N72-32797

CONTRACT NAS9-12068
DRL LINE ITEM 7

MSC 04482
SD 72-SA-0007

ORBITAL OPERATIONS STUDY

VOLUME II - INTERFACING ACTIVITIES ANALYSES

PART 2 - STRUCTURAL AND MECHANICAL ACTIVITY GROUP

FINAL REPORT

MAY 1972

APPROVED BY

L. R. Hogan

L. R. Hogan
Study Manager
ORBITAL OPERATIONS STUDY

Space Division
North American Rockwell

CONTRACT NAS9-12068
DRL LINE ITEM 7

MSC 04482
SD 72-SA-0007

ORBITAL OPERATIONS STUDY

VOLUME II - INTERFACING ACTIVITIES ANALYSES

PART 2 - STRUCTURAL AND MECHANICAL ACTIVITY GROUP

FINAL REPORT

MAY 1972

APPROVED BY

L. R. Hogan

L. R. Hogan
Study Manager
ORBITAL OPERATIONS STUDY

Space Division
North American Rockwell

TECHNICAL REPORT INDEX/ABSTRACT

ACCESSION NUMBER							DOCUMENT SECURITY CLASSIFICATION
							UNCLASSIFIED

TITLE OF DOCUMENT

ORBITAL OPERATIONS STUDY, FINAL
VOLUME II, PART 2 - STRUCTURAL AND MECHANICAL ACTIVITY GROUP

LIBRARY USE ONLY

AUTHOR(S)

*MATTSON, H.L., *GIANFORMAGGIO, A., *ANDERSON, N.R.

CODE	ORIGINATING AGENCY AND OTHER SOURCES	DOCUMENT NUMBER
QN085282	SPACE DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION, DOWNEY, CALIFORNIA	SD 72-SA-0007 VOLUME II, PART 2

PUBLICATION DATE	CONTRACT NUMBER
MAY 1972	NAS9-12068

DESCRIPTIVE TERMS

*ELEMENT INTERFACES, *ALTERNATE APPROACHES, *DESIGN CONCEPTS, *OPERATIONAL PROCEDURES, *FUNCTIONAL REQUIREMENTS, *DESIGN INFLUENCES, *MATING, *ORBITAL ASSEMBLY, *SEPARATION, *PAYLOAD DEPLOYMENT, *PAYLOAD RETRACTION

ABSTRACT

THIS DOCUMENT IS VOLUME II, PART 2 OF THE FINAL REPORT OF THE ORBITAL OPERATIONS STUDY. ELEMENT INTERFACES, ALTERNATE APPROACHES, DESIGN CONCEPTS, OPERATIONAL PROCEDURES, FUNCTIONAL REQUIREMENTS, DESIGN INFLUENCES, AND APPROACH SELECTION ARE PRESENTED FOR EACH OF THE FOLLOWING INTERFACING ACTIVITIES: MATING, ORBITAL ASSEMBLY, SEPARATION, EOS PAYLOAD DEPLOYMENT, EOS PAYLOAD RETRACTION.

Space Division
North American Rockwell

PRECEDING PAGE BLANK NOT FILMED

FOREWORD

This report contains the results of the analyses conducted by the Space Division of North American Rockwell during the Orbital Operations Study, Contract NAS9-12068, and is submitted in accordance with line item 7 of the Data Requirements List (DRL 7).

The data are presented in three volumes and three appendixes for ease of presentation, handling, and readability. The report format is primarily study product oriented. This study product format was selected to provide maximum accessibility of the study results to the potential users. Several of the designated study tasks resulted in analysis data across elements and interfacing activities (summary level); and also analysis data for one specific element and/or interfacing activity (detailed level). Therefore, the final report was structured to present the study task analysis results at a consistent level of detail within each separate volume.

The accompanying figure illustrates the product buildup of the study and the report breakdown. The documents that comprise the reports are described below:

Volume I - MISSION ANALYSES, contains the following data:

- o Generic mission models that identify the potential earth orbit mission events of all the elements considered in the study
- o Potential element pair interactions during on-orbit operations
- o Categorized element pair interactions into unique interfacing activities

Volume II - INTERFACING ACTIVITIES ANALYSIS, contains the following data:

- o Cross reference to the mission models presented in Volume I
- o Alternate approaches for the interfacing activities
- o Design concept models that are adequate to implement the approaches
- o Operational procedures to accomplish the approaches
- o Functional requirements to accomplish the approaches
- o Design influences and preferred approach selection by element pairs.

This volume is subdivided into four books or parts which are:

Part 1. INTRODUCTION AND SUMMARY - Condensed presentation of the significant results of the analyses for all interfacing activities

Part 2. STRUCTURAL AND MECHANICAL ACTIVITY GROUP

- o Mating
- o Orbital Assembly
- o Separation
- o EOS Payload Deployment
- o EOS Payload Retraction and Stowage

Part 3. DATA MANAGEMENT ACTIVITY GROUP

- o Communications
- o Rendezvous
- o Stationkeeping
- o Detached Element Operations

Part 4. SUPPORT OPERATIONS ACTIVITY GROUP

- o Crew Transfer
- o Cargo Transfer
- o Propellant Transfer
- o Attached Element Operations
- o Attached Element Transport

