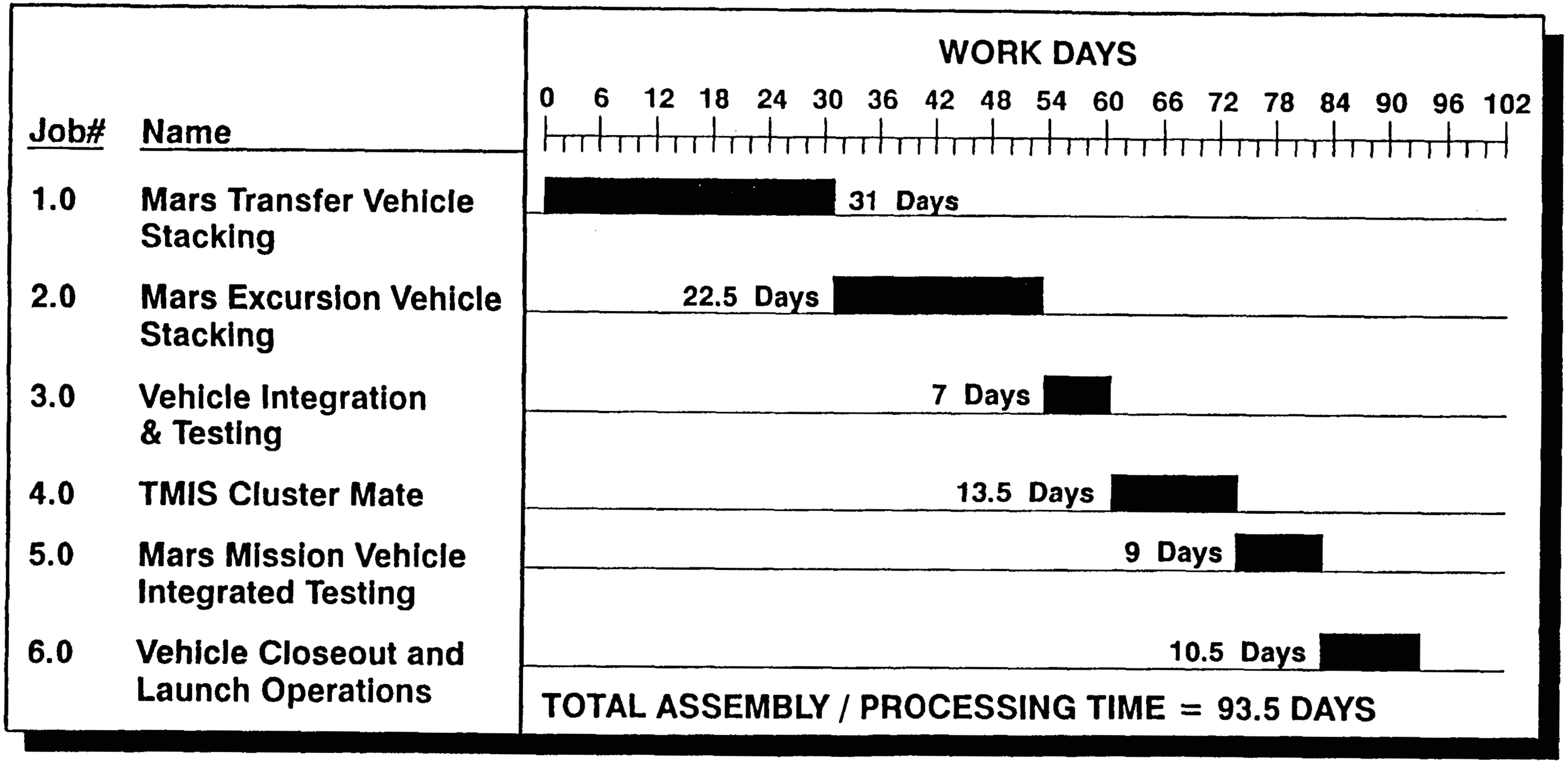
LPV/LCV Overall On-orbit Turnaround Flow



The Mars Mission vehicle on which an assembly analysis was performed was designed by Boeing Aerospace. The piloted vehicle consists of the Mars Transfer Vehicle (MTV), which houses the crew in a zero gravity mode during transit, attached by four manipulator arms to the Mars Excursion Vehicle (MEV), which lands on the Martian surface. The TEIS and MEV descent/ascent hydrogen and oxygen tanks are launched wet from Earth, but require top-off before trans-Mars injection. The TMIS core stage (with five integrated engines) and three strap-on tank sets arrive on orbit fueled, and do not require top-off due to the short dwell time prior to use.

The overall Mars mission on-orbit assembly flow shown was derived from previously generated Phobos Gateway assembly and Lunar Evolution refurbishment results. Aerobrake assembly, included in both the MTV and MEV stackings, was shortened due to a two segment aerobrake being used instead of the four segment Phobos Gateway aerobrake. TMIS clustering times were adjusted to reflect the core stage with three strap-on tank set configuration. The Mars mission assembly timelines are the first study results to incorporate realistic EVA and RMS operations enhancements. These timelines also incorporate Boeing-accepted, MDSSC-KSC study team design recommendations. The overall on-orbit processing time of 93.5 days reflects a time savings of 46% over the initial processing timeline.

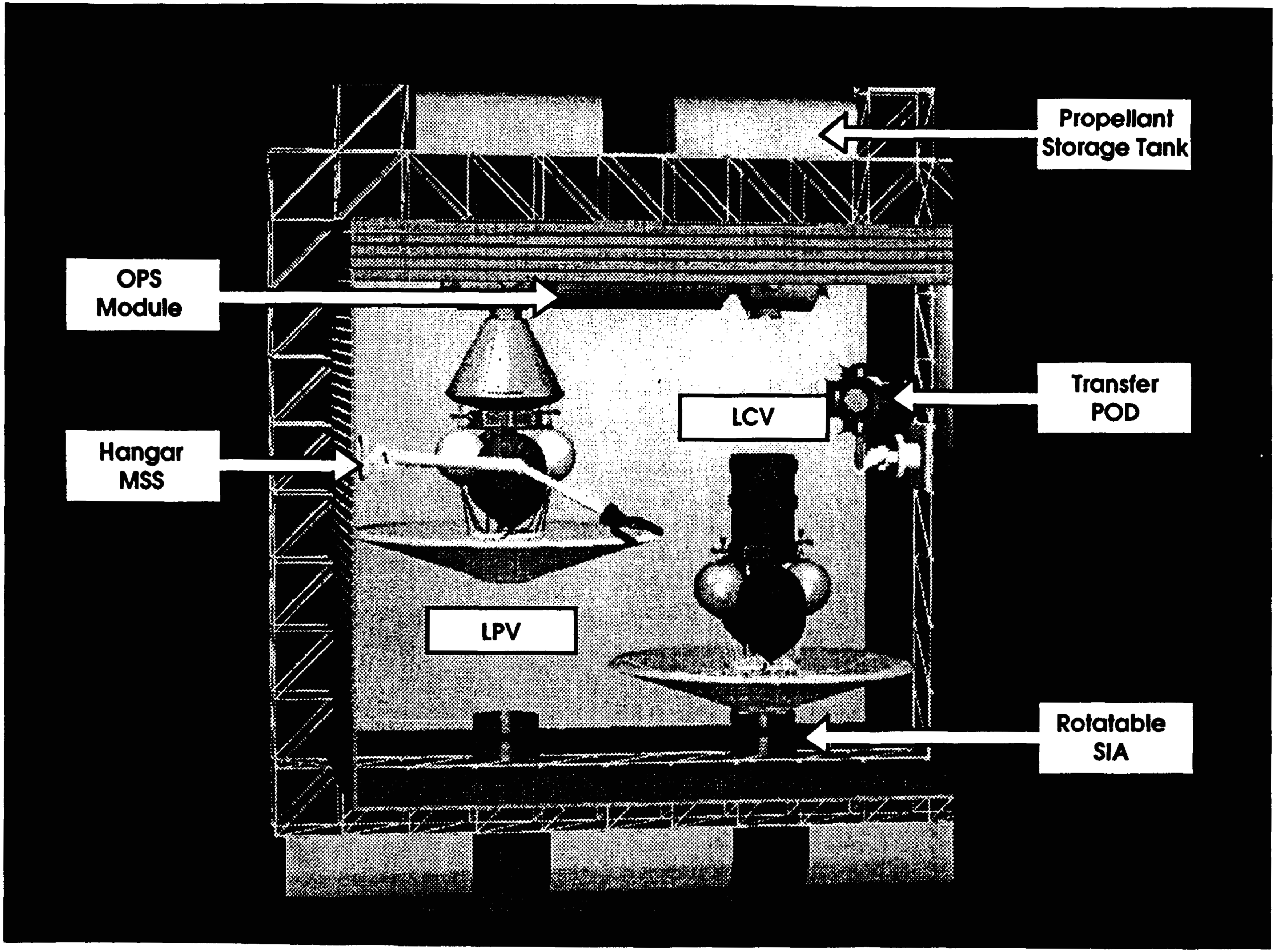
Mars Mission
Overall On-orbit Assembly Flow



In order to support LaRC in their providing input to Section 3.10 (Evolution) of the Space Station Program Requirements Document, the study team was tasked with generating a list of "hooks and scars" to the assembly complete station which would enable it to evolve into an OEXP transportation node. For the purpose of determining "worst case" impacts to SSF, all vehicle processing operations, including cryogenic propellant loading, were baselined as taking place at SSF. An additional requirement was that the "hooks and scars" must encompass either Mars vehicle processing or parallel processing of two Lunar vehicles. The SRD also stated that meteroid/debris protection was required for the Lunar vehicles while at SSF.

This dual mission processing facility, configured for Lunar vehicle refurbishment is shown. The lower keel location was determined by previous LaRC studies to be the site with least impact to the SSF stability, control, and microgravity requirements. Cryogenic propellant storage tanks are shown around the perimeter of the hangar.

SSF Processing Hangar



The procesing hangar will provide vehicle storage, power, cooling, and fluids servicing. Two Mobile Service Stations (MSS) are provided for simultaneous telerobotic processing of two vehicles. Vehicles can be berthed to rotatable Station Interface Adapters (SIA), which simplify MSS access for vehicle inspection and servicing. An airlock and crew transfer pod are used to transfer crew members and equipment between the ops module and the OEXP vehicles without having to perform EVA.

SSF Processing
Hangar Requirements

- Hangar bay (120 ft x 120 ft x 90 ft) – dual bays (Lunar Evolution) or single bay (Mars Evolution) configuration to support on-orbit assembly, testing and servicing
- Hangar utility tray pop-up interfaces at port-starboard locations
- Two mobile service systems (MSSs) which can translate up/down or across Hangar area
- Meteoroid/debris shield to protect OEXP vehicles and EVA crew
- Hazard monitoring system in hangar bay (hypergols, hydrogen, ammonia, & radiation)
- Storage provisions for equipment, tools, and ORUs
- Fixed area lighting and video cameras
- Fire detection and suppression
- Propellant storage and transfer (113 tons of cryogens and 12.4 tons of hypergols based on Cycle 2 OEXP vehicle specs, April '89)

Extensive effort was expended to define OEXP vehicle interface requirements at the processing hangar, truss interfaces, station modules, and OEXP vehicle umbilicals. Resource requirements were identified from known OEXP vehicle specifications and SSF system designs. Projected vehicle interfaces were compared to Space Station Program Office Architectural Control Documents, baseline configuration documents, and functions, power, and weight data books. Associated "hooks and scars" which reflect SSF evolutionary requirements that should be incorporated into the assembly complete station, are provided.

SSF "Hooks & Scars" to Accommodate Hangar

SYSTEM	SCARS	QUANTIFICATION	REFERENCE
GN&C, Structure & Propulsion	CMG truss strength/stiffness & attach points for hangar, MSC's, and propellant storage add thrusters/propellant	As required to maintain SSF stability/reboost with 999-ton vehicle and 170-ton facility attached	OXEP vehicle specs April '89 Mars Evolution Mission 2
Fluids/Gasses	Gaseous nitrogen stub (1 port, 1 starboard bay), water stub (1 port, 1 starboard bay), gaseous Helium system (1 port, 1 starboard bay)	78,270 cubic feet, 116 gallons, 36,063 cubic feet	STS ET scaled down STS closeout equivalent STS ET scaled down
Environmental Control Life Support System	2 fire detection/supression stubs (1 port, 1 starboard bay)		
Electrical Power (EPS)	2 120V dc stubs (1 for port, 1 for starboard bay)	33.8 KW nominal max to each bay (46,5 KW total peak for both bays–integrated testing not performed in parallel)	22 KW vehicle power based on Apollo, Spacelab, and Viking analogies + 6.5 KW hangar support power + 85% conversion efficiency (Phobos Gateway integrated testing)
Thermal Control System (TCS)	2 ammonia LOOP scars (1 for port, 1 for starboard bay)	35.5 kw heat rejection for each bay (48.8 KW peak for both bays)	105% of electrical load

The basic dual bay hangar facility includes a pressurized operations module, which functions as the monitor and control center for all vehicle processing and testing. It includes a node with cupola and RMS control station, and is located within the processing hangar to allow close proximity access and unobstructed visual line of sight to the OEXP vehicles. A pressurized "pocket lab" is recommended to permit shirt sleeve maintenance on items requiring frequent service. Nodes are used for vehicle berthing and logistic resupply of the vehicles.

SSF Processing Operations
Module Requirements

OPERATIONS MODULE WITH ATTACHED NODE, CUPOLA, AIRLOCK, AND CREW TRANSFER POD

Provide structural and utility interfaces on the Phase 1 station as a provision for a pressurized operations module to include a node, cupola, and airlock remote from all other pressurized modules and integrated to an assembly hangar to be located on the growth station.

JUSTIFICATION

- Operations module will provide a crew support station dedicated to support unique mission operations and equipment necessary to assemble, test, and refurbish OEXP vehicles and serves as an operations control center. This station includes an IVA workstation, MPAC, ATE/BITE, and Maintenance Support station.
- Cupola is in direct view of assembly area and includes an EVA/RMS Control workstation to facilitate EVA and RMS operations.
- Airlock will store EVA equipment and provide Egress/Ingress for a 4-man EVA crew.
- Crew transfer pod is a modified airlock to provide pressurized crew transfer between SSF modules, operations module, and OEXP crew cabins via RMS.

Operations module " hooks and scars" which reflect SSF evolutionary requirements that should be incorporated into the assembly complete station are provided. Additionally, living accommodations for the assembly/refurbishment work crews will be required.

SSF "Hooks & Scars" to Accommodate Ops Module

SYSTEM	SCARS	QUANTIFICATION	REFERENCE
Electrical Power (EPS)	1 DC 120V stub	8.5 KW nominal	W.P. 1
Thermal Control System (TCS)	1 ammonia LOOP stub	9.0 KW heat rejection	105% of electrical load
Data Management System (DMS)	1 DMS optical stub, 1 timing stub	39.04 MBPS	Mars piloted vehicle specs, June '89 MMC
Communications and Tracking	1 audio stub, 1 video stub, 1 control & monitoring stub, 1 caution & warning stub, 1 state vector stub	13.4 MBPS, 4.75 MBPS	Mars piloted vehicle specs, June '89 MMC
Structure	Attachment for OPS module with node, cupola, & airlock		
Environmental Control Life Support System	Oxygen stub, Nitrogen stub, water stub, water recover stub, fire detection/ suppression stubs	As required to support OPS module with node, cupola, & airlock	W.P.1

In support of a "Skunk Works" request, the study generated a list of proposed orbital support equipment (OSE), and estimated the total mass. Lunar vehicle refurbishment was selected for the OSE analysis since refurbishment requires more tasks to be performed on more systems than vehicle assembly. Shuttle ground support equipment (GSE) was used for the analogy. Shuttle GSE, however, fills warehouses and tool cribs, and had to be reduced to a realistic level for orbital operations. GSE for systems not found on the LPV (such as hydraulics and auxiliary power units) was deleted.

Upgrading GSE into OSE will require optimization for space usage such as weight and volume reduction, and use of advanced technology to function in vacuum, microgravity, and thermal extremes. Additional expense will be incurred certifying OSE as flight hardware. This OSE list was given to SSF Work Package 2 mass engineers at MDSSC-SSD at Huntington Beach for mass estimation. Total mass for this entire set of OSE is estimated at 3420 pounds. SSF logistics engineers will need to plan for ETO manifesting and packaging, and SSF storage of this OSE.

Orbital Support Equipment

Fluid System Test Devices
Aerometric Leak Detector
Air Measuring Unit
Atmospheric Pneumatic Flow Tester
Coolant Containers
Coolant Deaeration Unit (Fuel Cells)
Coolant Loop Service Unit
Coupler Assemblies
Dissolved Oxygen Analyzer
Drain & Purge Adapter Set (Water)
ECLSS Pressure Distribution Unit
ECLSS Radiator Flow C/O Unit
Entrained Gas Detection Unit - (FC-Coolant Loop)
Expanders/Reducers
Flow Rate Calibration Kit
Flow Meter and Test Set
Flow Meter Bypass Valve Assembly
Fluid Port Adapters
Fluid Sample Collector
Fluid System Test Device
Funnel with Cover and Tube
GO2 Pressure Regulator Unit
GO2 Service Set
High Pressure Flow tester
Iodine Injector Set
Lapping Kit
Leak Check Equipment (Hand Held Spectrometer or Infrared Sensor)
Leak Detectors - (Helium, Hydrogen, Nitrogen)
Leak TEC Solutions
LH2 Storage and Transfer Equip
Mop and Sop Spill Kit
Plugs/Caps
Pneumatic Analyzer Test Set
Portable Purge Unit
Portable Propellant Tank
Pressure Calibration Kit
Pressure Distribution Unit with Gages
PRSD Electrical Control and Monitor Unit
QD Filters
Rigid and Flex Hoses
Rigid and Flex Tubing Assemblies
Sample Probes (Hydroscope, etc.)
Tee's/Elbows
Temperature Calibration Kit
Thermometer
Tool Set/Value Adapters
Unions
Volumetric Leak Detector
Vacuum Cleaner
Valves

Electrical Support Equipment
7-Track Magnetic Tape Recorder Equivalent
Adapter Cables
Adapter Cables (Universal)
Airlock Electrical Control and Monitoring Unit
Antenna and Transmission Line C/O Set
Antenna Hats
Battery Charger
Breakout Boxes
Bridges (Multi-milliohms Range)
Brush Mark - Channel Recorder
Bus Monitor Unit
C&T Modular Index Measuring Unit
Clamp-on Ammeter with Probes
Digital Data Monitoring Unit
Digital Multimeter
Digital Theodolites
Digital Volt Meter and Fluke Meter
Electrical Patch Distribution Assembly
Electrical Testers (Rate Gyro's, Accelerometers)
Frequency Counter
Gimbal Actuator Test Set
GPC Monitoring Unit
Impedance Matching and Power Distribution Unit
Instrumentation Test Set
Interface Simulators
Mobile DMS Interface and Cable
Oscilloscope with Test Lead Pack and Probes
Patch Board (Universal)
Payload/Simulator Cargo
PCM Simulator
Phase Sequence Indicator
Portable Power Source (dc)
Resistor Pack (Load Pack)
RF Transmission Cables
RF Uplink Converter Unit
Shorting/Wrap-around Plugs
Signal/Frequency Generator
Soldering Equipment
Stray Voltage C/O Unit
TLM Test/CAL Set
Unbilical Port Breakout
Video/Audio Recorder

Mechanical Support Equipment
Alignment Equipment
Antenna Stow/Deployment Simulator
Astro Arc Welder
Brushes
Grounding Straps
Hose Clamp Pliers
Induction Blazing Equipment
Main Engine Alignment Set
Manual Valve Actuation Tool
O-Ring Removal Tool
ORU Guide Bars (Installation and Removal)
OSE Access Ladder
OSE Tool Kit
OSE Workstand
Protective Covers
RMS Checkout Test Controller
RMS Display and Control Panel C/O Unit
RMS End Effector Checkout Unit
RMS Grapple Fixture and Target
RMS Hand Controller C/O Unit
RMS Hand Controller Simulator
RMS Test C/O Equipment
RMS Wrist EXT Kit
Scrapper
Supply/Tool Tote Tray
Tank Sling
Torque Wrench/Remote Torque Wrench
TPS Tile Repair Kit

Maintenance Crew Items
Gloves ((Solvent Resistant)
Portable Vacuum Cleaner
Masks (Air Filtration)
Tape (Nylon, Masking, Teflon, Velcro)
Plastic Ties
Sealed Plastic Containers (for Fluid Collection)
Plastic Tubing
Flashlight (Handheld, Gooseneck)
Freon 12 (14-oz. Can w/Spray Nozzle)
Mirrors (Handheld)
Inspection Magnifying Glass
Zip Lock Bags (Various Sizes)

Propulsion System
Pneumatic Storage and Regulated Supply System
LOX Storage and Transfer System
LH2 Storage and Transfer System
Borescope Equipment
Engine Handling Fixture
Tank Handling Fixture
Entrapped Fluids Removal Unit
Filter/QD Assembly
Gas Analyzer
Sampling Equipment
Liquefaction System
Leak Check Equipment
ORU Mounts
Turbo Pump Lubrication Unit
Ultrasonic Extensometer
Waste Oil Collection Tank
Cover Plate Set -
- Umbilical Disconnects
- Overboard Vents
- Engine Throat Plugs
- Engine/PCA Interface
- Tank/PCA Interface

Waste Management System
Urinal Assembly Cleaning Kit
Transport Tube Cleaning Kit
WCS Checkout Unit

KSC ground processing experience has clearly demonstrated that on-orbit processing of space flight vehicles is very labor intensive. Consequently, it is absolutely essential that the design of *these vehicles, facilities, and support equipment be optimized to eliminate or reduce on-orbit operations.* EVA/telerobotic accessibility is of vital concern. Hardware desgin recommendations are provided.

These examples clearly demonstrate the importance of incorporating KSC processing experience early in the hardware design phase. In view of this, a collection of over 300 KSC "lessons learned" with applicability to on-orbit processing at SSF is included as a supplement to the GFY 89 study summary report. Also, it is strongly recommended that all future OEXP vehicle designs and mission manifests intending to utilize on-orbit assembly, refurbishment, or servicing be reviewed by KSC personnel with space vehicle flight hardware ground processing and launch operations experience.

Major study goals for GFY 90 include the incorporation of EVA and automation/robotic enhancements to the on-orbit processing flows, generation of revised "hooks and scars" for SSF evolution in time to support the rephased SSF PDR, entry of all processing flows and requirements into the VPOD data base, and support to the JSC and MSFC "Skunk Works" currently defining NASA's response to President Bush's Human Exploration Initiative.

Hardware Design Recommendations

- Design serviceable hardware for ease of EVA and/or telerobotic access
- All manipulated elements should contain integrated grapple fixtures
- Snap-in mounting of ORUs
- Built-in test equipment should be capable of automated fault detection and isolation (at least to ORU level)
- Automated umbilical mate/demate with auto-verification of mated interface
- Use quick-disconnect fluid (liquid and gas) connections for all EVA/RMS installed umbilicals, cables and lines
- Key connections and interfaces to preclude incorrect installation
- Propellant tanks, engines, and manifolds integrated on ground whenever possible
- On-board leak detection and isolation capability
- Minimize handling and bolting operations for Aerobrake assembly and replacement
- Standardize fasteners
- Launch crew modules outfitted with equipment and consumables
- Components should be certified for multi-mission operating life between refurbishments tasks
- Periodic maintenance and servicing requirements should be staggered in order to equalize workload from mission to mission
- Vertical integration of cargo shroud (as opposed to a payload bay configuration) will simplify cargo processing and allow larger and heavier payloads

ADVANCED ROBOTICS FOR IN-SPACE VEHICLE PROCESSING

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ABSTRACT

An analysis of spaceborne vehicle processing is described. Generic crew-EVA tasks are presented for a specific vehicle, the orbital maneuvering vehicle (OMV), with general implications to other on-orbit vehicles. The OMV is examined with respect to both servicing and maintenance. Crew-EVA activities are presented by task and mapped to a common set of generic crew-EVA primitives to identify high-demand areas for telerobot services. Similarly, a set of telerobot primitives is presented that can be used to model telerobot actions for alternative telerobot reference configurations. The telerobot primitives are tied to technologies and used for composing telerobot operations for an automated refueling scenario. Telerobotics technology issues and design accommodation guidelines (hooks and scars) for the Space Station *Freedom* are described.

Title

INTRODUCTION

The development of Space Station *Freedom* involves a multiplicity of large-scale space systems and a number of space vehicles are required to support a broad variety of station operations. Most prominent are the Orbital Maneuvering Vehicle (OMV) for near-Earth operations and the Space Transfer Vehicle (STV) for near-Earth and Earth-Lunar operations. Because the station and these vehicles are at various stages of development, there is a twofold interest in examining the potential for applications of robotics technology to vehicle processing. The first interest is in understanding the functional operations to be performed in the future station environment. The second interest is in understanding the potential design accommodations that robotics might require of the station--the so-called hooks (software accommodations) and scars (hardware accommodations) needed to ensure that future technology developments can be accommodated by Space Station *Freedom*.

ANALYSIS OF VEHICLE PROCESSING OPERATIONS

Space operations will involve large quantities of crew-EVA to perform a variety of tasks such as assembly, servicing, maintenance, and inspection. The requirements for housekeeping and servicing are typically stated in terms of budgeted crew-EVA hours for the tasks involved. Simply stated, EVA requirements are the "work" that needs to be performed to keep the spacecraft system in operational order and perform its mission(s). The task analysis seeks to optimize available EVA excursion time by planning in detail, the primitive subtasks to be performed. The term used for these human-performed primitive subtasks is "crew-EVA primitives." In a similar fashion, a set of "telerobot" primitives is defined for machine performance of tasks. The telerobot primitives are linked to technologies and assembled into procedures for performance of telerobot operations. The study establishes a common language to better understand the relationship between generic crew-EVA tasks and potential telerobot performance of such activities.

Figure 1

EVOLUTION PLANNING FOR ADVANCED DEVELOPMENT

OBJECTIVE

DEVELOP AN EVOLUTION PLANNING METHODOLOGY THAT MAPS EVA REQUIREMENTS INTO AN A&R TECHNOLOGY DEVELOPMENT PLAN

SELECT REFERENCE MISSIONS (On-Orbit Vehicle Proc.)
- OMV Servicing (incl. refueling & Inspection)
- OMV Maintenance (ORU Changeout)

↓

DEFINE & SCRIPT REFERENCE SCENARIOS
& DEVELOP MISSION TIMELINES

Develop EVA Primitives →

↓

TRANSLATE ACTIVITIES INTO EVA PRIMITIVES
& IDENTIFY CANDIDATE ACTIVITIES FOR EVA DISPLACEMENT

Develop Tele-Robot Primitives →

↓

TRANSLATE EVA PRIMITIVES INTO TELE-ROBOTIC PRIMITIVES

↓

DETERMINE A&R TECHNOLOGY DEVELOPMENT REQUIREMENTS

↙ ↘

DEFINE STATION HOOKS & SCARS TO
FACILITATE A&R IMPLEMENTATION

INTEGRATE RESULTS INTO A PLAN
FOR A&R TECHNOLOGY DEVELOPMENT

METHODOLOGY

The starting point for development of the study methodology was to collect empirical descriptions of the performance of a number of crew-EVA tasks, including "timeline data" that records the duration of successive segments of each task from Space Shuttle-based EVAs. The analysis proceeds hierarchically from projected task demands for user payloads and station and vehicle servicing and maintenance to the definition of generic crew-EVA tasks, activities, and primitives. A set of crew-EVA primitives are defined and each EVA task is segmented into a setup, kernel, and closeout activities. The crew-EVA primitive set is used to calibrate a generic model for estimating the EVA impacts of the given task. This study developed the following generic crew-EVA tasks at the task, activity, and primitive levels:

SSF Housekeeping

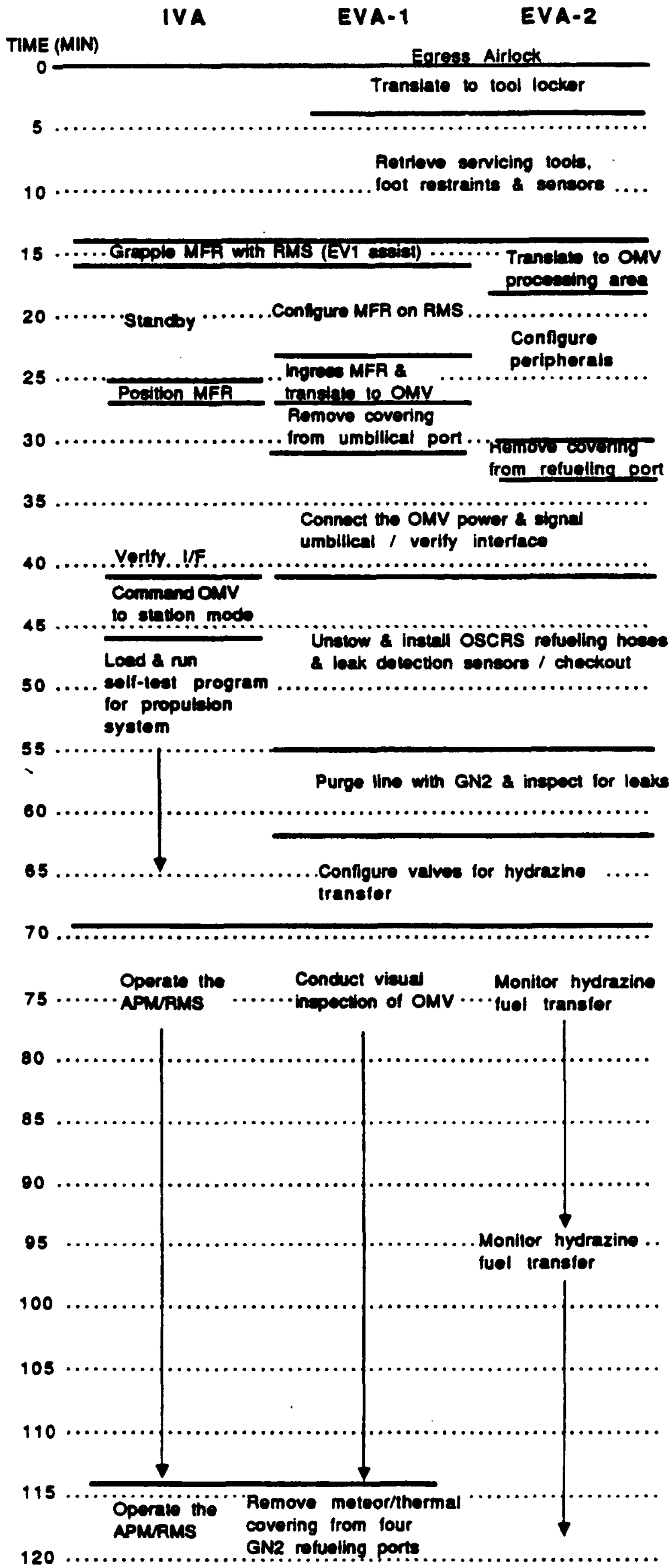
- Truss Assembly (SSF)
- ORU Changeout (SSF)
- Payload Changeout
- Servicing/Repair

Vehicle Processing (OMV)

- Truss Assembly (Planetary Vehicle)
- ORU Changeout (on OMV)
- Servicing (OMV refueling)
- Payload Integration

Figure 2

STATION-BASED OMV SERVICING TIMELINE



METHODOLOGY AND RESULTS

This figure illustrates the analysis process for a portion of the OMV servicing timeline by aligning the crew-EVA and equivalent telerobot-EVA primitives on the same timescale. Because of limitations inherent to the machine-performed task, the quantity of assumptions, descriptions, and definitions is inherently larger. The objective of this process is to explicitly map the telerobot operational timeline in order to surface technology and operational limits. The model used to estimate the generic crew-EVA times for each task, activity, and primitive is:

$$X^t_{S_j} + \sum_{i=1}^{4} X^t_{K_{ij}} + X^t_{T_j} = Y^t_j \quad (j = 1, \ldots N)$$

where:

$X^t_{S_j}$ $\equiv$ Setup time (hours) for activity j within time period t.

$X^t_{K_{ij}}$ $\equiv$ Task kernel time (hours) for activity j, category i, and time interval t.

$X^t_{T_j}$ $\equiv$ Teardown time (hours) for activity j within time period t.

Y^t_j $\equiv$ Total time for crew-EVA excursion number j within time interval t.

Note that the actual times, $X^t_{(*)}$, are sums of the product of task primitive standard times and frequency of occurrence:

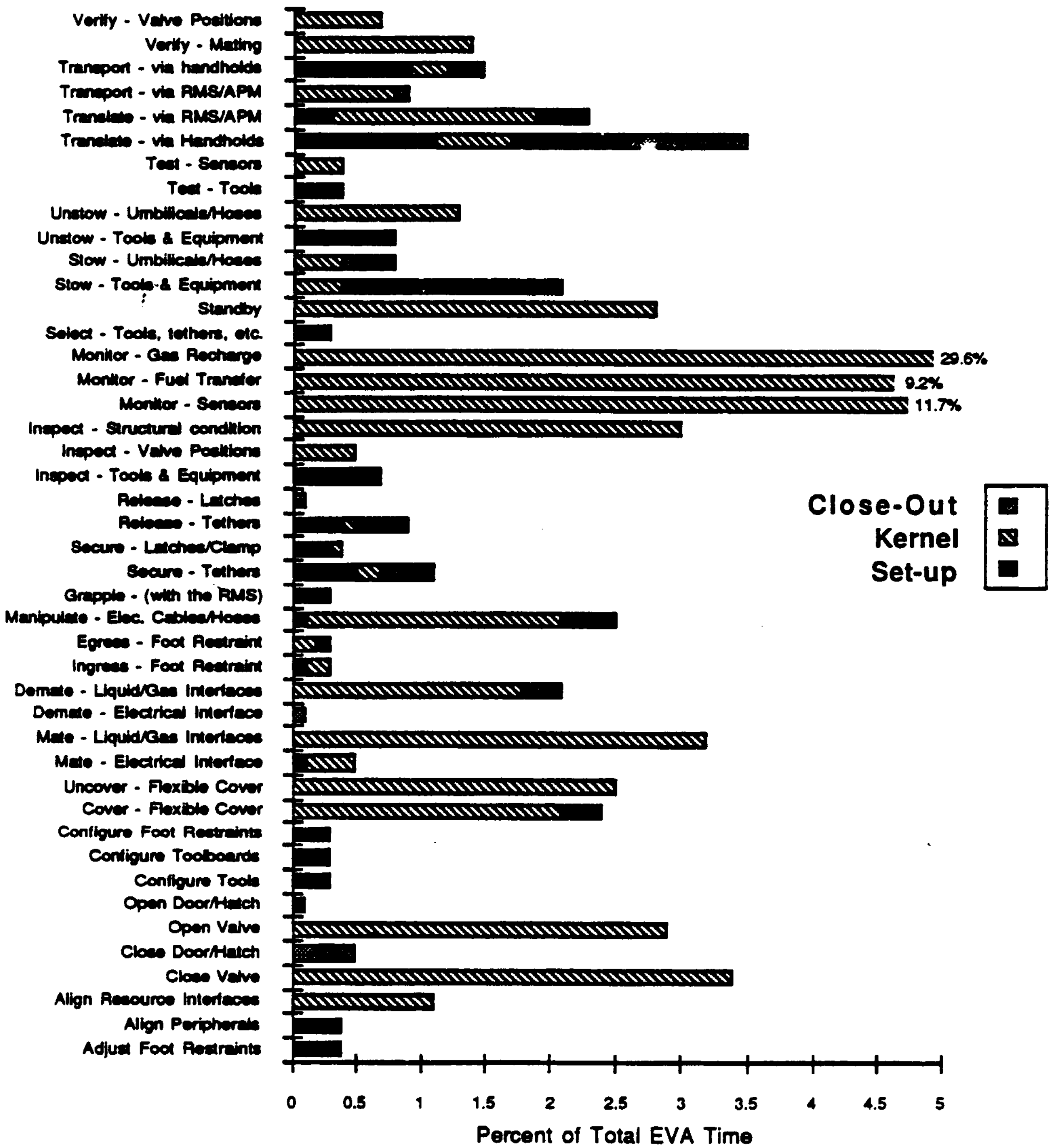
$$X^t_{S_j} = \sum_{m=1}^{n} \pi_m \cdot f_{S_m} \qquad X^t_{K_j} = \sum_{m=1}^{n} \pi_m \cdot f_{K_m} \qquad X^t_{T_j} = \sum_{m=1}^{n} \pi_m \cdot f_{T_m}$$

where, n = the total number of task primitives
π_m = standard time to perform task primitive m (minutes).
$f_{(*)m}$ = frequency of task primitive m for $* =$ S, K, or T.

By dividing generic task times into standardized times multiplied by frequency, a *standardized* timeline is obtained for each of the generic crew-EVA tasks. The standardized times are a powerful result that can be extended to other tasks. The problem of calculating task times is thus transformed from estimating highly variable task-specific times to one of estimating the number of times each generic task is to be performed.

Figure 3

OMV SERVICING EVA PRIMITIVE SUMMARY



RESULTS (CONTINUED)

Because there are empirical data on which to standardize the generic crew-EVA activities and primitives, time estimates for each of the generic tasks is estimated probabilistically using the above model. This figure illustrates the proportion of time spent performing each crew-EVA primitive as a fraction of the total EVA excursion time. Such analyses focus attention on promising areas for telerobot operations such as translation, monitoring (inspection), and selected opening and closing manipulations.

Figure 4

SET-UP OMV SERVICING ACTIVITIES

1. Translate to Tool Locker

EVA Primitive	Equivalent Telerobot Primitive(s)
Translate (via Handholds)	Select mode, Configure, Acquire, Range,Translate

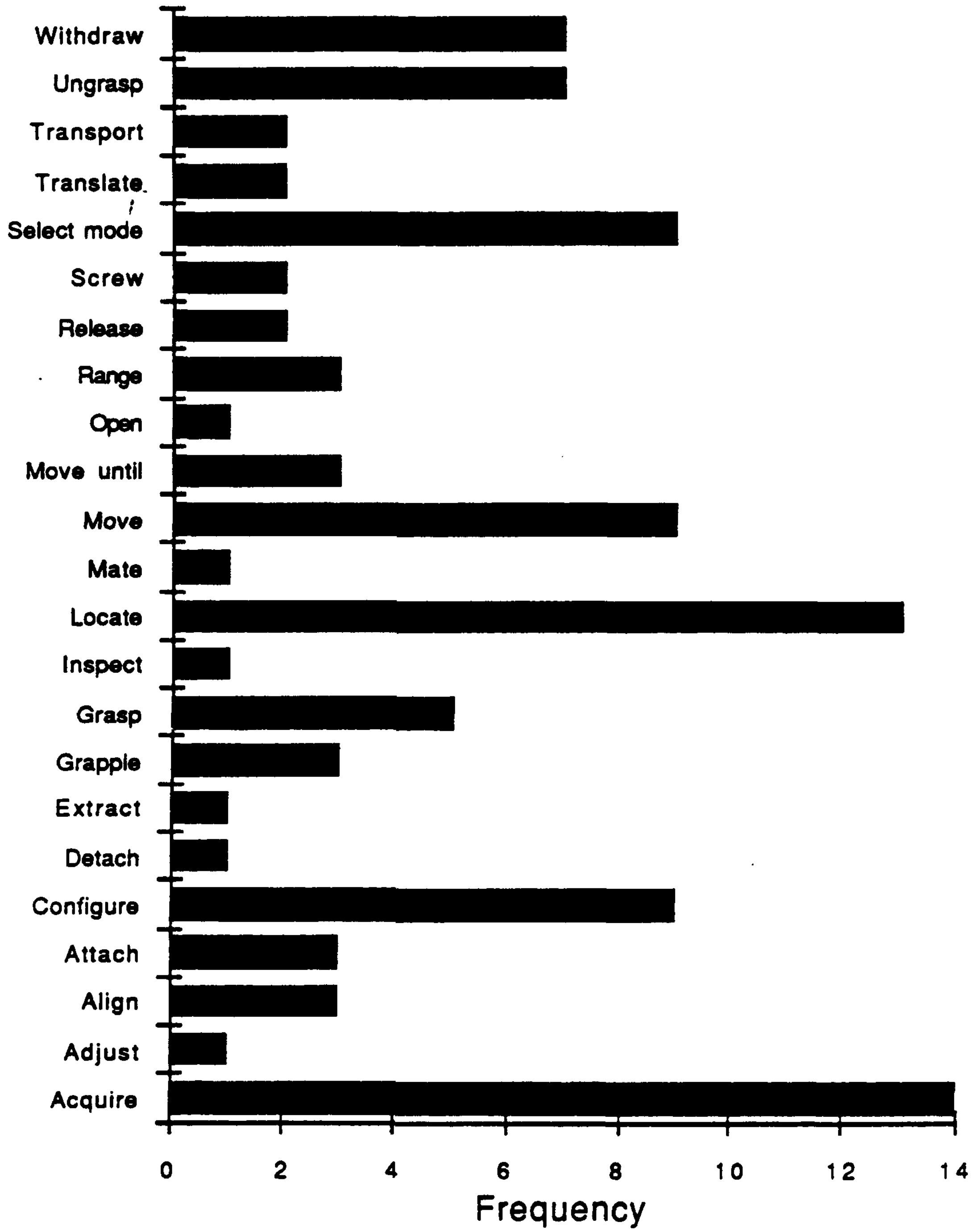
2. Retrieve Servicing Tools, Foot Restraints, & Peripherals

EVA Primitive	Equivalent Telerobot Primitive(s)
Secure (tethers)	Select Mode, Configure, Acquire (grapple fixture), Locate, Move, Grapple It is assumed that grapple fixtures will be required at the tool site to stabilize the robot during tool selection. This is equivalent to tethering, used by EVA crewmembers to stabilize themselves.
Open (door)	Acquire(door handle), Locate, Move, Grasp, Open, Ungrasp It is assumed that tools will be stored inside a tool cabinet which is accessed by means of a hinged door.
Select (tools, periph.)	Acquire (tools, periph.), Locate, This activity occurs in conjunction with unstowing. It addresses the time element involved in recognizing the tool(s) being searched for. The robot will recognize the tool by means of matching the sensed image with an image in the robots tool library.
Unstow (tools, periph.)	Move, Grasp, Detach, Extract (from tool cabinet) Tools are assumed to be secured within the tool cabinet either by means of a snap in/out arrangement, or by means of a velcro interface.
Configure (toolboard)	Acquire (toolboard), Locate, Attach (tools to tool-board or EMU) This involves attaching tools & equipment to the EMU or toolboard by means of short tethers or velcro.
Inspect (periph.)	Inspect
Release (tether)	Release (grapple fixture), Withdraw EVA crewmembers will untether to free themselves from restraint. The robot will merely release the grapple fixture.