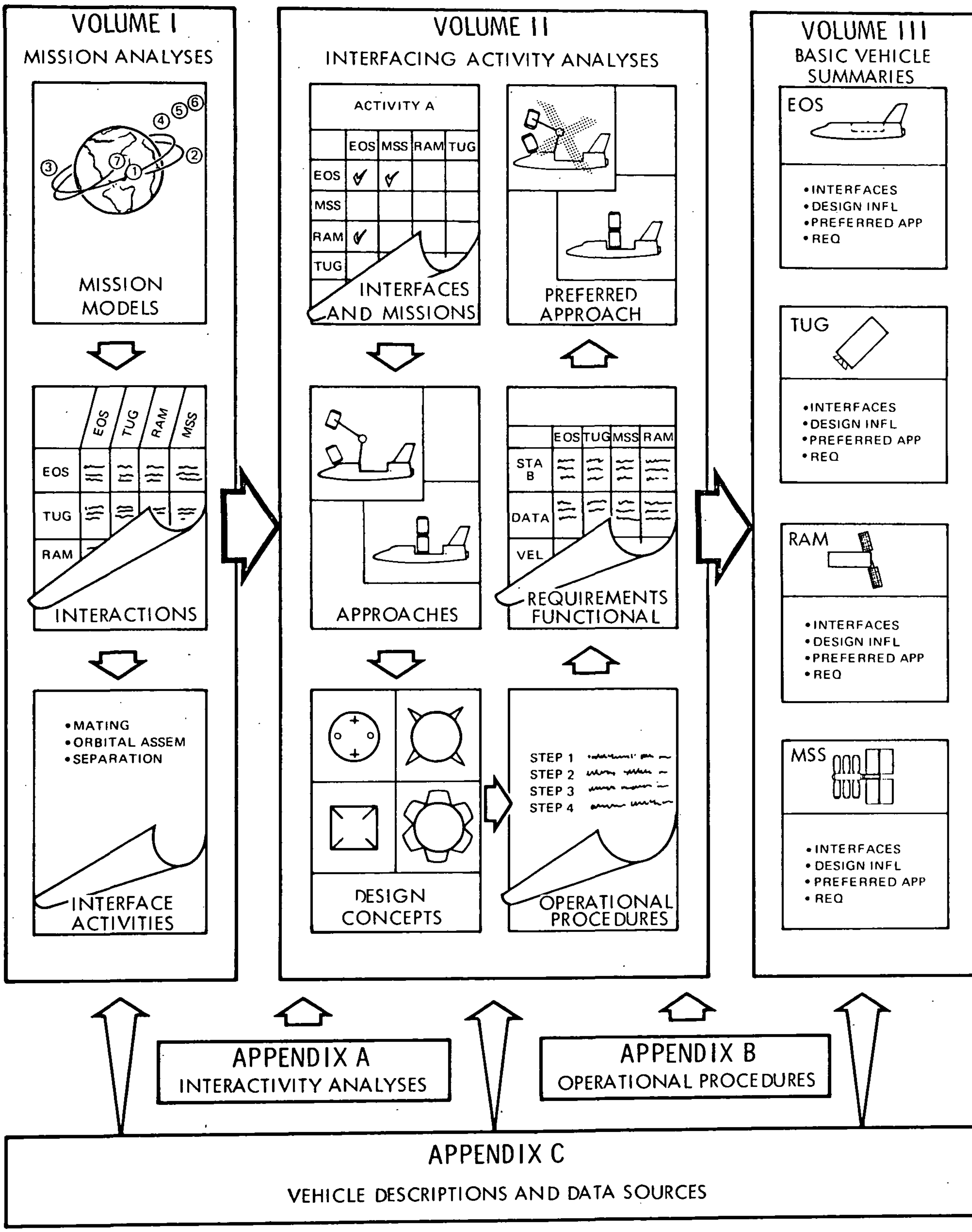
Volume III - BASIC VEHICLE SUMMARIES, contains a condensed summary of the study data pertaining to the following elements:

- o Earth Orbital Shuttle
- o Space Tug
- o Research and Applications Modules
- o Modular Space Station

Appendix A - INTERACTIVITY ANALYSES, contains many of the major trades and analyses conducted in support of the conclusions and recommendations of the study.

Appendix B - OPERATIONAL PROCEDURES, contains the detailed step-by-step sequence of events of each procedure developed during the analysis of an interfacing activity.

Appendix C - VEHICLE DESCRIPTIONS AND DATA SOURCES, presents a synopsis of the characteristics of the program elements that were included in the study (primarily an extraction of the data in Appendix I of the contract statement of work), and a bibliography of the published documentation used as reference material during the course of this study.


VOLUME I
MISSION ANALYSES
MISSION MODELS
EOS
TUG
RAM
MSS
INTERACTIONS
•MATING
•ORBITAL ASSEM
•SEPARATION
INTERFACE ACTIVITIES
VOLUME II
INTERFACING ACTIVITY ANALYSES
ACTIVITY A
EOS MSS RAM TUG
INTERFACES AND MISSIONS
PREFERRED APPROACH
APPROACHES
STA B
DATA
VEL
EOS TUG MSS RAM
FUNCTIONAL REQUIREMENTS
DESIGN CONCEPTS
STEP 1
STEP 2
STEP 3
STEP 4
OPERATIONAL PROCEDURES
VOLUME III
BASIC VEHICLE SUMMARIES
EOS
TUG
RAM
MSS
•INTERFACES
•DESIGN INFL
•PREFERRED APP
•REQ
APPENDIX A
INTERACTIVITY ANALYSES
APPENDIX B
OPERATIONAL PROCEDURES
APPENDIX C
VEHICLE DESCRIPTIONS AND DATA SOURCES

INTRODUCTION

This specific book is one part of the analyses conducted for each of fourteen interfacing activities. The results from five of the activities are documented in this book (Volume II Part 2). These activities are as follows:

Section 1.0 MATING

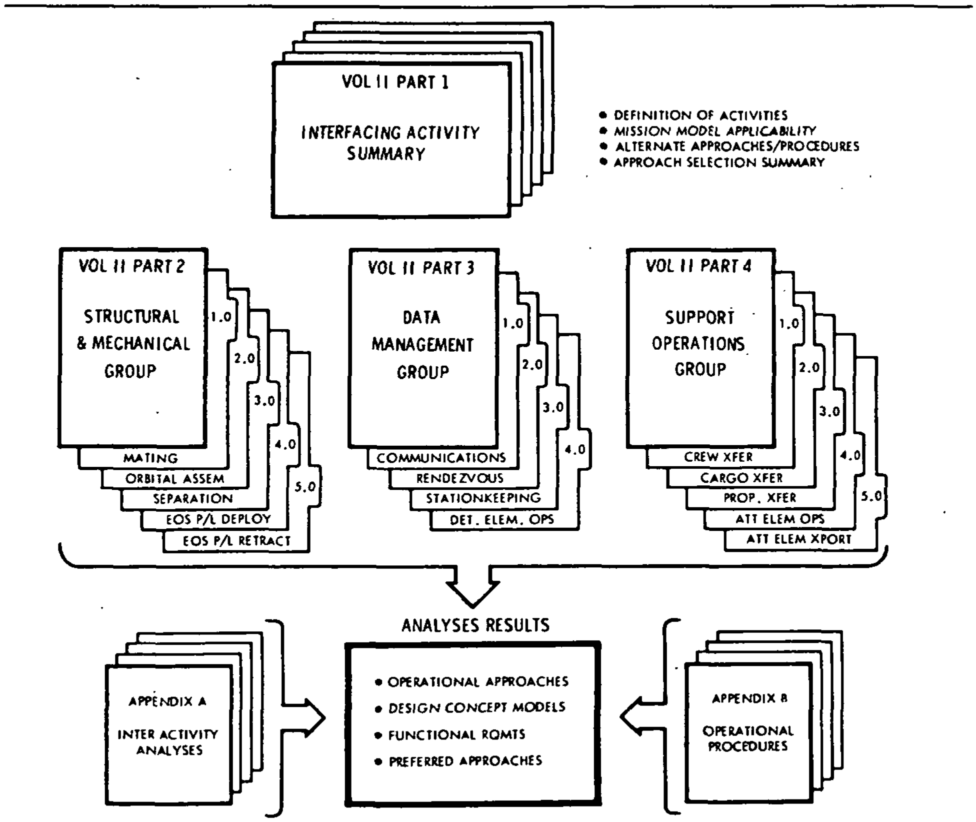
Section 2.0 ORBITAL ASSEMBLY

Section 3.0 SEPARATION

Section 4.0 EOS Payload Deployment

Section 5.0 EOS Payload Retraction and Storage

The following illustration shows the relationship of this book to the other related documents.



PRECEDING PAGE BLANK NOT FILMED

CONTENTS

		Page
SECTION 1.0 MATING		
1.1	Summary	1-1
1.2	Element Interfacing and Mission Model Matrices	1-3
1.3	Alternate Approaches	1-9
1.4	Design Concept Models	1-15
1.5	Operational Procedures	1-43
1.6	Functional Requirements	1-47
1.7	Design Influences and Approach Selection	1-103
SECTION 2.0 ORBITAL ASSEMBLY		
2.1	Summary	2-1
2.2	Element Interface and Mission Model Matrices	2-5
2.3	Alternate Approaches	2-9
2.4	Design Concept Models	2-15
2.5	Operational Procedures	2-29
2.6	Functional Requirements	2-33
2.7	Design Influences and Approach Selection	2-47
SECTION 3.0 SEPARATION		
3.1	Summary	3-1
3.2	Element Interface and Mission Model Matrices	3-3
3.3	Alternate Approaches	3-7
3.4	Design Concept Models	3-11
3.5	Operational Procedures	3-25
3.6	Functional Requirements	3-29
3.7	Design Influences and Approach Selection	3-55
SECTION 4.0 EOS PAYLOAD DEPLOYMENT		
4.1	Summary	4-1
4.2	Element Interface and Mission Model Matrices	4-5
4.3	Alternate Approaches	4-9
4.4	Design Concept Models	4-13
4.5	Operational Procedures	4-23
4.6	Functional Requirements	4-25
4.7	Design Influences and Approach Selection	4-31
SECTION 5.0 EOS PAYLOAD RETRACTION AND STOWAGE		
5.1	Summary	5-1
5.2	Element Interface and Mission Model Matrices	5-5
5.3	Alternate Approaches	5-9
5.4	Design Concept Models	5-13
5.5	Operational Procedures	5-25
5.6	Functional Requirements	5-27
5.7	Design Influences and Approach Selection	5-37

PRECEDING PAGE BLANK NOT FILMED

ILLUSTRATIONS

Figure Page

MATING

Figure		Page
1-1	Mating Interactions	1-4
1-2	Applicable Mission Models for Mating	1-7
1-3	Probe Length Incompatibility	1-12
1-4	Stationkeeping Concept	1-12
1-5	Dual Berth Concept	1-12
1-6	Mating Port Concept Options	1-19
1-7	Effect of Increased Docking Port OD	1-20
1-8	Rotational Oriented Mating Advantages	1-21
1-9	Mating Port Model	1-22
1-10	Ring Design with Apollo Probe Attached	1-23
1-11	Manipulator Configuration	1-25
1-12	Wrist Assembly	1-26
1-13	End Effector Probe and Receptacle	1-26
1-14	TV - Manipulator Interface	1-27
1-15	SCR Target Acquisition and Tracking	1-29
1-16	Payload Passive Reflector Geometry	1-30
1-17	Automatic Docking Either Vehicle with Laser Radar	1-33
1-18	Automatic Docking System Interfaces	1-34
1-19	Direct Docking - Manned Element to Unmanned Element	1-35
1-20	Direct Docking - Manned Element to Manned Element	1-36
1-21	Scanning Laser Radar Basic Block Diagram	1-37
1-22	Fluid Interface Mate Verification	1-39
1-23	Electrical Connector Mate Verification	1-40
1-24	Electrical/Fluid Line Interface	1-40
1-25	Mating Communications Interfaces	1-41
1-26	Procedure Comparison	1-46
1-27	Allowable Misalignment for Appendage Clearance	1-67
1-28	Mating Port Displacement Relative to Vehicle Att. Hold	1-69
1-29	Mass Relationships	1-72
1-30	Impact Energy Vs. Equivalent Mass	1-74
1-31	Energy Attenuation Criteria for Direct Dock	1-75
1-32	Stroke Criteria Vs. Allowable Force	1-76
1-33	Load Vs. Closing Velocity	1-77
1-34	Torque/Stroke Requirements to Null Out 0.05 Fps Relative Velocity	1-81
1-35	Torque/Stroke Requirements to Null Out 0.1 Fps Relative Velocity	1-82
1-36	Torque/Stroke Requirements to Null Out 0.2 Fps Relative Velocity	1-83

Figure		Page
1-37	Torque/Stroke Requirements to Null Out 0.3 Fps Relative Velocity	1-84
1-38	Individual Manipulator Joint Capabilities	1-85
1-39	Direct Docking Concepts for Mating to Small Satellites	1-107

ORBITAL ASSEMBLY

2-1	Orbital Assembly Interactions	2-6
2-2	Element Pair Matrix	2-7
2-3	Orbital Assembly Alternate Approaches Thru Hard Dock	2-10
2-4	Post Capture Rigidization Options	2-11
2-5	Utility Interconnect Alternate Approaches	2-13
2-6	Mating Port Model	2-17
2-7	Rotational Orientation Mating Advantages	2-18
2-8	Automatic Docking Either Vehicle with Laser Radar	2-19
2-9	TV Manipulator Integration	2-20
2-10	Manipulator Model	2-21
2-11	Claw End Effector	2-22
2-12	Probe End Effector	2-22
2-13	Modular Assembly Concepts	2-24
2-14	Parallel Module Assembly	2-25
2-15	Automatic Electrical Interfacing Concept	2-27
2-16	Automatic Multiple Connector Concept	2-28
2-17	Probe/Drogue Fluid Line Connection	2-28
2-18	Procedure Comparison	2-31
2-19	Work Space Requirements	2-38
2-20	MSS Assembly Concepts	2-48
2-21	Weight-Length-Density Correlation for MSS	2-49
2-22	Alignment Errors	2-51
2-23	Direct Dock Modular Cislunar Shuttle Assembly	2-53/54
2-24	Manipulator Modular Cislunar Shuttle Assembly	2-55/56
2-25	Optional Laser Radar Locations	2-57
2-26	Mating Port Mounted Multiple Docking Adapter	2-57
2-27	Engine Assembly Using Direct Dock/Capture Manipulator	2-59
2-28	Engine Assembly with Manipulator on EOS	2-60
2-29	MSS-EOS Module Interchange Using Direct Dock	2-61
2-30	EOS-Tug Module Interchange Using Direct Dock	2-62
2-31	MSS-EOS Module Interchange Using Manipulator	2-63
2-32	EOS-Tug Module Interchange Using Manipulator	2-64
2-33	Direct Dock/Manipulator Utilization for Module Interchange	2-66
2-34	MSS Assembly Stacked on CPS	2-67
2-35	Add-On Rigidization	2-68
2-36	Cislunar Shuttle Payload Assembly	2-69/70
2-37	Example of Controlled Interface Arrangement	2-74

Figure		Page

SEPARATION

3-1	Separation Interactions	3-4
3-2	Applicable Mission Models for Separation	3-6
3-3	Alternate Approaches for Separation	3-7
3-4	Extension - Retraction Probe	3-9
3-5	Manipulator Configuration	3-12
3-6	Claw End Effector	3-13
3-7	Probe End Effector	3-13
3-8	Manipulator Separation Concepts	3-14
3-9	Automatic Separation Either Vehicle with Laser Radar	3-17
3-10	Automatic Separation System Interfaces	3-18
3-11	Separation - Manned Element from Unmanned Element	3-19
3-12	Separation - Manned Element from Manned Element	3-20
3-13	Scanning Laser Radar Basic Block Diagram	3-21
3-14	Separation Communications Interfaces	3-23
3-15	Separation Procedural Comparison	3-28
3-16	Allowable Centerline Deviation for Separation	3-30
3-17	Reflector Spacing Example	3-32
3-18	Basic Shuttle Jet Configuration	3-60
3-19	Modified Jet Configuration	3-61

EOS PAYLOAD DEPLOYMENT

4-1	EOS Payload Deployment Interactions	4-6
4-2	Applicable Mission Models for EOS Payload Deployment	4-7
4-3	Alternate Approaches	4-9
4-4	Orbiter/Payload Envelope	4-13
4-5	Manipulator/Payload Handling	4-14
4-6	Classes of End Effectors	4-15
4-7	Manipulator Deployment Rates	4-16
4-8	Service Panels	4-17
4-9	Clamp Retention Concept	4-18
4-10	Rotating Hinge Retention Concept	4-19
4-11	Selected Retention Concept	4-20
4-12	Pivot Mechanism	4-22
4-13	Payload Shirtsleeve Access	4-30
4-14	Multiple Payload Handling Concept	4-34

Figure | Page

EOS PAYLOAD RETRACTION AND STOWAGE

5-1	EOS Payload Retraction and Stowage Interactions	5-6
5-2	Applicable Mission Models for EOS Payload Retraction and Stowage	5-7
5-3	Alternate Approaches	5-9
5-4	Orbiter/Payload Envelope	5-13
5-5	Manipulator/Payload Handling	5-14
5-6	Classes of End Effectors	5-15
5-7	Manipulator Deployment Rates	5-16
5-8	Service Panels	5-17
5-9	Clamp Retention Concept	5-18
5-10	Rotating Hinge Retention Concept	5-19
5-11	Selected Payload Retention Concept	5-20
5-12	Pivot Mechanism	5-22
5-13	Payload Deployment Mechanism	5-23
5-14	Payload Longitudinal c.g. constraints	5-32
5-15	Retention Point Locations	5-34
5-16	Payload Shirtsleeve Acess	5-35
5-17	Multiple Payload Handling Concept	5-39

TABLES

Table		Page
	MATING	
1-1	Mating Port Evaluation	1-18
1-2	Estimated System Performance Characteristics - SCR	1-38
1-3	Possible Procedural Development Array	1-43
1-4	Mating Procedures	1-44
1-5	Direct Docking Requirements	1-66
1-6	Alignment Component Criteria	1-71
1-7	Equivalent Mass of Mating Pairs (Slugs)	1-96
1-8	Direct Docking Closing Velocity Requirements	1-97
1-9	Mating Concept Comparison	1-104
1-10	Mating Hardware Preference	1-113
	ORBITAL ASSEMBLY	
2-1	Procedure/Criteria Matrix	2-30
2-2	Restraint Technique Characteristics	2-35
2-3	Requirement/Mode Applicability	2-43
2-4	Element/Mode Applicability	2-44
2-5	Alternate Comparison	2-72
	SEPARATION	
3-1	Estimated System Performance - Scanning Laser Radar	3-22
3-2	Functional Requirements by Element Pair	3-40
3-3	Separation Approach Comparison	3-56
3-4	Separation Hardware Preference	3-65
	EOS PAYLOAD DEPLOYMENT	
4-1	Approach Evaluation Selection	4-33