This figure illustrates the frequency of telerobot primitives for the set-up phase of the generic OMV servicing task. Because there is little, if any, analogous timeline data for telerobot operations, the frequency of primitive occurrence is used as a guidepost to promising telerobot primitives for advanced development. Telerobot primitives with high frequencies may be the initial candidates for autonomous operation, however, as specific time estimates for telerobot performance become available from laboratories and test flight measurements, improved projections of high-value functions for autonomous operations will be possible.

Figure 5

ROBOT PRIMITIVE SUMMARY
OMV SERVICING SET-UP PHASE



CONCLUSIONS: RECOMMENDED ROBOT DESIGN FEATURES

There are a number of design features that, if incorporated into the station design, will enhance considerably, the ability of the station to accommodate new robotic technologies in the future. These conclusions are an attempt to characterize the major impact areas for robot hooks and scars.

Figure 6

RECOMMENDED ROBOTIC DESIGN FEATURES FOR SPACE STATION FREEDOM TO SUPPORT A&R

- Autonomous translation of mobile robotic devices and supporting structures (e.g., MSC, MRMS) may require position location sensors embedded in truss members, laser ranging devices on the vehicle and at locations on the station, or other built-in aids to tracking precise location over time.

- Payload retention interfaces used on STS, SIA, OMV, servicing facility, etc, should be standardized to minimize on-orbit reconfiguration req'ts.

- Remotely operated latches with manual over-ride should be used for payload retention to facilitate robotics. Manual overrides should be robot operable.

- Where built-in automatic umbilical mating/demating devices are not employed, umbilicals should be robot compatible and located where adequate space is available for access and manipulation, and robot retention fixtures should be availible for anchoring the robot.

- Peripherals (lights, cameras) and foot restraints should be compatible for robot manipulation and installation as a PMC Phase I capability.

- Power/data umbilical mating between the SSF OMV berthing facility and the OMV should be enabled to be performed remotely to reduce EVA.

- Data storage & processing requirements increase significantly with A&R evolution (i.e., worksite modeling, planning systems, system test/monitoring/fault diagnosis, etc). Hardware & software should be expandable, modifiable (flexible).

- Since flexible covers & tape are difficult for robots to handle, making thermal covers an integral ORU component or designing the cover for easy removal & installation will facilitate robotic efficiency.

- Design robot compatibility into ORU & tool storage
  - Easy access by RMS & robot
  - Docking points for robot stabilization
  - Visual alignment guides on ORUs, tools, & storage facilities to reduce precision requirements & force sensing complexity
  - Record of removal and replacement (inventory control)

- EVA hand & power tools should be robot compatibile, at least to the level of enabling human or robotic stowing or retrieval (robots may work more effectively with their own tools).

CONCLUSIONS: RECOMMENDED OMV DESIGN FEATURES FOR ROBOTICS

There are also a number of design features that would enhance the functionality of performing vehicle servicing robotically. This figure summarizes such features.

Figure 7

RECOMMENDED ROBOTIC DESIGN FEATURES FOR SPACE STATION FREEDOM TO SUPPORT A&R

ON-ORBIT OMV REFUELING

On-orbit transfer of hazardous fluids from one tank to another must be accomplished using remotely operated equipment with manual over-rides.

- Scar the OMV to facilitate remote/robotic refueling:
  - Manifold the cold gas system to provide single point recharge capability
  - Co-locate hydrazine, cold gas, & electrical connectors (accessible by an automatic coupling device)
  - Use standard interfaces for fluid connectors, plugs, etc.
  - Design protective/thermal covers on OMV refueling & electrical ports to be retracted automatically by the umbilical coupling device
  - Scar the OMV propulsion module for automatic on-orbit refueling (i.e., colocated refueling ports designed for automatic umbilical mating)

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

SPACE STATION EVOLUTION SYMPOSIUM
FEBRUARY 8, 1990
JOHNSON SPACE CENTER

MCDONNELL DOUGLAS SPACE SYSTEMS CO. - KSC DIVISION
DATA MANAGEMENT SYSTEMS - ADVANCED TECHNOLOGIES

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

STUDY OBJECTIVES

The purpose of the ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING study is to determine the requirements to support automated processing and assure that the SSF Phase I design can be evolved to provide the required systems. The processing tasks considered are Exploration mission vehicle systems on-board a predicted Phase II Space Station. Automation, in this study refers to the replacement of all potential human tasks which includes both physical and cognitive tasks. Thus, both robotic manipulator and artificial intelligence technologies have been considered. The specific objectives required to meet these overall goals are described below:

Evaluate on-orbit vehicle processing tasks using a single hierarchy of developed criteria to determine which tasks are suitable for automation. The criteria include expected benefits, impacts on the station, task difficultly for humans, task complexity and technology capability.

Determine the effect of automation on the vehicle processing flows, including the overall task times and EVA shifts required based on complete automation analysis. Analysis includes detailed descriptions of all manual and automated tasks and the equipment and resources required for automation.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

STUDY OBJECTIVES

- ASSURE THAT THE PHASE I STATION CAN BE EVOLVED TO SUPPORT AUTOMATED PROCESSING SYSTEMS
- DETERMINE APPROPRIATE IN-SPACE VEHICLE PROCESSING TASKS TO BE AUTOMATED TO ENHANCE OR ENABLE NODE CAPABILITY
- PERFORM COMPLETE AUTOMATION ANALYSIS FOR SELECTED OEXP MISSIONS
- ASSESS THE EFFECTS OF AUTOMATION ON PROCESSING FLOWS
- DETERMINE SPACE STATION HOOKS AND SCARS REQUIRED TO SUPPORT AUTOMATION
- DEVELOP EXPLORATION VEHICLE DESIGN AND PROCESSING TECHNIQUES WHICH ENHANCE OR ENABLE AUTOMATION

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

STUDY APPROACH

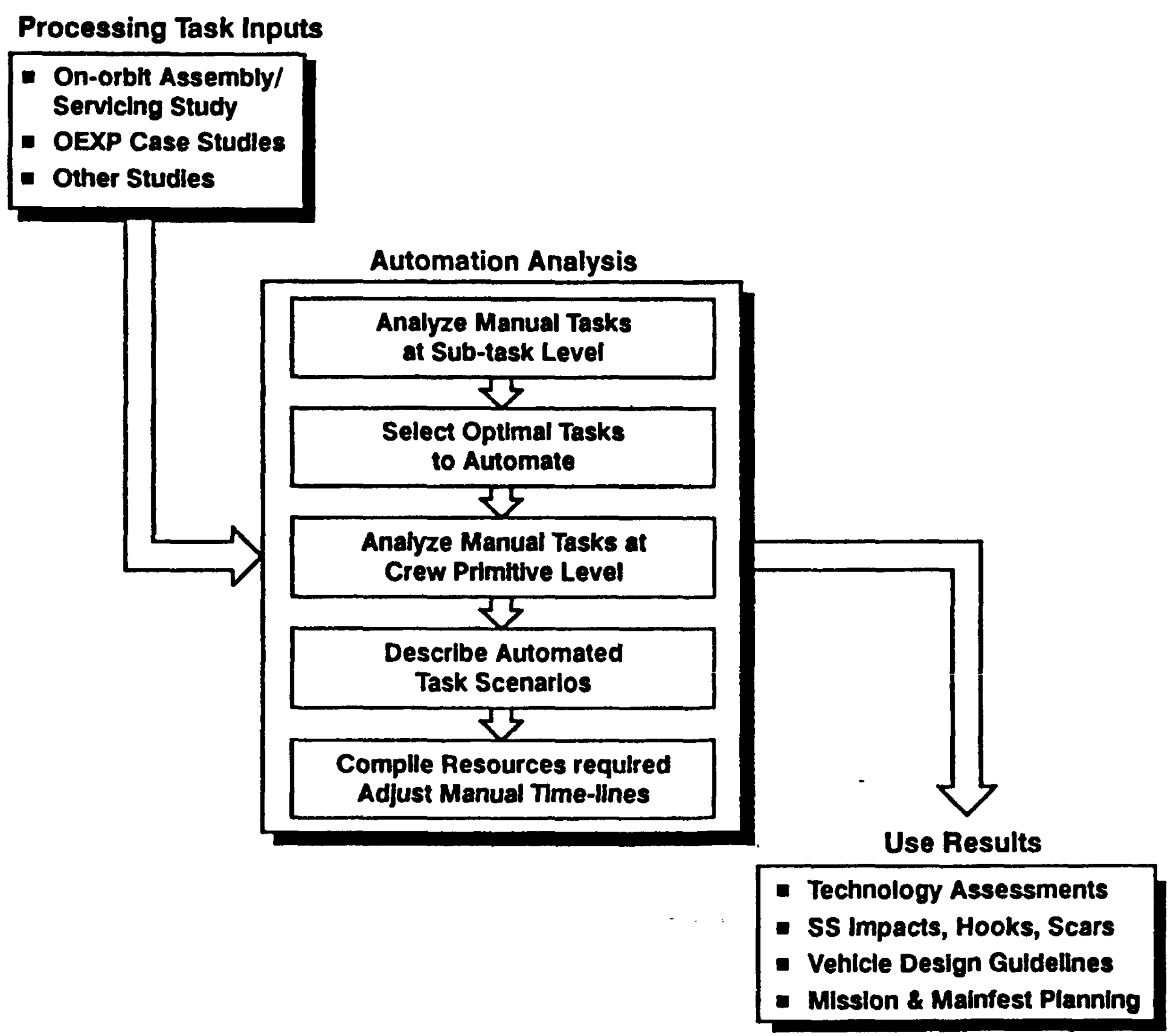
To meet the objectives described, an approach was developed utilizing a number of tools and techniques. A cohesive step by step process to perform automation analysis for exploratory missions has been developed. The process begins with the input of the required on-orbit vehicle process flows. The tasks are described at a sub-task level which represents the collection of a number of actual EVA/IVA functions to be performed. The tasks are next ranked for automation potential based on a evaluation methodology and a set of criteria. The highest ranking sub-tasks must then be described at a highly detailed level (EVA/IVA actions or primitives) in order to determine equivalent automated process scenarios. The resulting automated processes are then evaluated for elapsed time by applying automation versus human ratios for typical tasks to the manual timelines. The results are then used to predict requirements and performs a number of integrated analyses.

Data and information transfer and joint analysis tool development has been carried it with a wide number of study groups and NASA offices. The four primary study interfaces include:

On-Orbit Assembly/Servicing Task Definition Study -	Processing tasks
Advanced Robotics for In-Space Vehicle Processing Study -	Methodology development
Space Station Strategic Program Division (ST) -	Study direction
NASA Langley Research Center Space Station Office -	Study direction

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

STUDY APPROACH



ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

TOOLS DEVELOPED

A number of tools and methodologies have been developed to support the overall automation analysis approach. The most important of these has been the development of a set of manual and automation Primitive Functions and the required syntax. These functions represent all potential tasks and capabilities possible for both EVA and IVA astronauts (manual) or automation systems (manipulators and AI computers). The primitive functions represent a standard and uniform method of describing and analyzing any potential processing task. A task evaluation criteria and methodology has also been developed to rank the various processing sub-tasks based on their automation potential. A methodology has also been developed to estimate overall automated process flow times. This is based on a set of generic time ratios between each required manual primitive and a set of automation primitives which duplicate the manual task.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

TOOLS DEVELOPED

- COMPLETE SET OF MANUAL AND AUTOMATION PRIMITIVE TASK FUNCTIONS AND SYNTAX (JOINT EFFORT WITH JPL ROBOTICS STUDY)
- TASK SELECTION CRITERIA AND METHODOLOGY TO RANK TASKS FOR AUTOMATION POTENTIAL
- AUTOMATED PROCESS TIME ESTIMATION METHODOLOGY

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

MANUAL PRIMITIVES

Manual primitives represent a standard set of detailed tasks which an astronaut can perform either as Extra Vehicular Activity (EVA) or Intra Vehicular Activity (IVA). In essence the primitives represent a common language to describe manual EVA and IVA tasks. This study team, in conjunction with the NASA-JPL robotics study team, has developed an initial set of EVA and IVA primitive task descriptions which will define the standard tasks and capabilities of Space Station crew members. The primitives are listed on the facing charts. Experienced operational personnel at JSC have examined these and will in the future aid in predicting the associated task times. The study team is now cooperating with a wide community of groups in need of representing Manual and Automated task flows. These groups include the Flight Operations Division and Mission Planning Division at JSC ant the Flight Telerobotic Servicer Office.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

EVA Task Primitives

M1.1 ACTIVATE (ACTIVATE system)
Def. - Change system state from inoperative to operative.

M1.1.1 ACTIVATE MSC
M1.1.2 ACTIVATE Battery Charging
M1.1.3 ACTIVATE Fluid Transfer
M1.1.4 ACTIVATE RMS/APM

M1.2 ADJUST/ALIGN (ADJUST object)
Def. - Position object/control with respect to setting/features.

M1.2.1 ADJUST/ALIGN Knob or Valve
M1.2.2 ADJUST/ALIGN Element
M1.2.3 ADJUST/ALIGN Peripherals
M1.2.4 ADJUST/ALIGN Foot Restraints
M1.2.5 ADJUST/ALIGN Payload/ORU Components
M1.2.6 ADJUST/ALIGN Male/female Resource I/F

M1.3 CLEAN (CLEAN object)
Def. - Remove unwanted contaminants or impurities from object

M1.3.1 CLEAN lens cover
M1.3.2 CLEAN electrical connector
M1.3.3 CLEAN EVA suit

M1.4 CLOSE (CLOSE object)
Def. - Obstruct opening, conduit, etc. with object

M1.4.1 CLOSE Valve
M1.4.2 CLOSE Door/Hatch

M1.5 CONFIGURE (CONFIGURE {object})
Def. - Arrange objects/system into predefined relations to accomplish a specific task.

M1.5.1 CONFIGURE Extravehicular Excursion Unit (EEU)
M1.5.2 CONFIGURE Tools, tethers, etc.
M1.5.3 CONFIGURE Foot Restraint

M1.6 COVER (COVER *with* type cover)
Def. - Place and fasten barrier over/on object for protection from environment.

M1.6.1 COVER with snap-on cover
M1.6.2 COVER with bolted cover
M1.6.3 COVER with screwed cover
M1.6.4 COVER with velcro cover

M1.7 DEMATE/DISCONNECT (DEMATE/DISCONNECT joint|{objects})
Def. - Separate objects joined to each other directly or by connection joint.

M1.7.1 DEMATE/DISCONNECT Two loose ends
M1.7.2 DEMATE/DISCONNECT Mechanical latches
M1.7.3 DEMATE/DISCONNECT Threaded interfaces
M1.7.4 DEMATE/DISCONNECT Electrical interface
M1.7.5 DEMATE/DISCONNECT Captive Pin
M1.7.6 DEMATE/DISCONNECT ORU/Payload Interface
M1.7.7 DEMATE/DISCONNECT Liquid/Gas Interface

M1.8 EGRESS (EGRESS object)
Def. - Go out or exit all or part of body from enclosure.

M1.8.1 EGRESS MMU
M1.8.2 EGRESS Foot Restraint
M1.8.3 EGRESS Airlock

M1.9 GRAPPLE (GRAPPLE object *with* method)
Def. - To grasp and secure hold on object

1.9.1 GRAPPLE Stationary Object with RMS
M1.9.2 GRAPPLE Moving Object with RMS
M1.9.3 GRAPPLE Stationary Object with EVA
M1.9.4 GRAPPLE Moving Object with EVA

M1.10 INGRESS (INGRESS object)
Def. - Insert all or part of body into enclosure or holding device.

M1.10.1 INGRESS MMU
M1.10.2 INGRESS Foot Restraint
M1.10.3 INGRESS Airlock

M1.11 INSPECT (INSPECT object *for* purpose)
Def. - Examine object noting condition in relation to set of expected characteristics.

M1.11.1 INSPECT Structure for Damage/Failure
M1.11.2 INSPECT Equipment for Damage/Failure
M1.11.3 INSPECT Equipment for Latched/Stowed Configuration
M1.11.4 INSPECT Equipment for Control Position
M1.11.5 INSPECT Connection Interface
M1.11.6 INSPECT Object Recognition

M1.12 MANEUVER (MANEUVER object *with* method)
Def. - Move object from one position to another

M1.12.1 MANEUVER Peripherals with RMS
M1.12.2 MANEUVER ORU/Payload with RMS
M1.12.3 MANEUVER Spacecraft(OMV/STV) with RMS
M1.12.4 MANEUVER Peripherals with EVA
M1.12.5 MANEUVER ORU/Payload with EVA
M1.12.6 MANEUVER Spacecraft(OMV/STV) with EVA

M1.13 MANIPULATE (MANIPULATE object)
Def. - Handle flexible material, e.g., fold, roll, squeeze.

M1.13.1 MANIPULATE Cables, Hoses
M1.13.2 MANIPULATE Flexible Cover

M1.14 MATE/CONNECT (CONNECT joint|{objects})
Def. - Join or fit associated parts.

M1.14.1 MATE/CONNECT Two loose ends
M1.14.2 MATE/CONNECT Mechanical latches
M1.14.3 MATE/CONNECT Threaded interfaces
M1.14.4 MATE/CONNECT Electrical Interface
M1.14.5 MATE/CONNECT Captive Pin
M1.14.6 MATE/CONNECT ORU/Payload Interface
M1.14.7 MATE/CONNECT Liquid/Gas Interface

M1.15 MEASURE (MEASURE parameter)
Def. - Determine parameter values using reference scale.

M1.15.1 MEASURE Length
M1.15.2 MEASURE Deflection
M1.15.3 MEASURE Inertia

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

EVA Task Primitives (cont'd)

M1.16 MONITOR (MONITOR {object|process})
Def. - Observe to detect changes in condition in a system.

- M1.16.1 MONITOR Sensor (temp., pressure, flow, current, etc)
- M1.16.2 MONITOR System
- M1.16.3 MONITOR Battery Charging
- M1.16.4 MONITOR Fluid Transfer
- M1.16.5 MONITOR Gas transfer
- M1.16.6 MONITOR RMS

M1.17 OPEN (OPEN object)
Def. - Remove obstruction from entrance, conduit, etc.

- M1.17.1 OPEN Valve
- M1.17.2 OPEN Door/Latch

M1.18 OPERATE (OPERATE system)
Def. - To control or supervise a device or system.