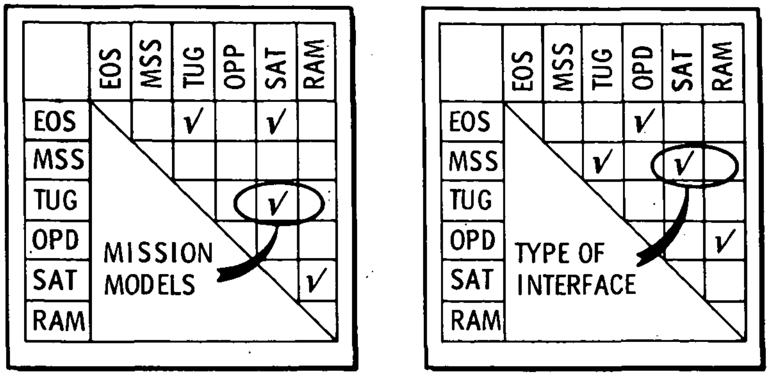
Table | Page

EOS PAYLOAD RETRACTION AND STOWAGE

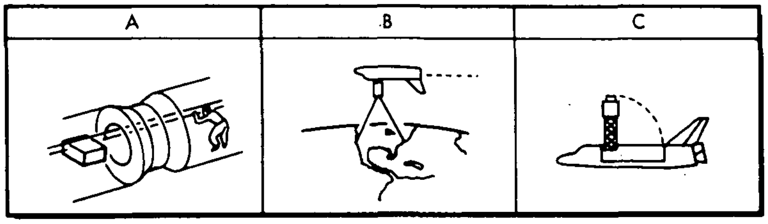
5-1 Approach Selection 5-38

1.0 MATING

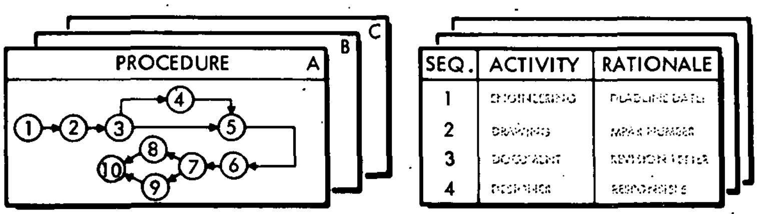
ELEMENT INTERFACES



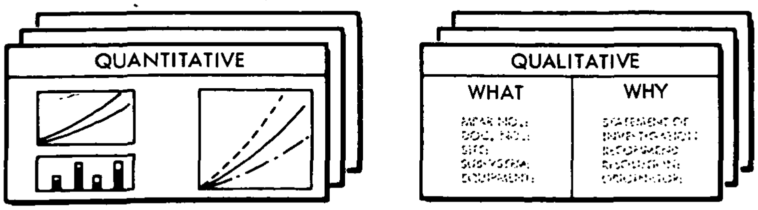
ALTERNATE APPROACHES AND DESIGN CONCEPTS



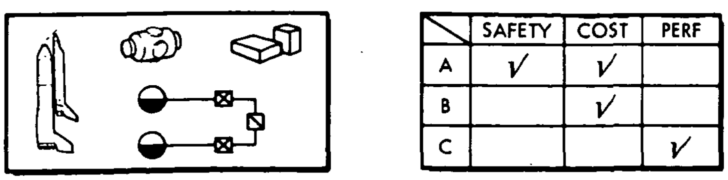
OPERATIONAL PROCEDURES



FUNCTIONAL REQUIREMENTS



DESIGN INFLUENCES AND APPROACH SELECTION



1.0 MATING

The mating activity is the joining together of two elements as opposed to the orbital assembly activity which always involves a minimum of three elements and/or modules. The mating activity includes precontact, contact, and post-contact events. Precontact events include alignment of the mating vehicles and reduction of relative velocities. Contact includes capture, impact energy attenuation and relative velocity nulling. Post-contact events include transposition and berthing (for the case of manipulator utilization), draw down of the interfaces, structural alignment and rigidization, and interconnect of interfacing utilities.

1.1 SUMMARY

From the total list of elements identified for this study, there are 117 combinations that exist where one or more orbital interfaces can occur. Of these, 105 combinations can involve a mating operation. Eleven representative mission models were developed to clarify the interrelationships between the various program elements. Of these eleven generic missions, all but two involve mating activities. The element interfaces and mission models section expands on these interfaces and provides matrices which identify the interfacing pairs and applicable missions.

Three generic concepts were identified as viable alternates for performing the mating operations: (1) direct docking, (2) extension-retraction mechanism, and (3) manipulator berthing. The extension-retraction mechanism was eliminated relatively early in the study because it was so similar to the manipulator concept (essentially a single degree of freedom manipulator), but did not provide the synergistic benefits exhibited by multiple degree of freedom manipulators. The direct docking concept was expanded to include manual and automatic approaches, each of which was independently analyzed.

The design concept model section identifies a series of conceptual models that were utilized to validate manipulator berthing and direct docking concepts. The models include mating port design, manipulator design, alignment and range and range rate determination aids, various utility interface methodology designs, and an RF communications model. Where applicable, the section includes trade analyses behind the selection of a model.

Three procedures were developed for performing mating and are presented in the operational procedure section and Appendix B. These three procedures are applicable to five different mating concepts: (1) manned element direct docking to a manned element, (2) manned element direct docking to an unmanned element, (3) unmanned element direct docking to an unmanned element, (4) manned element performing a manipulator berth with another manned element, and (5) manned element performing a manipulator berthing with an unmanned element. At least one of the five concepts is applicable to any of the element-to-element mating interfaces identified.

The functional requirements section is a list of the requirements applicable to the mating activity. In most cases, the requirements are generic in that they apply to any orbital mating operation. However, some are directly related to either the direct docking alternatives or the manipulator concept. Where applicable, the requirements have been quantified; in some cases with specific limits and other cases the range of limits have been specified.

The major requirements are vehicle closing velocities and alignment to execute a direct dock and vehicle alignment for capture by a manipulator. These requirements are summarized as follows:

Direct Dock

Logitudinal velocity:	0.2 fps to 0.4 fps
Lateral velocity:	0.09 fps to 0.5 fps
Angular velocity:	0.06 dps to 0.3 dps
Lateral miss distance:	plus or minus 6 inches
Misalignment (p,y,r):	plus or minus 3 degrees
Vehicle attitude hold:	plus or minus 0.2 degrees to plus or minus 1.0 degree

Manipulator Capture

Vehicle attitude hold:	plus or minus 0.2 degrees
Vehicle rate stabilization:	plus or minus 0.05 degrees/second

The preferred mating approach section analyzes the direct dock and manipulator approaches to mating and makes a preferred selection. If the mating activity is singularly considered and if all element pairs are considered viable and a single concept is to be selected, direct automatic dock is preferred. The design impact on small satellites for incorporation of a "standardized" docking port is impractical. Therefore, for missions involving satellite matings, supplemental hardware (kit) such as an extension-retraction device) must be employed by the EOS orbiter or tug vehicles for these selected operations. If a manipulator is to be included in the program, it is recommended that it be incorporated as a mating tool only on the EOS orbiter.

1.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

Figure 1-1 lists all the study elements and identifies in matrix form the feasible mating interfaces.

The matrix shows that of the potential 117 interfaces identified, 105 involve the mating activity. The 12 interfaces that do not involve matings are summarized as follows:

1. The nonreturnable tug by definition, once separated, will not be remated.

2. The EOS attached RAM is mated on the ground and never physically separates from the EOS during operations.

3. The EOS-delivered satellites and EOS plus third-stage satellites identify types of delivery. Satellite matings for return are identified under the return and resupply satellite column.