- M1.18.1 OPERATE RMS
- M1.18.2 OPERATE Power Tools
- M1.18.3 OPERATE Control System

M1.19 RECORD (RECORD process|event *via* method)
Def. - Store information for later recall.

- M1.19.1 RECORD Videotape
- M1.19.2 RECORD Photograph
- M1.19.3 RECORD Computer memory/mass storage

M1.20 RELEASE (RELEASE {object})
Def. - Free objects from restraints.

- M1.20.1 RELEASE Tether
- M1.20.2 RELEASE Velcro Interface
- M1.20.3 RELEASE Latches

M1.21 ROTATE (ROTATE object *with* method)
Def. - Turn object through angular arc.

- M1.21.1 Peripherals with RMS
- M1.21.2 ORU/Payload with RMS
- M1.21.3 Spacecraft(OMV/STV) with RMS
- M1.21.4 Peripherals with EVA
- M1.21.5 ORU/Payload with EVA
- M1.21.6 Spacecraft(OMV/STV) with EVA

M1.22 SECURE/ATTACH (ATTACH {object})
Def. - Fasten and object to restrain it.

- M1.22.1 SECURE Velcro Interface
- M1.22.2 SECURE Tether
- M1.22.3 SECURE Latches

M1.23 SELECT (SELECT {object})
Def. - Choose among several alternative options or objects.

- M1.23.1 SELECT Tools, tethers, etc.
- M1.23.2 SELECT Menu Option

M1.24 SHUTDOWN (SHUTDOWN system)
Def. - To change system state to inoperative.

- M1.24.1 SHUTDOWN MSC
- M1.24.2 SHUTDOWN Battery Charging
- M1.24.3 SHUTDOWN Fluid Transfer
- M1.24.4 SHUTDOWN RMS/APM

M1.25 STABILIZE (STABILIZE system|object)
Def. - To dampen or eliminate undesirable variations in a system.

- M1.25.1 STABILIZE Payload/ORU
- M1.25.2 STABILIZE Process

M1.26 STAND-BY (STAND-BY)
Def. - Wait, inactively but ready to resume upon command "Take no arguments".

- M1.26.1 STAND-BY MSC
- M1.26.2 STAND-BY Battery Charging
- M1.26.3 STAND-BY Fluid Transfer
- M1.26.4 STAND-BY RMS/APM

M1.27 STOW (STOW {object})
Def. - Place and secure objects in storage

- M1.27.1 STOW Tools, tethers, etc.
- M1.27.2 STOW Cables,hoses
- M1.27.3 STOW Umbilicals/hoses
- M1.27.4 STOW Payload/ORU

M1.28 TEST (TEST for condition)
Def. - Evaluate physical and functional characteristics by executing a sequence of operations and comparing results to expected results.

- M1.28.1 TEST For Continuity
- M1.28.2 TEST For Leaks
- M1.28.3 TEST For Cleanliness
- M1.28.4 TEST For Sensor Accuracy

M1.29 TRANSPORT (TRANSPORT object *via* method)
Def. - Move object from one position to another.

- M1.29.1 TRANSPORT via EVA Crew member
- M1.29.2 TRANSPORT via RMS/APM
- M1.29.3 TRANSPORT via EEU
- M1.29.4 TRANSPORT via MSC
- M1.29.5 TRANSPORT via Unassisted

M1.30 UNCOVER (UNCOVER *with* type cover)
Def. - Unfasten and remove protective envelope from an object

- M1.30.1 UNCOVER snap-on cover
- M1.30.2 UNCOVER screwed cover

M1.31 UNSTOW (UNSTOW {object})
Def. - Remove objects from storage.

- M1.31.1 UNSTOW Tools, tethers, etc.
- M1.31.2 UNSTOW Cables,hoses
- M1.31.3 UNSTOW Umbilicals/hoses
- M1.31.4 UNSTOW Payload/ORU

M1.32 VERIFY (VERIFY condition)
Def. - Confirm a state/condition of object/system.

- M1.32.1 VERIFY Data Analysis/Fault Diagnosis
- M1.32.2 VERIFY Equipment Latched or Mated/ Positioned Stowed
- M1.32.3 VERIFY Test/Checkout/Calibrate

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

AUTOMATION PRIMITIVES

The concept of primitive or generic functions is equally valid for automation equipment such as robotic manipulators and intelligent computer systems. In fact, any piece of automated equipment, when operational, must have a well defined set of operations and commands for control purposes. Thus a set of automation primitive tasks for physical manipulation and human-like cognitive operations has also been developed. Again, this effort was performed in conjunction with the JPL robotics study team. All attempts have been made to develop, and use a set of common primitive tasks accepted by the entire aerospace community. The automation primitives are listed on the facing charts.

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

Physical Automation Task Primitives

1.1 ACTIVATE (ACTIVATE System/Process)
Def. - To start or turn-on a System or Process

- 1.1.1 ACTIVATE Pump
- 1.1.2 ACTIVATE Camera

1.2 DE-ACTIVATE (DE-ACTIVATE System)
Def. - To de-energize, stop or turn-off a System or Process.

- 1.2.1 DE-ACTIVATE Pump
- 1.2.2 DE-ACTIVATE Camera

1.3 ADJUST (ADJUST Device)
Def. - Arrange, calibrate, or cause movement of a physically constrained Device.

- 1.3.1 ADJUST Mirror
- 1.3.2 ADJUST Test Equipment

1.4 FASTEN (FASTEN Object with Device)
Def. - To bind, clasp an Object by using a Device or Tool or activating a connecting system.

- 1.4.1 FASTEN Bolt
- 1.4.2 FASTEN Connector

1.5 UN-FASTEN (UN-FASTEN Object with Device)
Def. - To unbind, unclasp or loosen an Object by using a Device or Tool.

- 1.5.1 UN-FASTEN Bolt with Tool
- 1.5.2 UN-FASTEN Connector with Tool

1.6 GRASP (GRASP Object with Device)
Def. - To grasp, grapple or grip an Object using a particular Device so the object becomes attached to the device.

- 1.6.1 GRASP Element
- 1.6.2 GRASP Tool

1.7 RELEASE (RELEASE Object from Device)
Def. - To cause a Device or Fixture to un-grasp, release or free an Object

- 1.7.1 RELEASE Element
- 1.7.2 RELEASE Tool

1.8 INSERT (INSERT Object in Device)
Def. - To place an Object in a Device or receptacle, usually associated with mating or connecting two objects.

- 1.8.1 INSERT Tool in Magazine
- 1.8.2 INSERT Hose in Connector

1.9 INSPECT (INSPECT Object for Circumstance)
Def. - To examine, check, observe an Object(s) for a particular set of Circumstances or anomalies. Typically requires the inspection sensor to be maneuvered about the object with a manipulator.

- 1.9.1 INSPECT Element for Damage

1.10 MOVE (MOVE Device to Location)
Def. - To change the configuration of a Device to meet a specified Location which includes both the required position and orientation of the Device. Typically describes manipulation motions.

- 1.10.1 MOVE Manipulator to Flex Hose
- 1.10.2 MOVE MSC to Work Stand

1.11 FINE POSITION (FINE POSITION Object to Reference)
Def. - To make small changes of the position or orientation of an Object based on some Reference command using some predefined device.

- 1.11.1 FINE POSITION Hose to Connector
- 1.11.2 FINE POSITION Gripper to Valve

1.12 GROSS POSITION (GROSS POSITION Object to Location)
Def. - To move an Object with some predefined device to a particular Location which specifies both position and orientation of the object

- 1.12.1 GROSS POSITION Tool to Magazine
- 1.12.2 GROSS POSITION Element
- 1.12.3 GROSS POSITION Hose to Connector

1.13 TRACK (TRACK Object with Device)
Def. - To follow an Object with a Device. This is different than MOVE in that the motion of the device is not predetermined but is the result of the object which it is tracking.

- 1.13.1 TRACK EVA

1.14 OPEN (OPEN Object with Device)
Def. - To unblock or uncover an Object with a particular Device.

- 1.14.1 OPEN Valve
- 1.14.2 OPEN Door

1.15 CLOSE (CLOSE Object with Device)
Def. - To block, cover or shut an Object such as a door or hatch with a particular Device.

- 1.15.1 CLOSE Valve
- 1.15.2 CLOSE Door

1.16 REPLACE (REPLACE Object in Device)
Def. - To place an Object back in its original storage location or Device. This term is used to describe

- 1.16.1 REPLACE Tool in Magazine
- 1.16.2 REPLACE Tool in Tool Board

1.17 REMOVE (REMOVE Object from Device)
Def. - To take an Object out of its current storage Device or location.

- 1.17.1 REMOVE Hose from Connector
- 1.17.2 REMOVE Bolt from Magazine

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

Cognitive Automation Task Primitives

2.1 ANALYZE (ANALYZE Data Type)
Def. - To change the form of Data/information so as to reduce and interpret.

- 2.1.1 ANALYZE Images
- 2.1.2 ANALYZE Instrument Data

2.2 DIAGNOSE (DIAGNOSE Data/System)
Def. - To assess, examine or test Data or System.

- 2.2.1 DIAGNOSE Image Anomalies

2.3 MONITOR (MONITOR System/Process for Circumstance)
Def. - To observe or oversee a System or Process and *acquire data or information for further analysis.*

- 2.3.1 MONITOR Fluid Transfer
- 2.3.2 MONITOR Battery Charge

2.4 PLAN (PLAN Task)
Def. - To arrange, organize and schedule a series of events to accomplish a task.

- 2.4.1 PLAN Manipulator Motion
- 2.4.2 PLAN Processing Events

2.5 REPORT (REPORT Status to System)
Def. - To inform or communicate Status to a System or Operator.

- 2.5.1 REPORT Anomalies to Operator
- 2.5.2 REPORT When Transfer Complete

2.6 SEARCH (SEARCH Data Base for Item)
Def. - To scan or sort information in Data Base for a particular Item.

- 2.6.1 SEARCH DataBase for Tool Locations
- 2.6.2 SEARCH DataBase for Event Schedule

2.7 VERIFY (VERIFY Object/Condition)
Def. - To evaluate, confirm or validate Objects, Conditions or Data.

- 2.7.1 VERIFY Tool Identity
- 2.7.2 VERIFY Connector Condition
- 2.7.3 VERIFY Connection Complete

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

PHOBOS/GATEWAY MISSION

The Phobos/Gateway mission was the first mission investigated in the study. It was initially conceived by the Office of Exploration (OEXP) and is viewed as a less ambitious goal, easier and cheaper to accomplish than a manned Mars landing. The original manually assembled timeline based on KSC ground equivalent times is 96.5 days. Each subtask in the process flow was evaluated on a set of predefined criteria, and those tasks which obtained the highest rankings were automated. The effect of automation increased the processing flow to 147.5 days, an increase of 51 days, however, 44 days of EVA operations were eliminated.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

PHOBOS/GATEWAY MISSION

Task #	Task Name	Manual Time	Ratio	Automated Time
1.1-1.7	Aerobrake Assembly Less Offload, Calibration & Test (1.1, 1.5B, 1.6)	18	2.1:1	37.8
2.1-2.38	All Offload & Mate Ops	22.5	2.2:1	49.5
4.1-4.9	All Offload & Mate Ops Inspect & Disconnect)	3.5	2.2:1	7.7
Total Times (Shifts)		**44**		**95.0**
Total Original Phobos Vehicle On-Orbit Processing Time				96.5
Minus Manual Time Of Tasks To Be Automated				-44.0
Plus Ratioed Time Of Tasks To Be Automated				+95.0
Total Time of Automated Processing Scenarios				**147.5 (Days)**

*Note: Time in Work Days

PARTIAL AUTOMATION OF PHOBOS/GATEWAY MISSION

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

PHOBOS/GATEWAY MISSION

The Phobos/Gateway mission was the first mission investigated in the study. It was initially conceived by the Office of Exploration (OEXP) and is viewed as a less ambitious goal, easier and cheaper to accomplish than a manned Mars landing. The original manually assembled timeline based on KSC ground equivalent times is 96.5 days. Each subtask in the process flow was evaluated on a set of predefined criteria, and those tasks which obtained the highest rankings were automated. The effect of automation increased the processing flow to 147.5 days, an increase of 51 days, however, 44 days of EVA operations were eliminated.

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

PHOBOS/GATEWAY MISSION

Task #	Task Name	Manual Time	Ratio	Automated Time
1.1-1.7	Aerobrake Assembly Less Offload, Calibration & Test (1.1, 1.5B, 1.6)	18	2.1:1	37.8
2.1-2.38	All Offload & Mate Ops	22.5	2.2:1	49.5
4.1-4.9	All Offload & Mate Ops Inspect & Disconnect)	3.5	2.2:1	7.7
Total Times (Shifts)		**44**		**95.0**
Total Original Phobos Vehicle On-Orbit Processing Time				96.5
Minus Manual Time Of Tasks To Be Automated				-44.0
Plus Ratioed Time Of Tasks To Be Automated				+95.0
Total Time of Automated Processing Scenarios				**147.5 (Days)**

*Note: Time in Work Days

PARTIAL AUTOMATION OF PHOBOS/GATEWAY MISSION

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

LUNAR EVOLUTION MISSION

The Space Station was evaluated to determine whether it can support vehicle processing and refurbishment to support a lunar base. The lunar base will require transfer vehicles to transport crew and materials to and from the lunar base. Between missions, components will have to be refurbished and sometimes replaced, and the vehicle refueled and all consumables replaced. The refurbishment tasks are typically more complex and difficult to accomplish than the assembly tasks required for Phobos and Mars expeditions. The original manual flow required 121 shifts to complete the vehicle refurbishment tasks. Each sub-task in the process flow was evaluated on a set of predefined criteria. The majority of the highest ranking tasks were umbilical tasks. By automating all umbilical tasks, 19 EVA shifts were eliminated and the resulting total processing flow equalled 140 shifts.

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

LUNAR EVOLUTION MISSION

Task #	Task Name	Manual Time	Ratio	Automated Time
2.1	Tank Drain/Inert	4.0	2.0:1	8
8.1	Top Off Fluids	6.0	2.0:1	12
8.2	Top Off Gases	4.0	2.0:1	8
9.2.2	Umbilical Mate	2.0	2.0:1	4
9.2.6	Umbilical De-Mate	.5	2.0:1	1
10.1	De-Mate Electrical & Fluid Umbilicals	1.0	2.0:1	2
10.4	Mate Electrical & Fluid Umbilicals	1.5	2.0:1	3
Total Times (Shifts)		**19.0**		**38**
Total Original Lunar Vehicle On-Orbit Processing Time				121
Minus Manual Time Of Tasks To Be Automated				- 19
Plus Ratioed Time Of Tasks To Be Automated				+ 38
Total Time of Automated Vehicle Processing				**140 (Shifts)**
Note: Time in EVA Shifts				

PARTIAL AUTOMATION OF LUNAR EVOLUTION MISSION

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

FULL-UP MARS MISSION

The Full-Up Mars Mission scenario is the result of the Mars Mission Profile defined by the Marshall Space Flight Center 'Skunk Works' in support of President Bush's Human Exploration Initiative. The processing scenario is somewhat similar to the original Phobos/Gateway mission, except that the vehicle incorporates two aerobrakes and that Heavy Lift Launch vehicles are used to bring the components to the station. The original manual flow required 93.5 workdays to complete the vehicle assembly and checkout. Each sub-task in the process flow was evaluated on a set of predefined criteria. The aerobrake assembly tasks and the off-loading, transfer and mating tasks were automated. A total of 44 EVA shifts were eliminated and the total flow was increased to 144 shifts.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

FULL-UP MARS MISSION

Task #	Task Name	Manual Time	Ratio	Automated Time
1.1-1.7	Aerobrake Assembly Less Offload, Calibration & Test (1.1, 1.5B, 1.6)	7.5	2.1:1	15.8
1.8-1.29	MTV Stacking Less Offld, Internal Inspect & I/F Verify (1.8, 1.10, 1.14-1.17, 1.20-1.22, 1.25, 1.26, 1.29)	11.5	2.2:1	25.3
2.1-2.7	Aerobrake Assembly Less Offload, Calibration & Test (2.1, 2.5B, 2.6)	7.5	2.1:1	15.8
2.8-2.21	MEV Stacking Less Offld, Internal Inspect & I/F Verify (2.8, 2.11, 2.12, 2.15-2.17, 2.20, 2.21)	6.0	2.2:1	13.2
4.1-4.17	TMIS Cluster Mate Less Offld, I/F Verify & Test (4.1, 4.4, 4.5, 4.8, 4.9, 4.12 4.13, 4.16, 4.17)	5.5	2.2:1	12.1
6.1	Top Off Fluids & Gases	4.0	2:1	8.
6.2	Close out (For Final Inspect & Disconnect)	2.0	2.2:1	4.4
Total Times (Shifts)		**44.0**		**94.5**
Total Original Mars Vehicle On-Orbit Processing Time				93.5
Minus Manual Time Of Tasks To Be Automated				-44.0
Plus Ratioed Time Of Tasks To Be Automated				+94.5
Total Time of Automated Processing Scenarios				**144.0 (Shifts)**
Note: Time In EVA Shifts				

PARTIAL AUTOMATION OF MARS MISSION

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

SUMMARY MISSION RESULTS

Three OEXP case study missions were analyzed in this study. These include: the Phobos/Gateway, Mars Evolution (now Human Exploration Initiative) and Lunar Evolution refurbishment missions. All task definitions and manual process flows were provided by the On-Orbit Task Definition Study. The Phobos and Mars missions are very similar with respect to processing automation. The primary tasks automated in both missions were generic offload and transfer tasks, aerobrake assembly and vehicle component mating. Many of these tasks are highly similar to the Space Station assembly process itself. The results of applying automation are quite similar. Approximately 45 shifts were added to the processing flows, but 44 EVA shifts were eliminated.

The Lunar mission in contrast is primarily a vehicle refurbishment task, and the resulting processing flows are quite different. By automating only umbilical connection tasks, a savings of 19 EVA shifts has been shown.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

MISSION RESULTS

Generic Tasks to be Automated

Mission Name	Phobos (Days)	Mars (Shifts)	Lunar (Shifts)
Offload and Transfer	X	X	
Aerobrake Assembly	X	X	
Component Mating	X	X	
Umbilical Connections			X

–Time Results for Automated Mission Processing

Mission Name	Phobos (Days)	Mars (Shifts)	Lunar (Shifts)
Total Original Vehicle On–Orbit Processing Time	96.5	93.5	121.0
Minus Manual Time Of Tasks To Be Automated	-44.0	-44.0	- 19.0
Plus Ratioed Time Of Tasks To Be Automated	+95.0	+94.5	+ 38.0
Total Time of Automated Processing Scenarios	147.5	144.0	140.0

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

IMPACTS ON SPACE STATION

Complete assessments of the Data Management System and Mobile Servicing System were made based on vehicle processing scenario descriptions. Several Space Station Freedom hooks and scars have been identified. Due to the lack of detailed descriptions of the vehicles, specific design requirements have not been developed. However, several general capabilities required to support on-orbit vehicle processing have been identified.

The Artificial Intelligence tools and Operating System should provide a variety of representation formalisms and inference mechanisms which can be incorporated into applications in a very flexible and modular manner. Two SSRMS manipulators will be required for many processing scenarios. This will have a direct impact on various support utilities. Design for automation will significantly improve the ability to use robotic systems for vehicle processing tasks. This includes the incorporation of features such as self-aligning mating components, partial-turn connectors, sufficient spacing between parts, pre-defined visual cues, etc.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

IMPACTS ON SPACE STATION

- DESIGN AI TOOLS AND OPERATING SYSTEMS TO PROVIDE A VARIETY OF REPRESENTATION FORMALISMS AND INFERENCE MECHANISMS.
- PROVIDE TWO MSS/SSRMS MANIPULATORS TO SUPPORT AUTOMATED VEHICLE PROCESSING.
- INCORPORATE SPECIAL GRASPING POINTS OR RIGID ASTRONAUT HAND-HOLDS TO ASSIST MANIPULATOR SYSTEMS.
- INCLUDE POWER AND DATA FIXTURES, UMBILICALS, UTILITY PORTS, ETC. THROUGHOUT THE PROCESSING WORK AREAS.
- SUPPORT REAL TIME UPDATES TO CAD/CAE DATA FOR THE VEHICLES BEING PROCESSED, THE SPACE STATION EXTERNAL STRUCTURE, AND THE ROBOTIC SYSTEMS.
- DESIGN SSF TO SUPPORT AUTOMATION (SELF-ALIGNING UMBILICALS , PARTIAL-TURN CONNECTORS, PRE-DEFINED VISUAL CUES, ETC.)
- DESIGN SSF TO ALLOW A VEHICLE PROCESSING TURNTABLE TO BE MOUNTED TO THE BOTTOM KEEL.
- CONTINUE TO DEVELOP THE OMV OR AN OMV TYPE VEHICLE TO MANEUVER MASSIVE OBJECTS.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

NEW TASKS AND OBJECTIVES

As this study enters the second year of a planned three year effort a number of more detailed analyses and improved analysis tools will be required. The primary improvement is the ability to automatically produce the required task analyses and flows. This will greatly enhance the current lengthy turnaround time in evaluating mission scenarios. Tools to automatically select manual tasks to be automated and automatically convert manual task sequences into automated tasks are what is needed. In addition to this the study team is also developing a system entitled "Automated Processing Animation System (APAS)" which is envisioned to convert test based process flows from the VPOD database into complete 3D graphic animations. All of these tools will be applied to the most current studies and scenarios developed for the HEI. The current task primitives will be improved with the addition of parameters with the syntax to allow for accurate time and resource analysis. Typical parameter required to predict task times are object sizes, distance to move etc.

ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

FY90 STUDY NEW TASKS AND OBJECTIVES

- **DETAILED AUTOMATION ANALYSIS OF HEI MISSION SCNENARIOS AVAILABLE**
- **EXTENSIVE USE OF VEHICLE PROCESSING OPERATIONS DATABASE**
- **DEVELOP COMPUTER BASED AUTOMATION ANALYSIS TOOLS**
  - AUTOMATIC CONVERSION OF MANUAL TASKS TO AUTOMATED TASKS
  - COMPUTER ANALYSIS OF AUTOMATED PROCESS TASK TIMES
  - AUTOMATED 3D GRAPHIC ANIMATION OF PROCESSES FROM VPOD INPUT
- **MORE DETAILED SS HOOKS AND SCARS REQUIRED**
- **DETAILED SS AUTOMATION SYSTEM ANALYSES (FTS, MSS, DMS ETC.)**
- **IMPROVED PRIMITIVES INCLUDING PARAMETERS FOR ANALYSIS**

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ADVANCED AUTOMATION FOR IN-SPACE VEHICLE PROCESSING

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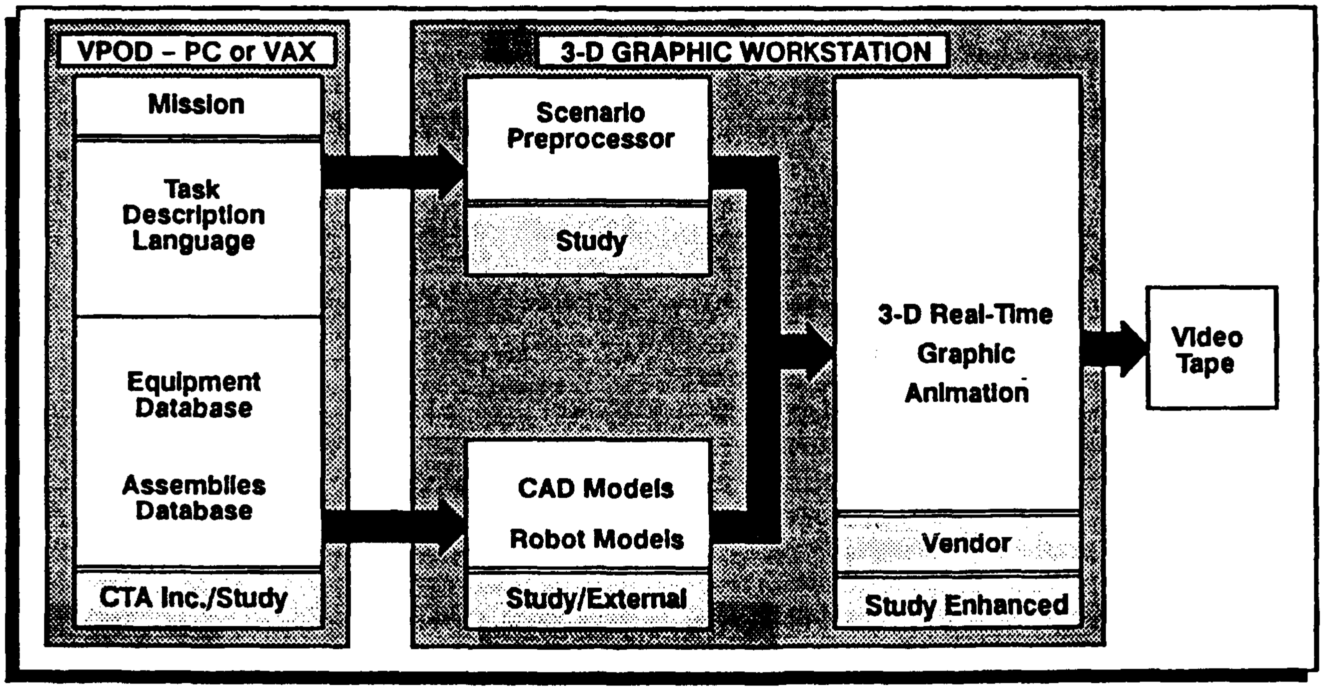
APAS DIAGRAM



SPACE VEHICLE DEPLOYMENT FROM SPACE STATION ORBIT

JPL

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Presentation to the Space Station Evolution Symposium
League City, TX

February 6-8, 1990

SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

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ABSTRACT

When launching a spacecraft from Earth parking orbit to deep space, it is highly desirable to have the hyperbolic excess velocity vector (v-infinity) contained in the parking orbit plane. Ground launches can force the parking orbit plane to contain the v-infinity vector by using launch azimuth and lift-off time as independent variables. When launching from the Space Station, a new set of variables comes into play. The Station orbit is of fixed inclination but precessing due to the Earth's oblateness. Its plane will seldom (and may never) contain the desired v-infinity vector. Consequently, the departure strategy will usually require multiple burns and include a plane change. Also, the concept of "launch period" will be somewhat different from Earth surface launches. An analysis of the deployment of interplanetary spacecraft from Space Station is described, with emphasis on the effect of the trajectory characteristics on station operations. Several planetary mission types are analyzed for manned Mars missions. In addition, high declination departures of spacecraft on unmanned missions to an asteroid are examined. The constraint of Station orbit nodal position is quantified and the operational implications for station reboost strategy are examined.

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SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

BACKGROUND

- PLANETARY MISSION LAUNCHES FROM THE GROUND USE LAUNCH TIME AND AZIMUTH TO CONTROL INCLINATION AND NODE OF PARKING ORBIT
- GROUND LAUNCHES CAN FORCE PARKING ORBIT AND DEPARTURE HYPERBOLA FROM PARKING ORBIT TO BE CO-PLANAR.
- SPACE STATION INCLINATION (FIXED AT 28.5°) AND NODAL POSITION IS A FUNCTION OF FIRST ELEMENT LAUNCH TIME AND NODAL REGRESSION RATE HISTORY (ALTITUDE DEPENDENT)
- SPACE STATION ORBIT ONLY BRIEFLY (AND PERHAPS NEVER) CO-PLANAR WITH DESIRED INTERPLANETARY TRANSFER TRAJECTORY

BACKGROUND

The purpose of this study was to identify the operational requirements and constraints on Space Station *Freedom* resulting from the use of the station to deploy spacecraft on manned missions to Mars and unmanned missions to high declination targets such as asteroids or comets.

Planetary departures from the orbit of a space station fundamentally differ from ground launches. A surface launch to a planetary target allows an orientational targeting choice by careful selection of launch time and ascent azimuth direction; the pre-existing station orbit provides no such options. Further, the orientation of the station's orbit continuously changes due to the oblateness of the equatorial bulge of the Earth, which causes a relatively rapid regression of the station's orbital plane (by about -7.2 deg/day). An orbital launch window occurs every time the regressing orbit plane sweeps over the V-infinity vector of the transplanetary Earth escape hyperbola for the target planet considered. At all other times, energy-expensive plane change maneuvers are required at departure (References 1 and 2).

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SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

OBJECTIVE

- ANALYZE THE ORBITAL MECHANICS AND TRAJECTORY OPTIONS FOR DEPLOYING PLANETARY SPACECRAFT FROM THE STATION
- IDENTIFY THE EFFECT OF DEPLOYMENT TRAJECTORY REQUIREMENTS ON STATION OPERATIONS
  - REBOOST STRATEGY
  - DEPARTURE PERIOD MAXIMIZATION
  - PROPELLENT REQUIREMENTS
- FOCUS ON PILOTED MISSIONS TO MARS
  (NOTE: THIS WORK WAS COMPLETED PRIOR TO THE ANNOUNCEMENT OF THE HUMAN EXPLORATION INITIATIVE)

OBJECTIVE

This report summarizes a study performed at the Jet Propulsion Laboratory in fiscal year 1989. The study examined the trajectory issues involved in using Space Station *Freedom* as the departure site for piloted missions to Mars, and unpiloted missions on high-declination departure trajectories to planetary bodies such as asteroids and comets. Previous studies in this area (References 1 and 2) dealt with a broad range of issues, including assembly of spacecraft at the station, the effects of mission staging on other payloads, and safety. Reference 1 also presented a preliminary examination of the trajectory issues for unmanned spacecraft. This study focusses exclusively on the trajectory issues identified in the previous studies, and examines the effects on station operations resulting from the interaction of the departing spacecraft trajectory and the orbit of the station. Of particular interest is sensitivity of the on-orbit propellant requirements on the misalignment of the station orbital plane and the plane of the desired transplanetary trajectory. The extent to which the station orbital plane orientation can be managed by modifying the reboost strategy also has operational impacts.

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SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

SPACE STATION DEPARTURE CASES STUDIED

CASE	DESTIN-ATION	NOMINAL DEPARTURE DATE, EARTH	ARRIVAL DATE, (FLY BY DATE, VENUS)	TRAJECTORY
EXPEDITION #1	MARS CARGO	2001, 4/15	2002, 1/27	EM
EXPEDITION #2	MARS PILOTED	2002, 9/3	2003, 6/15 (2002, 12/29)	EVME
EVOLUTION #1	MARS PILOTED	2004, 5/31	2005, 4/10 (2004, 11/17)	EVME
EVOLUTION #2	MARS PILOTED	2005, 8/22	2006, 2/13	EME
HIGH DECLIN.	EROS	2005, 1/20	2005, 12/25	DEEP-SPACE PLANE CHANGE RENDEZVOUS
HIGH DECLIN.	EROS	2005, 1/1	2005, 12/25	3-IMPULSE FLY-BY
HIGH DECLIN.	EROS	2005, 1/23	2005, 12/25	3-IMPULSE RENDEZVOUS

SPACE STATION DEPARTURE CASES STUDIED

This phase of the space station staging study focused on an assessment of Earth departure penalties for space-assembled and -launched manned and unmanned Mars missions. Specifically, four sample missions were selected from the then-current (Spring 1989) Gateway Case Study repertoire: two exploration mission cases (flights number one and two) and two evolution mission cases (also flights one and two). Table 1 shows the pertinent characteristics of these sample cases – Earth departure dates, Mars arrival dates, Venus flyby dates (if applicable), and trajectory configuration, where E = Earth, V = Venus and M = Mars.

The work reported here was performed prior to the announcement of the Human Exploration initiative. Consequently, flight opportunities in an earlier time frame – 2001-2005 – were analyzed. The general conclusions should be valid, however, over a wide range of piloted Mars missions.

In this study, the first two ''Mars Expedition'' and ''Mars Evolution'' missions described in Reference 3 were analyzed. These missions include both direct Earth-Mars transfer trajectories and Earth-Venus-Mars flyby gravity assist missions. Also included in this mission set are trajectories that adhere to a free return to Earth'' constraint to maximize crew safety. This constraint would very likely also be applied to the Human Exploration Initiative missions to Mars.

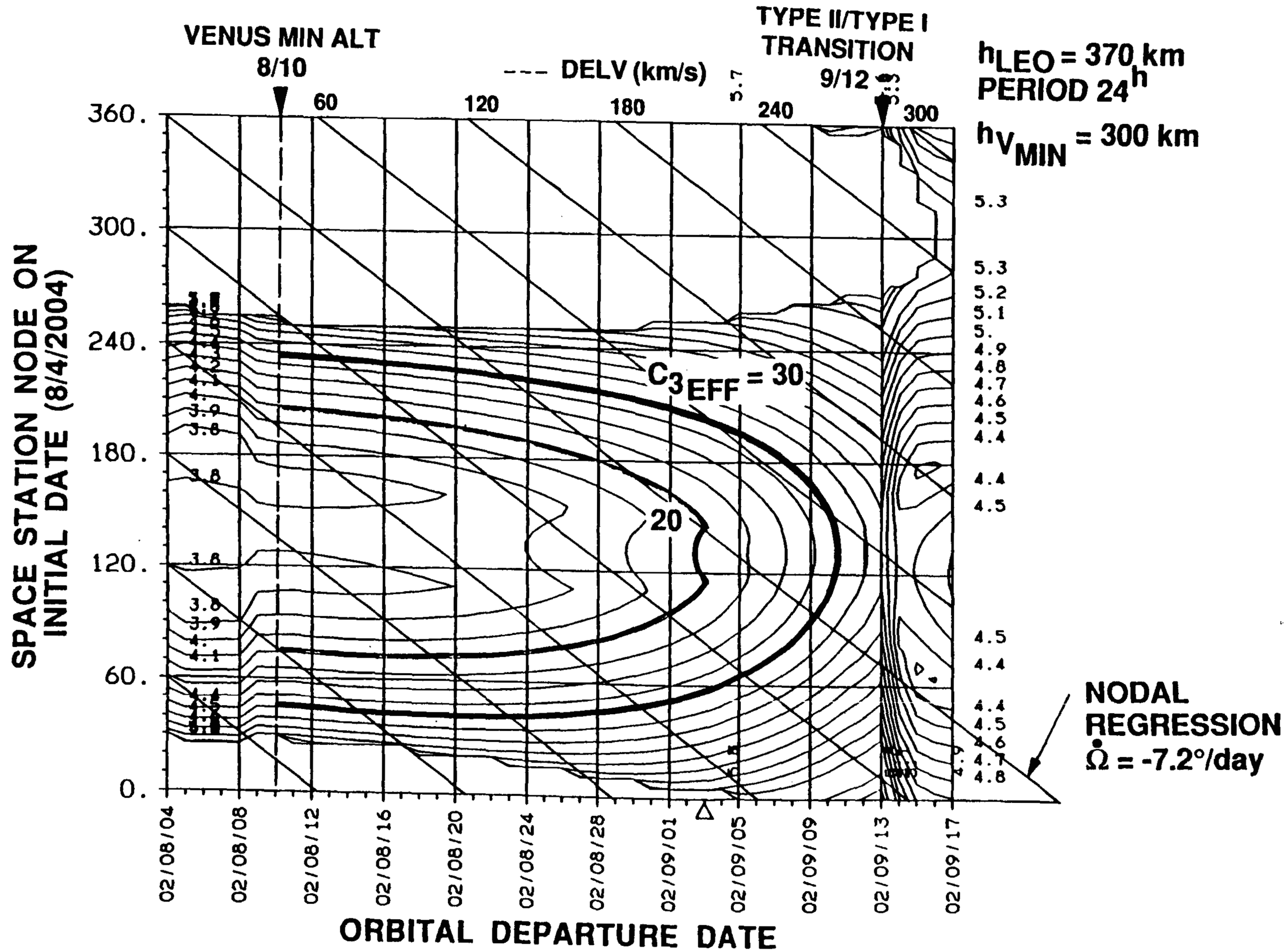
In addition to the Mars missions, the study also examined high declination departures from station orbit, specifically, a mission to the asteroid 433 Eros. High declination missions differ from the Mars missions in that the precessing station orbit plane may never be co-planar with v-infinity vector and a relatively large plane change will be required.

Due to the need to limit the pages of this report to a number commensurate with its intent as a summary document, only the results of the analysis of the Mars second expedition mission will be presented. It is representative of the missions studied in that most relevant points can be illustrated in example form. For the complete analysis, the inquiring reader is referred to the FY89 Final task report: Planetary Exploration Departures from the Space Station: Trajectory Effects on Station Operations, JPL D-6896.

SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

JPL MARS EXPEDITION CASE STUDY FLIGHT No. 2

(3 IMP. INJ., EVME ABORT CAP'Y, MARS ARRIVAL 6/15/2003)



MARS EXPEDITION CASE STUDY FLIGHT No. 2
(3 IMP. INJ., EVME ABORT CAP'Y, MARS ARRIVAL 6/15/2003)

The orbital departure imposes a plane change penalty on the mission, the implementation of which can be performed as a 3-impulse maneuver: co-planar (with respect to the space station) injection into a 24 hour elliptical parking orbit, a plane change at the high apogee such that the new plane contains the departure V-infinity vector, and a perigee injection burn onto the departure hyperbola.

When evaluated over all possible nodal positions (0-360 degrees) of the space station for each potential departure date, a contour plot of effective C3 can be constructed (shown by bold contour lines in the accompanying figure). Empty, uncontoured regions are ''forbidden'' areas, the result of exceeding the geometric range angle constraint (discussed in more detail in References 1 and 2). The figure clearly shows regions of low (~15 km^2/sec^2) C3, which are forbidden to apsidal 3-impulse maneuvers (Reference 2), and a region of intermediate C3 requirements, sandwiched between the previous two, showing reasonably long departure periods. The thin lines are contours of constant total V_{3IMP} in km/sec. The slanted straight lines labeled ''nodal regression'' represent the continuous shift of nodal longitude of the space station with elapsed time. Hence any departure period from the orbital station of known nodal orientation will lie along one of these slanted lines, as shown. Some periods are short, others long, depending on the nodal longitude at an arbitrary initial reference date and the way the slanted regression line intersects the C3 contours, arranged in a ''horseshoe'' pattern around the forbidden zone. As can be seen in the figure, some departure periods are discontinuous and multiple, while others are uninterrupted over the entire launch period range.

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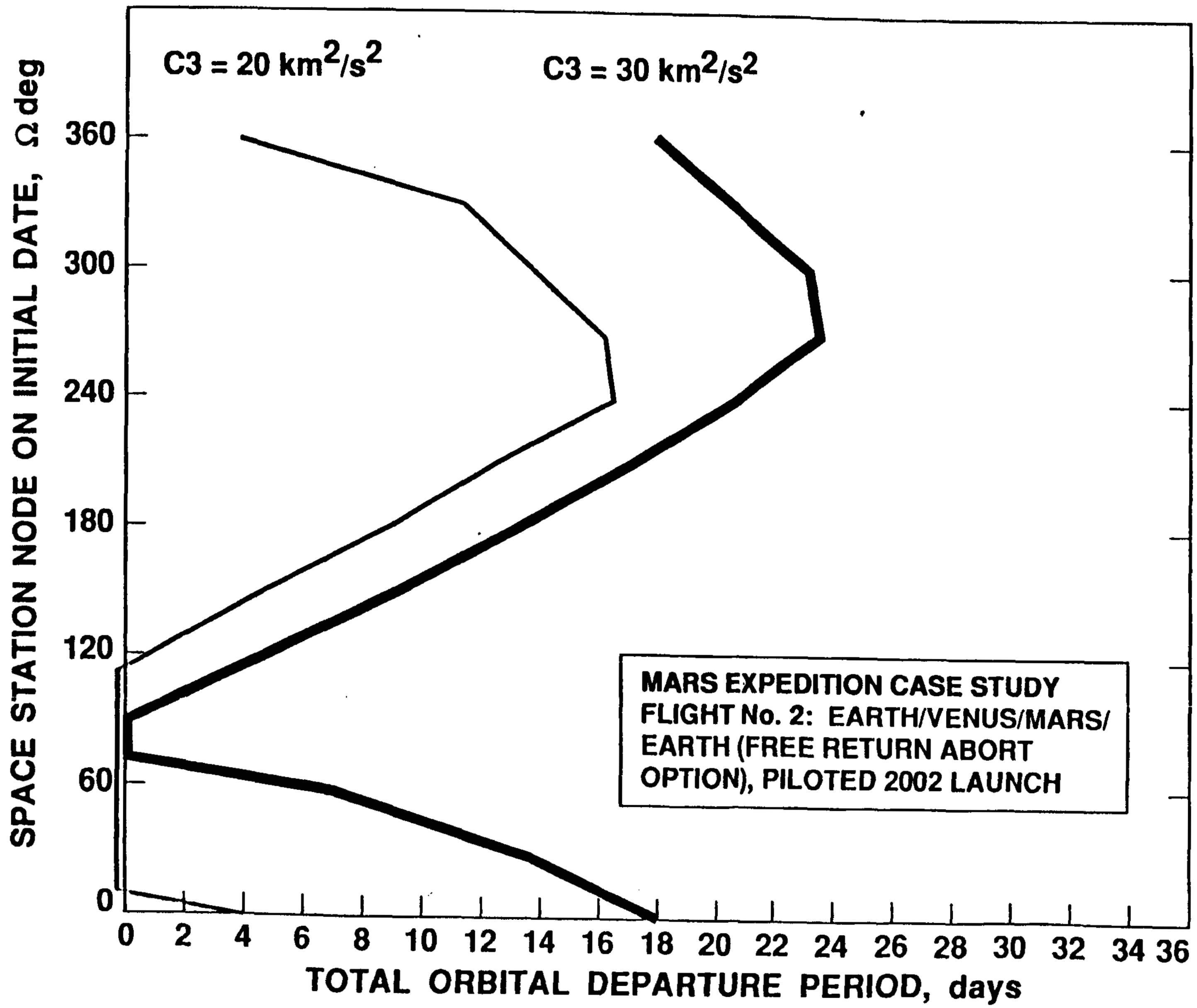
SPACE VEHICLE DEPLOYMENT FROM SPACE STATION
ORBITAL DEPARTURE PERIOD AVAILABILITY
(FOR TWO VALUES OF EFFECTIVE DEPARTURE C3 OR PROPELLANT MASS IN m TONS)



ORBITAL DEPARTURE PERIOD AVAILABILITY

The final plot for this mission case shows departure period availability with respect to the station's nodal orientation. Two aspects of this plot should be stressed:

a) If a minimum (single or dual) departure period duration value is specified, one can determine the effective C3 energy required to satisfy that requirement, e.g., for an 20 day guaranteed window, C3 = 30 km^2/sec^2 is needed. This in turn could dictate the maximum allowable payload if an existing injection booster capability is given.

b) If a specific energy is given (i.e., fixed stage and payload), the plot shows the region of the nodal space in which orbital launch *cannot* occur. For instance, if 18 days are required for the departure period in order to make last-minute repairs to the spacecraft, exchange systems or crew, deliver spares from ground or get a second launch off, then, at a C3 = 30 km^2/sec^2, nodal longitudes between 0 and 180 degrees are not allowable. If these are indeed the naturally occurring nodal orientations of the station, then only three options exist:

1) Go to a higher energy injection stage or stages

2) Leave some of the payload in Earth orbit

3) Move the ascending node of the station away from the critical zone. Reboost strategy, as discussed later in this report, is one of the techniques that could be used.

Another aspect of interest is the departure period itself – what is a departure period of any given duration intended to accomplish? Can the number of days between two allowable ''half periods'' be utilized in the waiting process?

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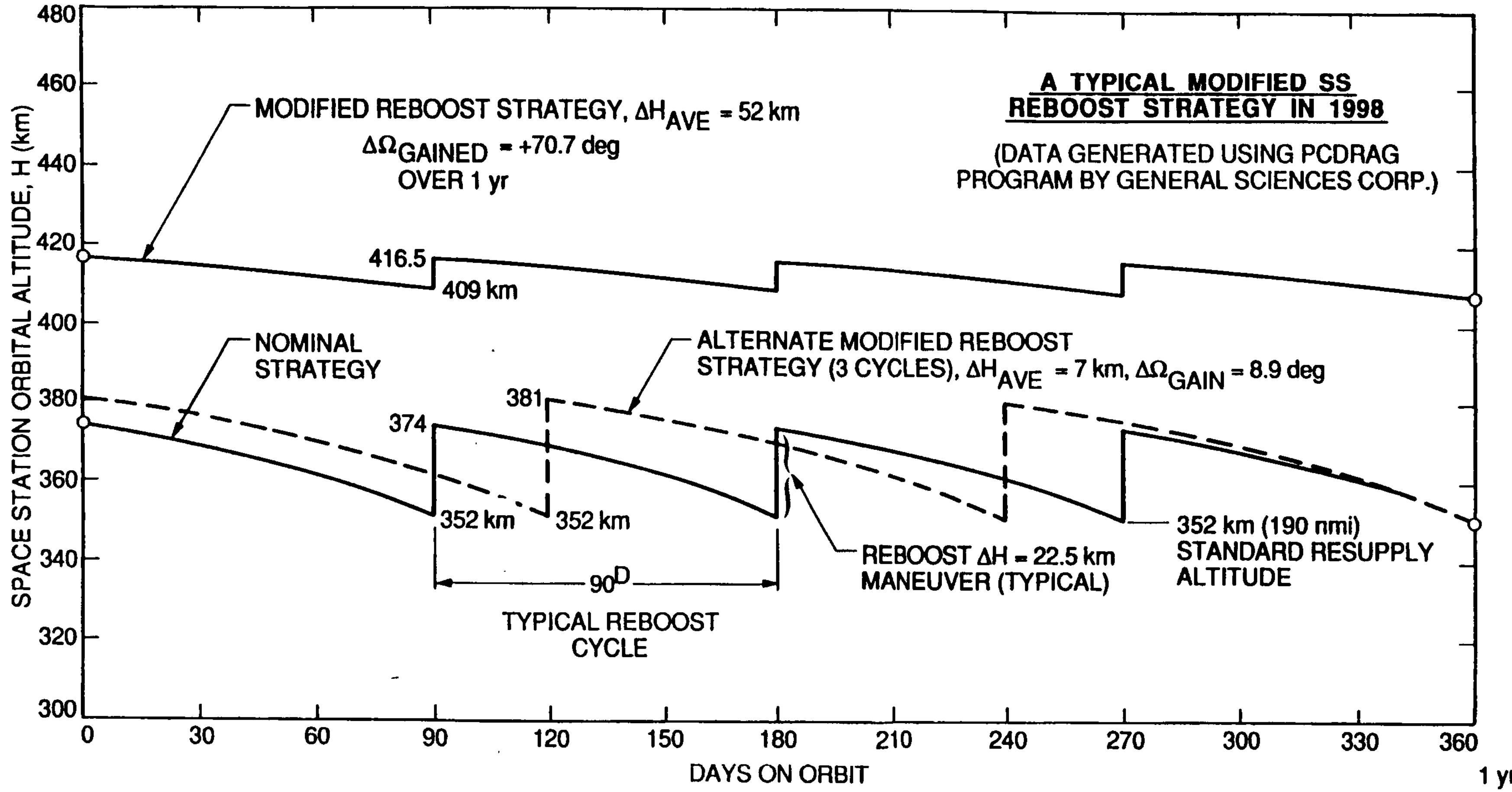
SPACE VEHICLE DEPLOYMENT FROM SPACE STATION
EXAMPLE REBOOST STRATEGY



EXAMPLE REBOOST STRATEGY

It is highly unlikely that a planetary mission departing from the space station will have the luxury of sufficient C3 capability to make its departure independent of the station's nodal position.

Periodic space station altitude reboost maneuvers will be required throughout the station's life. The upper atmosphere produces drag, resulting in the loss of orbital altitude. The amount of drag depends on frontal area mass loading and atmospheric density, which in turn strongly depends on altitude and the state of solar activity – the more active the Sun, the higher the upper atmospheric density and thus higher drag and an increase in the orbital decay rate.

Two example strategies are shown to provide an indication of the sensitivity of nodal regression rate to orbital altitude. Suppose the typical lower/upper altitude bounds of 352-374 km is raised to 409-416.5 km. For a 1998 atmospheric density prediction, both strategies result in a 90 day reboost cycle (four per year), but the higher altitude strategy gains 70.7 degrees of nodal longitude at a year's end. However, the resupply altitude would then be higher, resulting in a lesser payload delivered by the Shuttle. The Shuttle's sensitivity of payload to altitude is approximately -25 kg/km.

The second example strategy shown would raise only the upper altitude bound from 374 to 381 km (same 1998 atmospheric density assumptions). This would result in a change of the reboost cycle duration to 120 days (three per year), and would leave the original resupply altitude unchanged but with a corresponding reduction in frequency of logistics resupply and crew changeout. Also, the gain in nodal longitude would be much less significant: 8.9 degrees change per year. Many other combinations of reboost altitudes are possible, and the reboost strategy may have to be quite complex to accommodate other station activities.

It is quite possible that the strategy to manage the station's nodal position will have to be started well in advance, perhaps years in advance, of the scheduled departure date. Fortunately, the inexorable motion of the planets permits precise advance knowledge of the station's required orbital orientation. This allows sufficient time to adjust the station's nodal rate. The most unpredictable variable in this case will be unforeseen variations in solar activity and the resultant changes in the station's orbital decay rate. Flexibility in reboost strategy would have to be maintained to compensate for these variations.

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SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

PROPELLANT MASS REQUIRED FOR MARS MISSION

(TO INJECT NOMINAL 176 t PAYLOAD)

$C3_{EFF}$	ΔV_{TOT} 3 IMP	TOTAL MASS ON ORBIT M_{OO} (t)	PROPELLANT MASS M_{pp} (t)	TANKAGE MASS M_{TANKG} (t) & P/S
10	3.634	449.6	246.20	27.36
15	3.853	478.0	271.76	30.20
20	4.068	508.0	298.78	33.20
25	4.278	539.7	327.36	36.37
30	4.486	573.4	357.62	39.74

h_{LEO} = 370 km

ISP = 460 sec

Tankage Factor = 0.1

PROPELLANT MASS REQUIRED FOR MARS MISSION

One purpose of this study was to determine the penalty for orbital launch missions in terms of total (fueled) mass on orbit required by a typical space station-launched manned payload bound for Mars. Since the amount of propellent required for Earth orbital departure scales linearly with injected payload mass, a standard value of 176 metric tons was assumed for the payload mass for all mission cases (from Reference 3).

As previously shown, the departure period availability, measured in days, greatly depends on the amount of energy available for injection - for higher energies, longer departure periods become available. However, some orientations of the space station's ascending node are very hard to accommodate, thereby driving the effective C3 energy requirement to very high values.

In order to assess the total mass on orbit, M_{OO} from known effective C3 requirements, a table was prepared relating these two quantities. A single stage cryogenic (LOX + LH_2) propellent departure maneuver and injection vehicle was assumed, exhibiting a specific impulse of 460 seconds, with a tank/engine mass factor of 10 percent of the propellent mass. The propellant requirements table shows the total resulting mass on orbit, including the propellent and tankage masses required for different levels of effective injection C3. The use of multiple stages would lower the total mass on orbit somewhat.

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SPACE VEHICLE DEPLOYMENT FROM SPACE STATION
CONCLUSIONS

- NO INSURMOUNTABLE TRAJECTORY BARRIERS TO PILOTED MARS MISSIONS DEPARTING FROM THE STATION.
- CAREFUL ADVANCE PLANNING NECESSARY TO MANAGE STATION NODAL REGRESSION TO BE IN ACCEPTABLE ORIENTATION ON DESIRED DEPARTURE DATE.
- CLOSELY SPACED DEPARTURES (LESS THAN 2 YEARS APART) COULD REQUIRE RELATIVELY LARGE AVERAGE STATION ALTITUDE CHANGES (~100 km) TO ADJUST REGRESSION RATE.
- MANAGEMENT OF THE NODE WOULD IMPOSE A MASS-TO-ORBIT PENALTY DUE TO HIGHER STATION ALTITUDES.
- ANY OTHER ASSEMBLY FACILITY IN LEO WOULD ENCOUNTER THE SAME CONSIDERATIONS REGARDING NODAL POSITION, DEPARTURE PERIOD DURATION AND MASS-TO-ORBIT TRADEOFFS.

CONCLUSIONS

The conclusion of this study is that for piloted Mars missions departing from the station, trajectory considerations appear to impose no insurmountable barriers. Careful attention must be paid to overall system performance, cost and risk optimization (including station operations, ground-to-station logistics, and the departing mission). Astute advance planning would permit the station to be a very advantageous assembly and departure point for manned exploration mission although closely spaced departures could present a problem in the trade-off of nodal position and mass-to-orbit.

It should be noted that any other assembly and staging site in low earth orbit would encounter essentially the same problems as the station regarding nodal regression and the trade-offs required to assure advantageous departure geometries. Nodal regression rates differ with inclination and altitude and it is conceivable that some mission-specific advantage might accrue in having, say, more mass-to-orbit capability (i.e., a lower orbit altitude) or a different inclination. However, in the absence of such mission-specific trajectory constraints, the space station appears quite capable of supporting the trajectory requirements of manned solar system exploration.

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SPACE VEHICLE DEPLOYMENT FROM SPACE STATION

CONCLUSIONS (cont.)

- DEPARTURE PERIOD DURATIONS FOR DIFFERING MISSION TYPES (e.g., E-M, E-M-E, E-V-M-E etc.) AND DIFFERENT OPPORTUNITIES SHOWS GREAT TOPOLOGICAL DIVERSITY

- DEPARTURE PERIOD DURATION IS A VERY ERRATIC FUNCTION OF SPACE STATION NODAL LONGITUDE, Ω, ON DEPARTURE DATE

- IN MOST SITUATIONS, GAPS IN DEPARTURE PERIOD DURATION EXIST IN SOME BANDS OF VALUES, ESPECIALLY AT THE LOWER EFFECTIVE INJECTION ENERGIES, C_{EFF}.

- FOR REASONABLE DEPARTURE PERIOD DURATIONS, THE RESULTING INCREASE IN ON-ORBIT PROPELLANT REQUIREMENTS FOR TRANSPLANETARY INJECTION IS MODERATE (GENERALLY BETWEEN 10 AND 25% OF DEPARTURE FROM OPTIMUM PARKING ORBIT).

CONCLUSIONS (cont.)

The departure window availability for differing mission types (e.g., Earth-Mars, Earth-Mars-Earth, Earth-Venus-Mars-Earth,) and different launch opportunities exhibits great topological diversity. To derive any generalized meaning from this diversity, one needs to consider the ''big picture'' of how such major missions would be planned. As is typical of space missions, the effective C3 capability of the departure booster will be the limiting factor in the trade-off between payload mass and launch window duration. While spacecraft designers always seem to need more mass, mission managers want the longest possible launch window. These competing demands must be reconciled with the C3 limitations of the launch vehicle. For a given launch vehicle capability, it is clear from the graphs of station departure window availability that positioning the ascending node of the station orbit in the most advantageous position can have a profound effect on the length of the departure window. For endeavors of the magnitude of manned Mars missions, this would clearly be part of the mission plan, as no mission is likely to have the luxury of sufficient C3 capability to be totally independent of station nodal alignment.

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2. Sergeyevsky, Andrey B. (JPL), *Planetary Mission Departures From Space Station Orbit*, Preprint AIAA-89-0345, 27th Aerospace Sciences Meeting, January 1989, Reno NV.

3. Craig, Marc K. and U. M. Lovelace, *Study Requirements Document – FY1989 Studies*, NASA Office of Exploration, Document Z-2.1-002, March 1989.

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The work reported here is one of several Space Station Utilization Studies performed in fiscal year 1989 at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration's Office of Space Station.

GRAPHICAL ANALYSIS OF MARS VEHICLE ASSEMBLY

KEVIN W. LEWIS
NASA/JOHNSON SPACE CENTER
FEBRUARY 8, 1990

The task assigned to the Mission Planning and Analysis Division for FY89 was to produce a video tape depicting the assembly of a Mars Piloted Vehicle at a man tended vehicle assembly platform, co-orbiting with Space Station Freedom. This request was made by the Transportation Node Integration Agent of the Lunar/Mars Exploration Office. Along with the request, a data package was provided which contained the latest technical briefings by the Transportation Node and Space Transportation Integration Agents. This information was used as the basis of a conceptual study performed using kinematic manipulator simulations.

MARS VEHICLE ASSEMBLY ANALYSIS

CONCEPTUAL STUDY OF THE ASSEMBLY OF A MARS VEHICLE AT A CO-ORBITING, MAN-TENDED TRANSPORTATION NODE PERFORMED IN SUPPORT OF THE TRANSPORTATION NODE INTEGRATION AGENT OF THE LUNAR/MARS EXPLORATION OFFICE

- BILL CIRILLO AND KAREN BRENDER - LaRC

BASELINE ASSUMPTIONS:

- MARS VEHICLE ASSEMBLY FIXTURE BASED ON LOCKHEED "SKYHOOK"
- FLIGHT MANIFESTS BASED ON WORK BY EAGLE ENGINEERING
- ERECTABLE AEROBRAKE DESIGN (HUB AND PETAL)
- ETO LAUNCH VEHICLE: SHUTTLE "Z" (124.4 MT TO LEO)
- MANIPULATOR OPERATIONS PERFORMED USING CURRENT (PRE-SCRUB) DESIGN OF SPACE STATION FREEDOM (SSF) MOBILE SERVICING CENTER (MSC)

RESULTS OF ANALYSIS:

- COMPUTER GRAPHICS VIDEO TAPE OF ASSEMBLY OPERATIONS

Due to time constraints, it was decided to use the Space Station Freedom Mobile Servicing Center (MSC) as the manipulator for this study, since this system was already modeled in the simulation. The provided design of the Mars Vehicle Assembly Fixture, dubbed the Skyhook by its developers at Lockheed, was incompatible with MSC in terms of manipulator reach capability and mobile base positioning requirements. In addition, the Skyhook provided inadequate storage facilities for the Trans-Mars Injection Stages, which were also used to store the propellant required for the interplanetary mission. For these reasons, the Skyhook was modified.

The flight manifests developed by Eagle Engineering dealt only with the lift capability of the Shuttle "Z" launch vehicle and made no mention of the arrangement of the elements in the cargo bay. Since this analysis was conceptual in nature, it was decided to worry only about volume constraints when depicting the individual flight manifests involved in the vehicle assembly process. These volume constraints also drove the design of the aerobrake. The data package provided hub-and-petal designs which involved either eight or ten petals. Sizing of the aerobrake and attempting to fit it in the Shuttle "Z" cargo bay forced the development of a twelve petal model.

Deployment of the completed Mars vehicle is a major operational concern. A mechanism will probably be required to provide adequate clearance between the vehicle and the assembly fixture before any separation reaction control system firings are allowed. In addition, the size and mass of the Trans-Mars Injection Stages would seem to make the standard MSC design unsuitable for their transportation to and from the storage area. In response to these problems the concept of a "High Mass Mobile Transporter" was devised. This mechanism, which is modeled as the transportation mechanism of the MSC fitted with fifteen meter slide mechanism for the purpose of payload handling, was used in this study for both of the aforementioned tasks.