4. The OIS is a ground to orbital delivery element and all mating operations are performed on the ground.

Interactions that involve matings are summarized in the following paragraphs.

The EOS orbiter and tug elements are utilized as the prime logistics vehicles. In this capacity they perform a variety of operations shuttling hardware, consumables, and personnel between ground and orbiting elements and between interorbital elements. The transfer of cargo (hardware, consumables and personnel) from an EOS orbiter or a tug can be accomplished utilizing a direct mating between the EOS orbiter or tug and another element, or a cargo module that can fly between the EOS orbiter or tug and the element, or a cargo module that can be transported via manipulators between the EOS orbiter or tug and the element, or a cargo module that can be docked directly to the element using the EOS orbiter or tug as a propulsive and control element. The EOS orbiter also is used as the prime orbital delivery vehicle, transporting elements or modules of an element from ground to low earth orbit or to an already orbiting element. Conversely, the EOS orbiter can be used to retrieve low earth orbiting elements or modules of low earth orbiting elements and return them to ground.

The ground-based tug and space-based tugs also are used to retrieve orbiting hardware for return to earth. However, tug operations start at a low earth orbital altitude. The ground-based tug is delivered to a low earth orbit (approximately 100 nautical miles) by an EOS orbiter from which it separates and performs the retrieval operation and then returns with its cargo to the EOS orbiter for return to earth.

The space-based tug performs similar operations as the ground-based tug, except that this vehicle, being space-based, does not normally return to ground

		SPACE VEHICLE INVENTORY																								
			TUG				RAM				SATELLITE				MSS		CPS				LUNAR PROGRAM SYSTEMS					
		EOS	NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP	EOS RESUP MODS	LOW EO	GEO SYNCH	OIS	EO SHTL	CLS	RNS	OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	OPD
	EOS	M	X	M	M	M	X	M	M	M	X	X	M	M	M	M		M	M	M	M	M	M	M	M	M
TUG	NON RET											X														
TUG	RETURNABLE											X														
TUG	GRD BASED				M	M			M	M		X	M	M		M		M	M	M		M	M	M		M
TUG	SPACE BASED					M			M	M		M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
RAM	ATT. EOS																									
RAM	DET. EOS																									
RAM	ATT. MSS														M	M		M		M						
RAM	DET. MSS														M	M		M		M						
SATEL	EOS DELIV																									
SATEL	EOS + 3RD ST																									
SATEL	RETR, RESUP																									
	EOS RESUP MODS													M	M	M		M	M	M		M	M	M		M
MSS	LOW EO														M											
MSS	GEOSYNCH															M		M		M						
CPS	OIS																	X	X	X	X					X
CPS	EO SHTL																	M								M
CPS	CLS																		M		M	M	M	M	M	M
	RNS																			M	M	M	M	M	M	M
LPS	OLS																				M	M	M	M		
LPS	TUG UNMAN																							M	M	M
LPS	TUG MAN																							M	M	M
LPS	RESUP MOD																							M	M	M
LPS	LSB																								M	
	OPD																									M

LEGEND

Potential Interactions	117
Actual Interactions	105
M - Mating Activity	
X - Not Applicable	

Figure 1-1. Mating Interactions

after an operation is accomplished but returns to a home base, the base selection depending upon the tug configuration (i.e., a manned tug would utilize a space station as a home base, whereas an unmanned tug may utilize a space station, an OPD, an independent orbit, etc.). As shown in the matrix, the space-based tug mates with all the elements the ground-based tug mates with, plus the low earth orbital MSS, the OIS, the OLS, and the LSB. The reason for the ground-based tug exceptions are the effective utilization of available elements. Whereas the space-based tug appears efficient for low earth orbital logistics operations, the ground-based tug for the same purpose appears inefficient (except for possible retrieval or rescue missions) when an EOS orbiter is available for the same task. The ground-based tug, however, could be utilized because of configuration and operational involvement, as a tanker for refueling operations and is so noted in the matrix where high propellant usage vehicles (EO shuttle, CLS, and RNS) are utilized.

RAM elements involve attached and detached configurations. The EOS attached RAM's, by definition, never separate from the EOS orbiter. The MSS attached RAM's are separated from the MSS elements for periodic replacement and refurbishment. The RAM replacement activity utilizes logistics vehicles for transport. Detached RAM's are associated with EOS and MSS operations. The EOS orbiter operation depends solely upon EOS orbiter support. The EOS orbiter delivers the RAM to orbit, resupplies it, and retrieves it when the experiment is concluded. The MSS supported detached RAM's are periodically transported between the MSS and the RAM operational orbit utilizing logistics vehicles or the RAM may maneuver independently between the MSS and its operational orbit.

Satellites can be retrieved and returned to earth or resupplied on a periodic basis. The retrieval and resupply operations involve logistics vehicles for support. These interfaces are shown in the matrix under the satellite return and resupply column. The EOS plus third-stage satellite mating with the space-based tug comes about when the satellite is not equipped with a third stage. The operation requires the EOS orbiter to deliver the satellite to a low earth orbit, whereupon, the space-based tug picks up the satellite and essentially becomes the third stage and delivers the satellite to a higher energy orbit.

Earth orbital resupply modules are designed to be shuttled between earth and orbiting elements. The transporting element always will be one or more of the logistics vehicles. Because resupply modules are not limited to low earth orbital missions, mating activities will occur between the high-energy orbit delivery elements (CPS, RNS) and the resupply module. This operation has one or more of the logistics vehicles transporting the resupply module to one of the high-energy orbital vehicles for further transport activities.

Low earth orbital MSS mating activities include modular assembly of the element, cargo module logistic support, RAM support, and EOS orbiter support activities. Each of these operations can involve some type of mating activity. The geosynchronous MSS involves all of the low earth orbital MSS mating activities and adds the mating interaction with the EO shuttle and the RNS. This latter activity occurs when the MSS modules are to be transported to the geosynchronous orbit for final assembly.

The CPS (OIS) element is utilized to deliver heavy payloads to low earth orbit that cannot be transported by an EOS. Other CPS elements (EO shuttle and CLS) are used to transport heavy payloads from low earth orbit to higher energy orbits. The single mating interface between the OIS and the space tug occurs if the OIS requires support for delivery to a particular parking orbit or for disposal assistance. The EO shuttle and the CLS vehicles would require mating with any element it is going to deliver to a higher energy orbit. In addition, these elements can be multi-stage elements which can be mated in orbit and remated after the required operations have been completed.

The RNS element is used in the same manner as are the EO shuttle and CLS and can also be partially assembled and disassembled in low earth orbit.

Lunar program systems can be assembled in low earth orbit into an intermediate configuration such that the delivery element payload can be optimized and the configuration assembled to withstand the boost loads. Lunar tugs and resupply modules mate with low earth orbital logistics elements for inter-transfer of cargo.

Finally, the OPD is involved in mating activities whenever an element arrives for refueling. Also, the OPD can be designed for modular assembly and disassembly operations.

Figure 1-2 utilizes the same matrix format as Figure 1-1 to identify the type of missions where the noted mating activities can occur. As shown, mating activities can be involved in almost all of the 11 missions developed in Volume I. The only exceptions are Missions 1 and 3. Mission 1 is strictly an emplacement mission, whereby an EOS orbiter delivers a payload to orbit and returns directly to earth. Mission 3 is an EOS orbiter sortie mission, where the EOS orbiter delivers an experiments payload to earth orbit, remains attached to the payload for a specified length of time while the experiment operations are conducted, and then returns to earth.

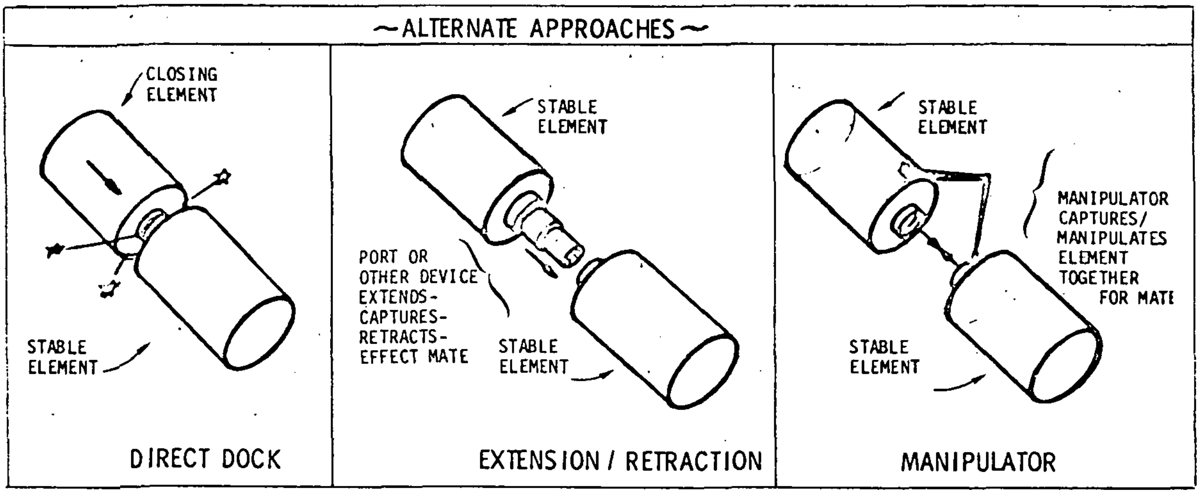
		SPACE VEHICLE INVENTORY																							
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	2		2,7	2,7,8	2,4,5		2	2	2			2	2	2	2		2,10	2,10	2,11	2	2	2	2	2	2
TUG	NON RET																									
	RETURNABLE																									
	GRD BASED				8	8			8	7,8			8	7,8		7,8		8	8	8		7,8	7,8	7,8		8
	SPACE BASED					4			5	4,5		4	4,5	5	5	5	5,6,9	5,6,10	5,6,10	5,6			4	4,5	4,5	5,6
RAM	ATT. EOS																									
	DET. EOS																									
	ATT. MSS														2,4,5,8	4,5,7,8		2,4,5,8		2,4,5,8						
	DET. MSS														2,4,5,7,8	4,5,7,8		10		11						
SATEL	EOS DELIV																									
	EOS + 3RD ST																									
	RETR, RESUP																									
	EO. RESUP MODS													2,4,5,8	2,4,5,8	4,5,8		2,4,5,8,10	2,4,5,8,10	2,4,5,8,11		2,4,5,8	2,4,5,8	2,4,5,8		2,4,5,8
MSS	LOW EO														2,4,5,6,8											
	GEOSYNCH															4,7,8,10,11		10		11						
CPS	OIS																	9	9	9	9					9
	EO SHTL																	10								10
	CLS																		10		10	10	10	10		10
	RNS																			11	11,2,4,5	11,2,4,5,8	11,2,4,5,8	11,2,4,5,8	11,2,4,5,8	11
LPS	OLS																				2,4,5,9,10,11	2,4,5,8,9,10	2,4,5,8,9,10,11	2,5,7,8,9,10,11		
	TUG UNMAN																							2,4,5,7,9,10,11	9,10,11	2,4,5,8,10,11
	TUG MAN																							2,4,5,7,9,10,11	9,10,11	2,4,5,8,10,11
	RESUP MOD																							2,4,5,7,9,10,11	2,4,5,7,9,10,11	2,4,5,8,10,11
	LSB																								2,4,5,7,9,10,11	
	OPD																									2,4,5,6,7,8,9

Figure 1-2. Applicable Mission Models for Mating

PRECEDING PAGE BLANK NOT FILMED

1.3 ALTERNATE APPROACHES

Three generic concepts were initially considered to be viable options for mating the identified element pair configurations: (1) direct docking, (2) extension-retraction capture mechanism, and (3) manipulator berthing. Each of these approaches are candidates for employing manual controlled or automatic/remote controlled techniques. The following figure illustrates these three alternates.



DIRECT DOCKING

The "historical" approach to docking consists of flying one vehicle into the other to make contact at a docking interface. The docking interface must then be designed to control the collision by absorbing the impact energy, effecting a capture to prevent rebound separation, and force alignment of the two vehicles. Rigidizing of the two vehicles in the docked position is accomplished by providing a draw down or shock absorber retract capability, such that a series of rigidizing latches engage the opposing docking port to structurally hold the vehicles together.

A classical example of a manually controlled impact docking is the Apollo docking maneuver. The Russian Salyut docking maneuver is an example of an automatic/remote-controlled impact docking with similar functions as that of the Apollo docking system. The Russian example illustrates that even though the spacecraft is manned, automated control of the approach to docking contact can be provided by electronic alignment, range, and range rate sensors if found desirable.