MARS VEHICLE ASSEMBLY ANALYSIS

MARS VEHICLE ASSEMBLY FIXTURE (SKYHOOK) MODIFIED TO ACCOMMODATE:

- MSC CAPABILITIES
  - REACH AND CLEARANCE
  - MOBILE TRANSPORTER DESIGN
- TRANS-MARS INJECTION STAGE (TMIS) STORAGE REQUIREMENTS

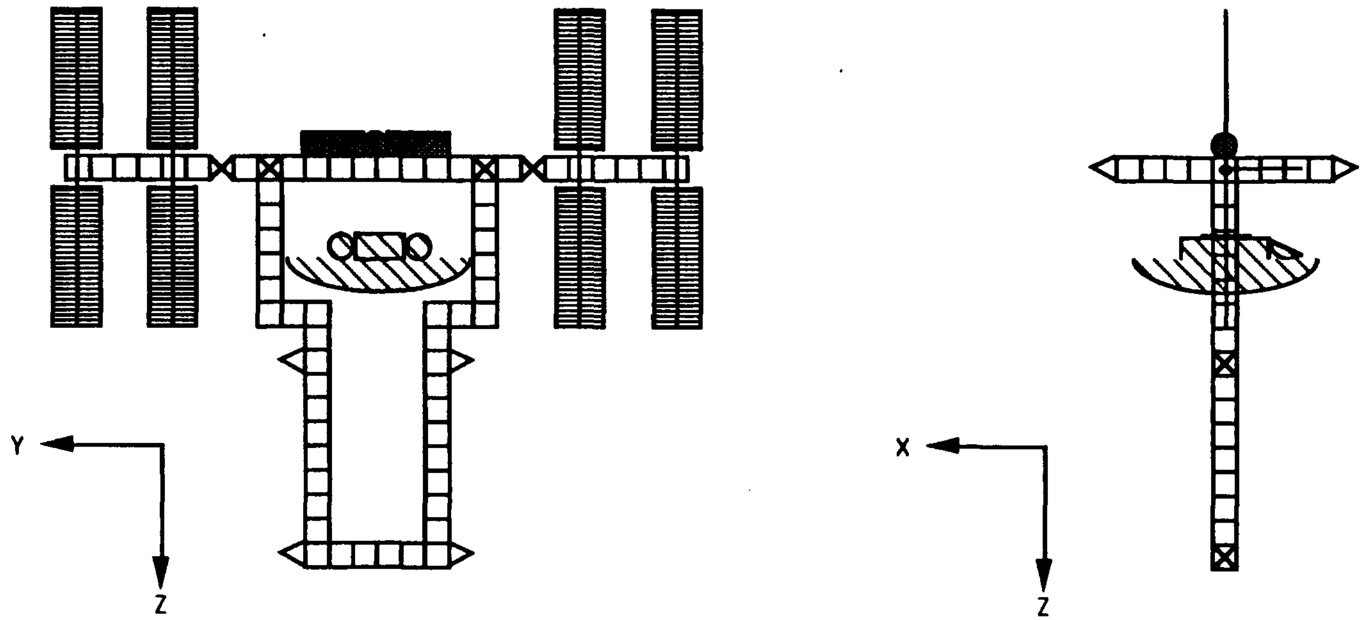
INDIVIDUAL FLIGHT MANIFESTING BASED SOLELY ON VOLUME CONSTRAINTS

DEVELOPED TWELVE PETAL AEROBRAKE DESIGN TO ACCOMMODATE SHUTTLE "Z" VOLUME CONSTRAINTS

INTRODUCED "HIGH MASS MOBILE TRANSPORTER" (HMMT) TO ACCOMMODATE:

- DEPLOYMENT OF COMPLETED MARS VEHICLE
- TRANSPORTATION OF FULLY FUELED TMIS

MARS VEHICLE ASSEMBLY ANALYSIS

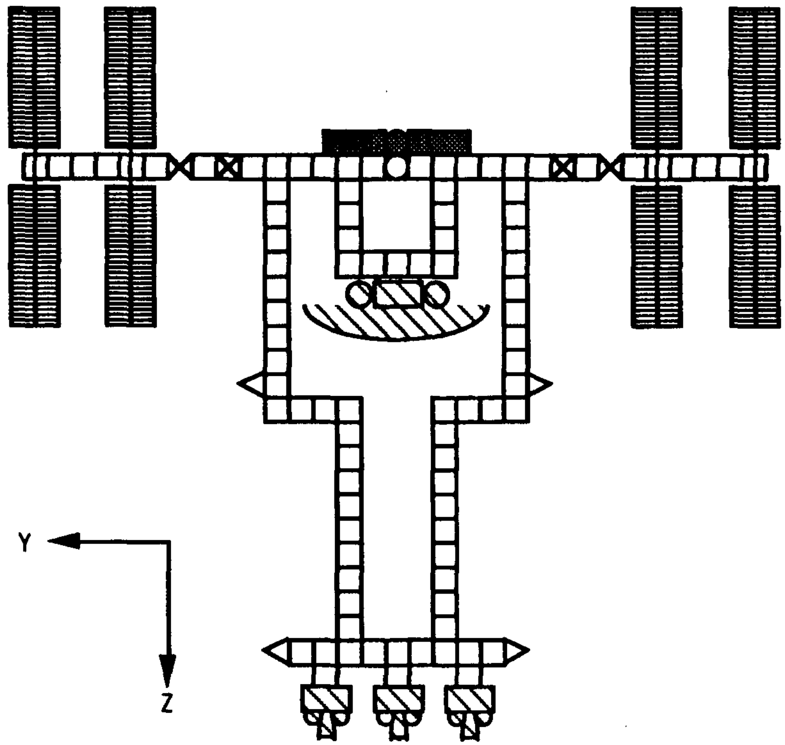


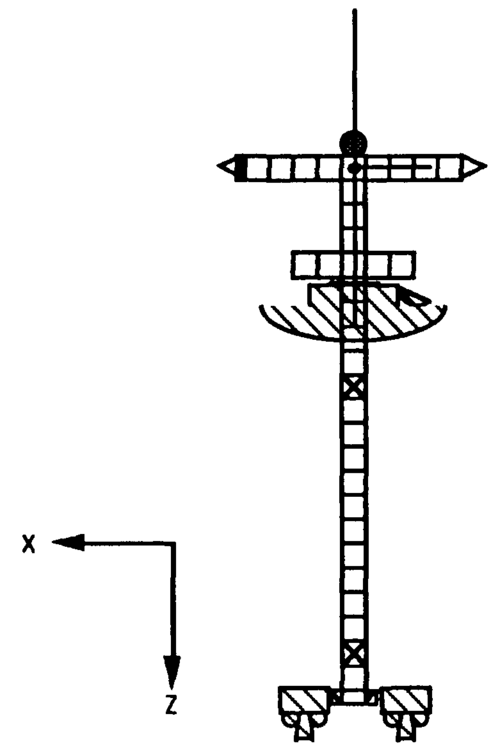
LOCKHEED SKYHOOK

The original design of the Lockheed Skyhook consists of a transverse boom, front and back "porches", and two descending keels, which extend to a short lower boom. Unfortunately, with this design, the MSC does not have anyplace to stand which allows adequate proximity to the primary work areas inside the hollow of the aerobrake. The aerobrake must be positioned as shown in the figure to allow for the installation of the excursion vehicle later in the assembly sequence. Another important drawback in this design involves the intersection of the keels and porches with the transverse boom. The manner in which the MSC attaches to the truss structure precludes the mechanism form standing on a trussbay face which makes an inside corner with another trussbay face. It is therefore impossible for a MSC which is operating on either the transverse boom or on one of the porches to maneuver itself onto one of the keels. This constraint also exists for the High Mass Mobile Transporter.

While the basic design for the modified Skyhook is unchanged, the transverse boom has been extended to allow an appropriate offset between the porches and the keels. Additional truss structure has been added to allow the MSC access to the primary working area during assembly. The size of this new structure is driven by the necessity of the MSC to be able to acquire access to the structure and maneuver freely on it. The excursion vehicle fits through the opening in the structure to its attach point on the central hub of the vehicle. Comparison of the lower keel on this modified vehicle assembly fixture with its counterpart on the original Skyhook will illustrate the lack of adequate storage space on the original design.

MARS VEHICLE ASSEMBLY ANALYSIS





MODIFIED SKYHOOK

The modification of the Skyhook resulted in a significant increase in size, which is illustrated in this table. Since the major difference is in the number of trussbays, the change in mass is relatively minor.

MARS VEHICLE ASSEMBLY ANALYSIS

RESULTS OF SKYHOOK MODIFICATION

	BEFORE	AFTER
MASS (MT)	89	94
TRUSS BAYS	96	154
HEIGHT(M)	120	150
WIDTH(M)	135	160
DEPTH(M)	50	50

The next two charts show the flight manifests depicted in the assembly video.

MARS VEHICLE ASSEMBLY ANALYSIS

FLIGHT MANIFESTS

- FLIGHT ONE
  - MARS PILOTED VEHICLE (MPV) CORE (INCLUDES AEROBRAKE HUB)
  - TRANS-EARTH INJECTION STAGE (TEIS) TANKS
  - AEROBRAKE PETALS
  - TMIS
- FLIGHT TWO
  - TEIS ENGINES
  - SOLAR ARRAYS (2)
  - HABITATION MODULE SUPPORT TUBES (2)
  - COMMUNICATIONS ANTENNA FARM
  - TMIS
- FLIGHT THREE
  - HABITATION MODULE ASSEMBLIES (2)
  - TMIS

Integration of the design of the transportation node with the design and operational requirements of the supporting manipulator system is mandatory in order to optimize the size and cost of both systems. The fact that the assembly fixture used in this study is an order of magnitude larger than Space Station Freedom reflects this fact. While this study shows that the current design of the MSC provides adequate reach to support the assembly of large interplanetary vehicles, it is also clear that the mass handling capability of the current MSC design is insufficient for this task. Deployment of the completed vehicle will also be a major driver in vehicle, assembly fixture, and mechanism design.

MARS VEHICLE ASSEMBLY ANALYSIS

FLIGHT MANIFESTS (CONTINUED)

- FLIGHT FOUR
  - PHOBOS/DEIMOS EXCURSION VEHICLE
  - TMIS
- REMAINING FLIGHTS DELIVER TMISs AND FUEL

The following pages contain figures which were produced using the same database and software package which was used to produce the video which documents this study. The credits which apply to this video are as follows:

Mission Planning and Analysis Division
Integrated Graphics and Operational Analysis Laboratory (IGOAL)

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- Kevin Lewis

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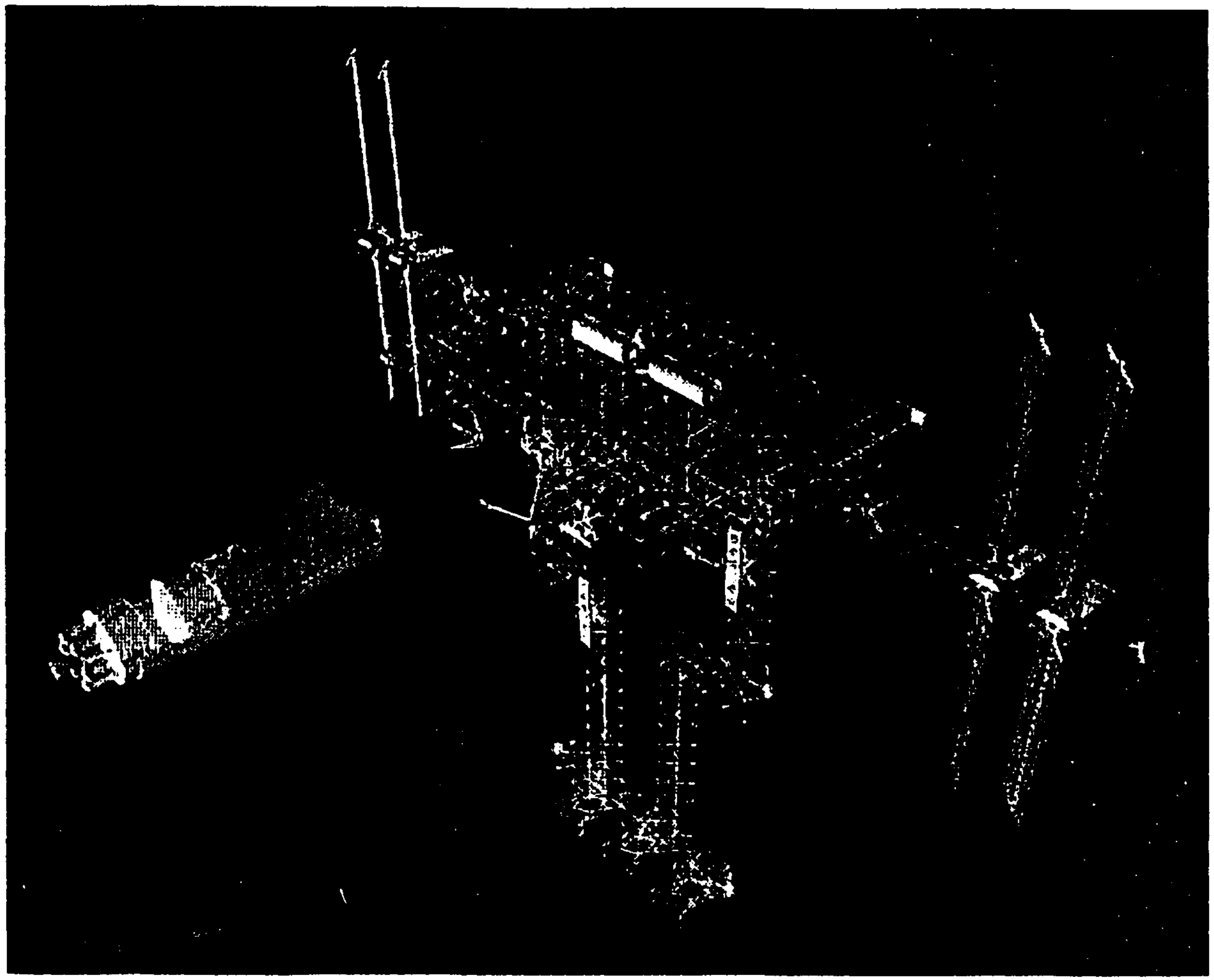
- Brad Bell
- David Shores
- Sharon Goza

OOM Image Generation Software by:
- Brad Bell
- Sharon P. Goza
- David Shores

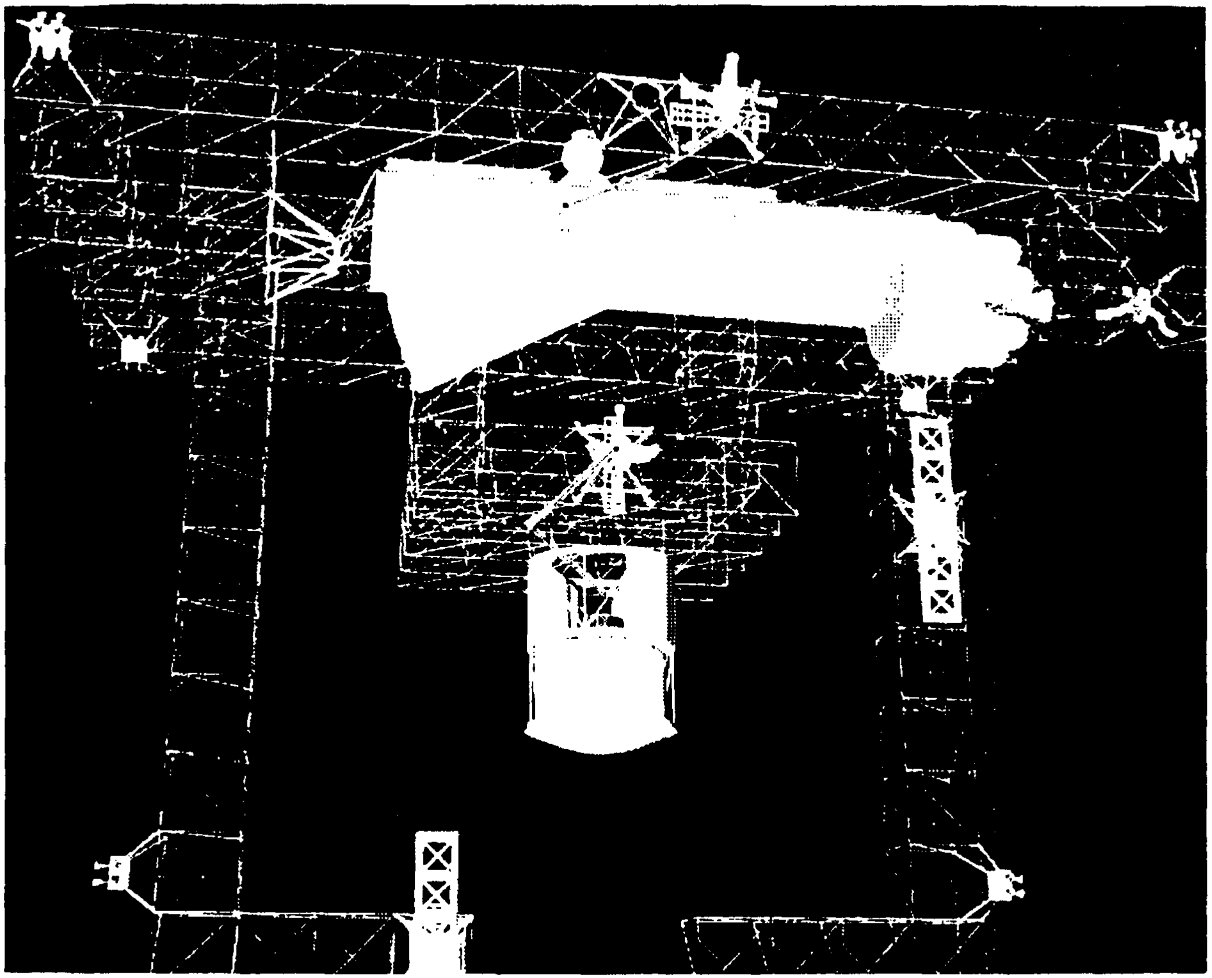
MARS VEHICLE ASSEMBLY ANALYSIS

CONCLUSIONS/KEY ISSUES

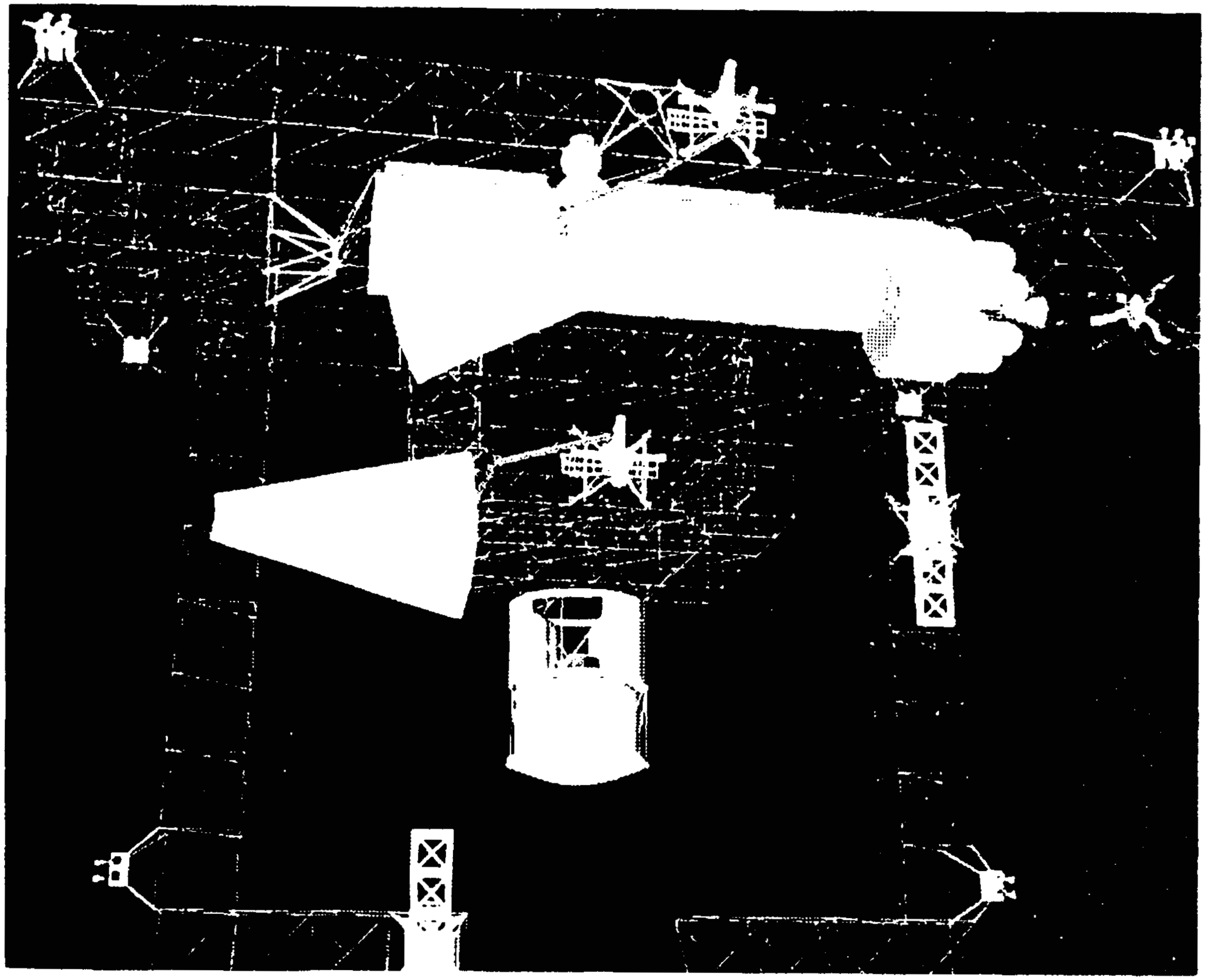
- TRANSPORTATION NODE MUST BE DESIGNED TO ACCOMMODATE MANIPULATOR OPERATIONS
- TRANSPORTATION NODE ORDER OF MAGNITUDE LARGER THAN SSF
  - 154 BAYS OF TRUSS VS. 21
  - 17 BAYS BETWEEN ALPHA JOINTS VS. 15
- REACH CAPABILITY OF CURRENT SSF MSC ADEQUATE TO PERFORM ALL ASSEMBLY TASKS ANALYZED
- MASS HANDLING CAPABILITY OF CURRENT SSF MSC INADEQUATE TO PERFORM ALL ASSEMBLY TASKS ANALYZED.
  - MSC MUST MANEUVER FULLY LOADED SHUTTLE "Z" (137.4 MT)
- MOBILE TRANSPORTERS MUST HAVE FULL PLANE CHANGE AND CORNER TURNING CAPABILITY
- DEPLOYMENT DEVICE (HMMT) MUST BE CAPABLE OF HANDLING FULL-UP MARS VEHICLE (MPV + 6 TMIS: 1050 MT)



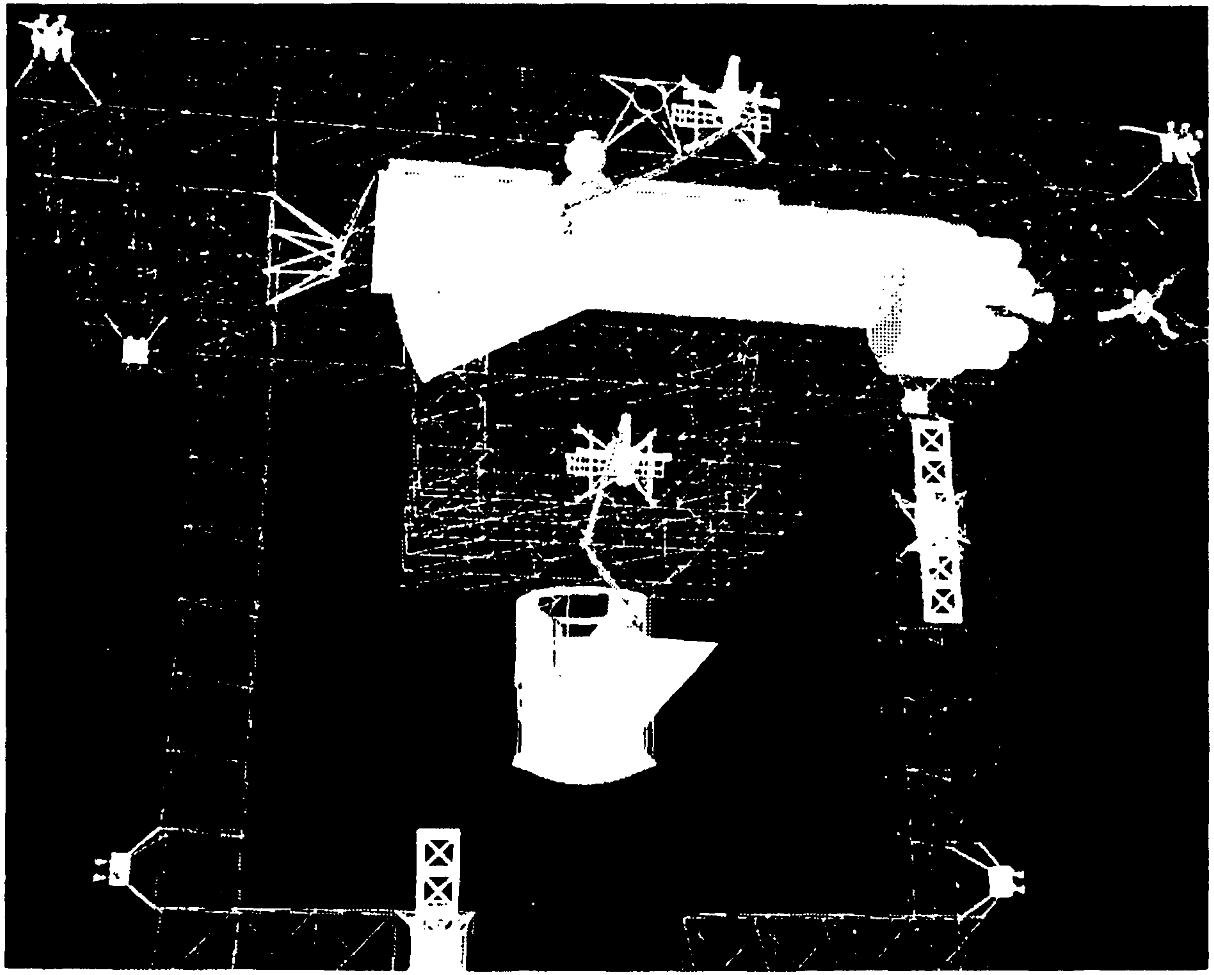
Shuttle z Approaching Skyhook



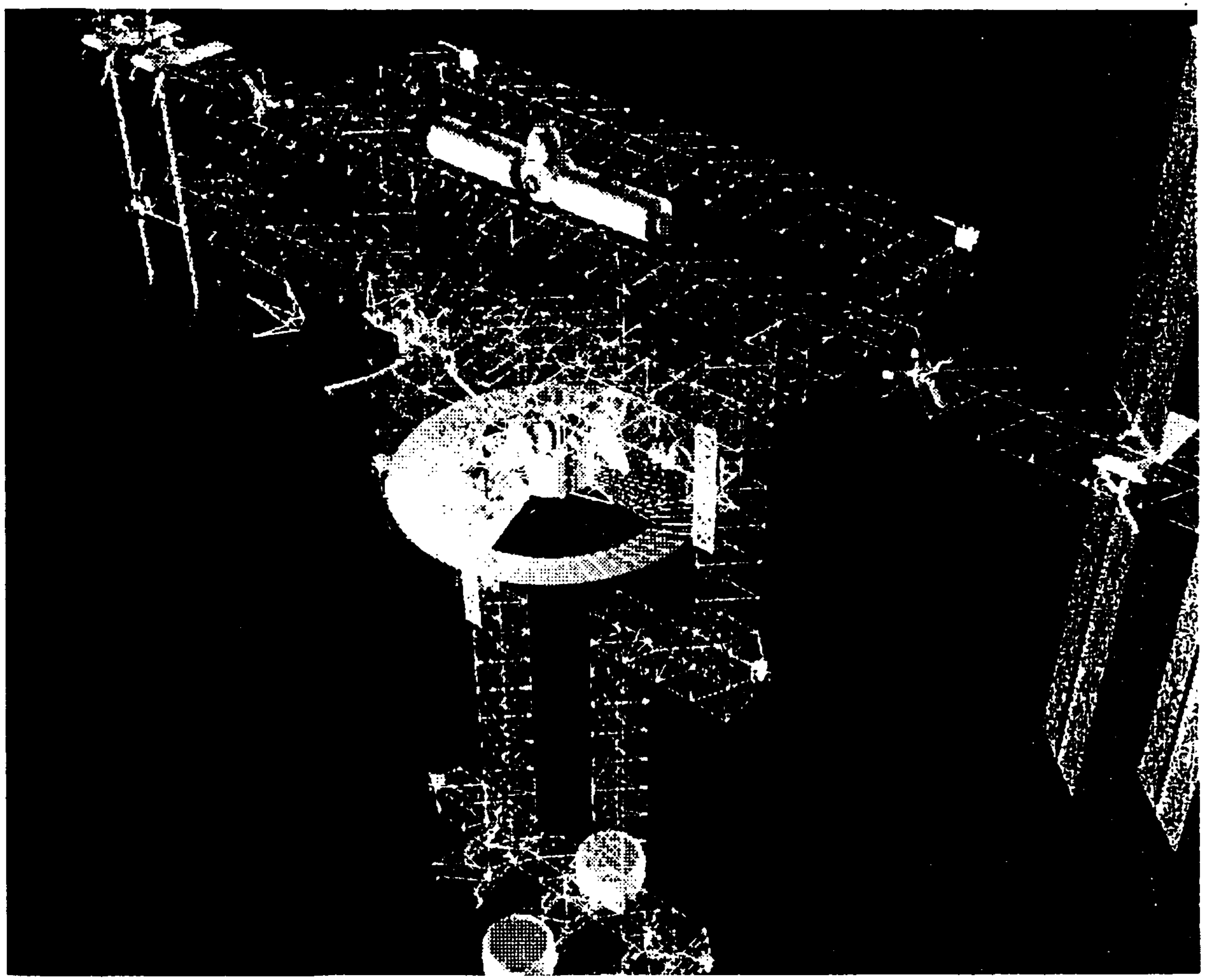
MSC placing core in construction position



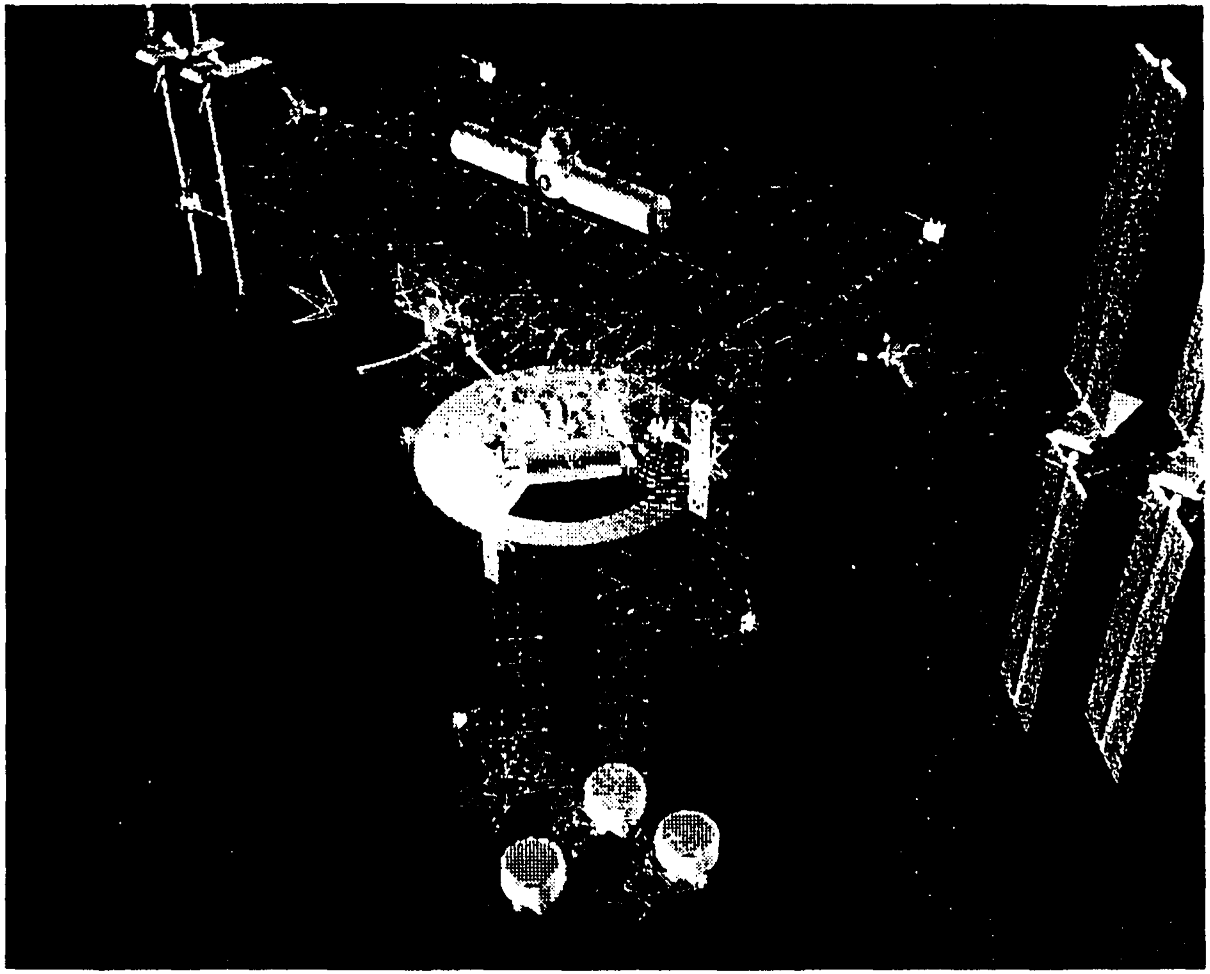
Misc structures 1st aero shell piece



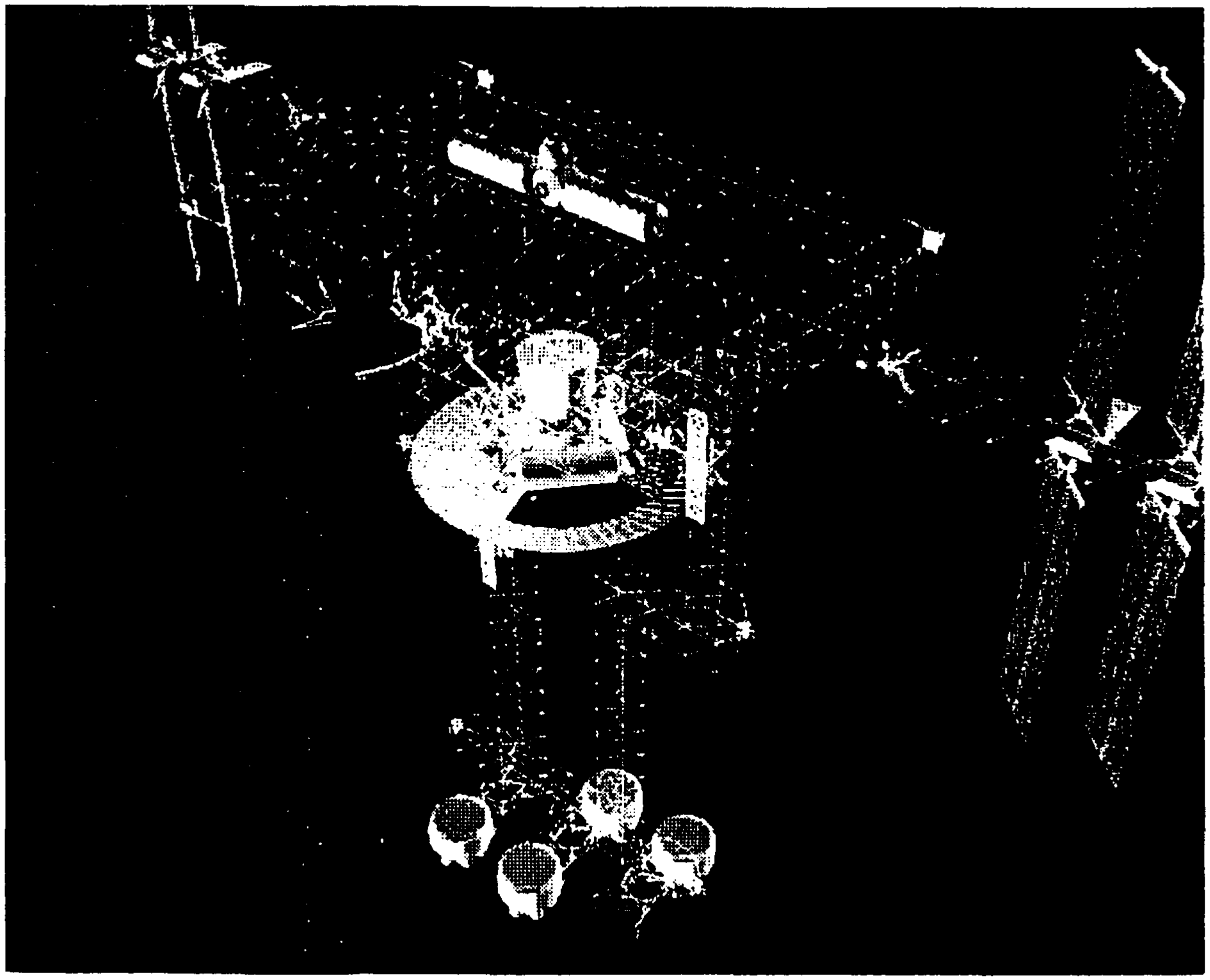
MSC places 1st aeroshell piece



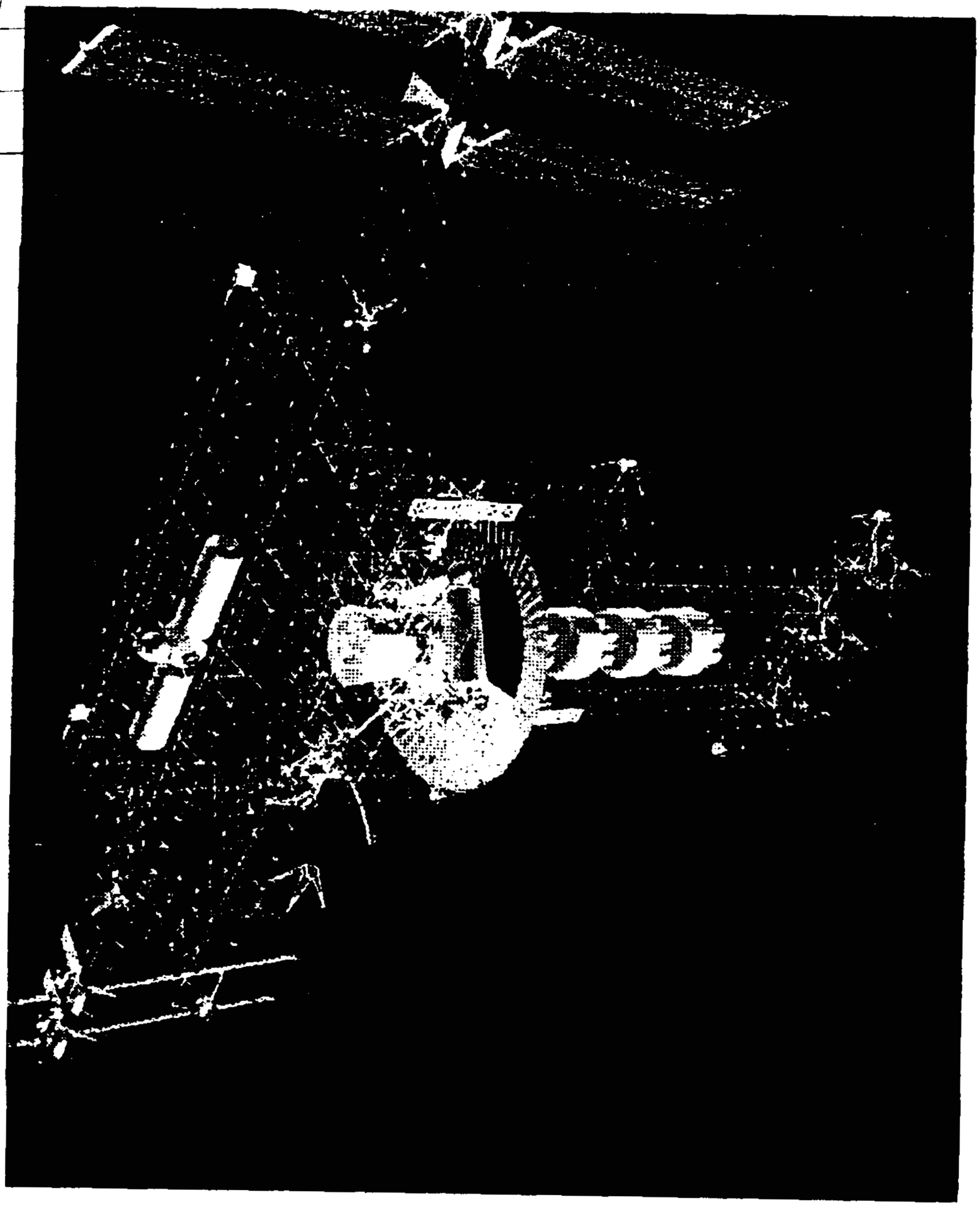
Finish of Flight 2



finish of flight 3



finish of flight 4



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16. Abstract
This report contains the individual presentations delivered at the Space Station Evolution Symposium in League City, Texas on February 6, 7, 8, 1990. Personnel responsible for Advanced Systems Studies and Advanced Development within the Space Station Freedom Program reported on the results of their work to date. Systems Studies presentations focused on identifying the baseline design provisions (hooks and scars) necessary to enable evolution of the facility to support changing space policy and anticipated user needs. Also emphasized were evolution configuration and operations concepts including on-orbit processing of space transfer vehicles. Advanced Development task managers discussed transitioning advanced technologies to the baseline program, including those near-term technologies which will enhance the safety and productivity of the crew and the reliability of station systems. Special emphasis was placed on applying advanced automation technology to ground and flight systems.

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