EXTENSION-RETRACTION

Rather than flying two free-flying vehicles together to accomplish mating, a docking system that can extend or reach out to the other vehicle and effect capture can avoid high-energy impacts. The extension-retraction mating concept has two elements stationkeeping within close proximity of each other, aligning docking ports, stabilizing, and maintaining attitude control. A docking probe is extended from one of the ports and is captured by the other port. The probe is then retracted, pulling the vehicles together into a hard mate. Probe lengths and stationkeeping clearance distances are critical parameters for this option. The criteria are configuration-dependent, and a universal probe and separation distance may not be achievable. Figure 1-3 illustrates this problem. Another problem is that of stowing the device. Considerable space is required at the interface of the mated elements in order not to interfere with the passageway and utility interconnects. Because of these two problems and because this concept is essentially a single-degree-of-freedom manipulator subject to the same requirements and procedures as a multiple degree-of-freedom device, it will not be independently considered any further in this study.

MANIPULATOR

The dexterity and low momentum of the manipulator, compared to maneuvering the entire vehicle for direct docking, permits a low-energy capture. Beyond the capture phase, however, the manipulator system must provide the same functions as the impact system. It must force alignment of the two vehicles, draw them together in the berthing mode, and seat the vehicle interfaces so that latches actuate to hold the vehicles in position.

The "classical" example of manipulative operations are those found in the handling of radioactive elements or deep-sea vehicle applications, where the manipulator acts as an analog of human arms in an environment totally hostile to the human. At present, their application to space activity is the subject of intense study. Historically, manipulators have been operated manually by a human operator. Computer-aided control has been used to assist the manipulator in achieving near-human dexterity. More recently, fully automated manipulators with manual remote control override capability have been developed.

Manipulators include single degree-of-freedom devices and multiple degree-of-freedom devices.

The multiple degree-of-freedom device is more complex; however, it has the flexibility of performing operations other than mating (i.e., assembly and cargo transfer). Whereas the single degree-of-freedom manipulator must be located at each port, the multiple-degree device can be located at any single position on an element (the criteria being arm length and number of degrees of freedom). Two methods can be utilized to perform mating operations utilizing the multiple degree-of-freedom manipulator:

1. "Stationkeeping" method has the two elements stationkeep within reach of a manipulator, and a third element is manipulated across the span into a hard berth. Figure 1-4 illustrates this operation utilizing an EOS transporting a cargo module to an MSS. The EOS and MSS stationkeep, and the cargo module is manipulated into proper position on the MSS.

2. The "dual berth" method first has the element containing the manipulator capture one of the mating elements. To perform this operation, the active element stationkeeps at a proper distance from and at the proper attitude with respect to the other element. The manipulator is then deployed and maneuvered to engage a receptacle on the element being captured. The manipulator removes undesired relative motion between the elements by resisting this motion in the joints of the manipulator or through some other scheme. The captured element is then manipulated into a hard berth. The third element can then be manipulated to the proper position on the berthed element. Figure 1-5 depicts this operation utilizing an EOS transporting a cargo module to an MSS. The EOS, with a manipulator, berths the MSS to a port on the EOS. The cargo module is then manipulated onto the proper MSS port. This method provides the best stability during the docking operation and is more adaptable to automation.

COMPARISON

The design task of docking two large masses is primarily that of energy attenuation. The primary task can change to that of controlling rebound and vehicle stability simply by reducing the mass of one vehicle with respect to the other to the point where impact loads are "stored" and not absorbed. A single attenuation system can be designed to accommodate a range of vehicle equivalent masses. For example, the range of equivalent mass ($M_1M_2/M_1 + M_2$) attenuated by the Apollo docking system is 1000 slugs in translunar docking and 100 slugs in lunar orbital docking - a ratio of 10 to 1. It is not known at what point the ratio becomes impractical to accommodate.

The manipulator can essentially breach the ratio limit by providing a very low load attenuation of relative motion of small vehicles and a very long stroke for the low load attenuation of large vehicle motion. If the long stroke is obtained by designing long reach arms, weight constraints will dictate highly flexible structure and handling of a payload or captured vehicle on the end of a manipulator greater than 60 feet long will become increasingly difficult to control. Thus the tradeoff between impact systems and extendable capture/berthing systems from a dynamic standpoint is that of deciding which is most practical: (1) to develop a system that can handle a large range of vehicle masses, (2) to use already developed technology and design a number of impact docking systems of limited but overlapping attenuation capability to cover the large range of vehicle masses, or (3) develop a nonlinear attenuation system.

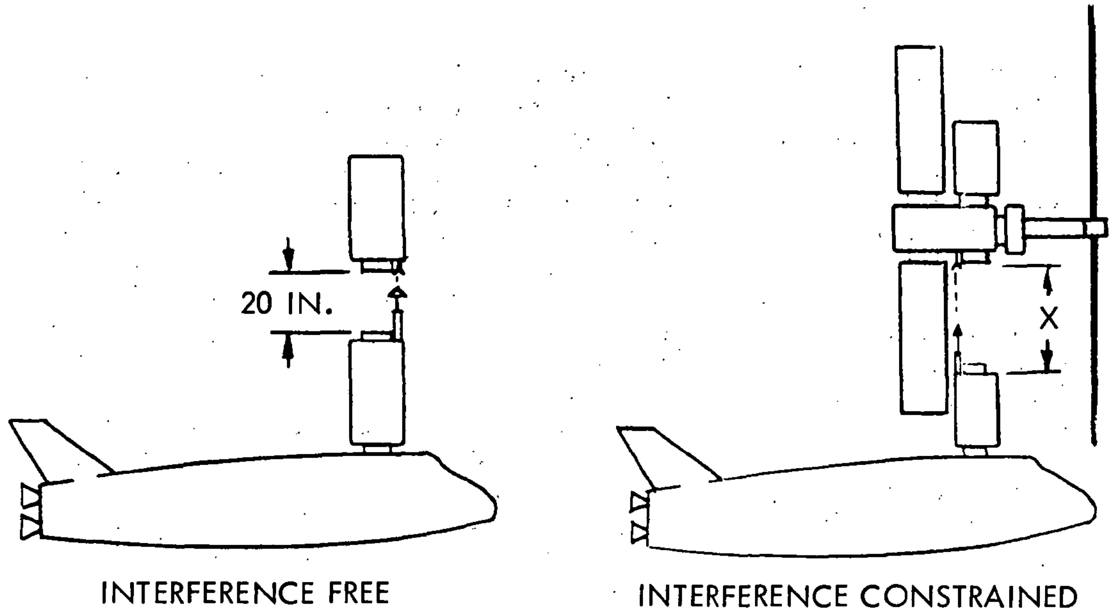


Figure 1-3. Probe Length Incompatibility

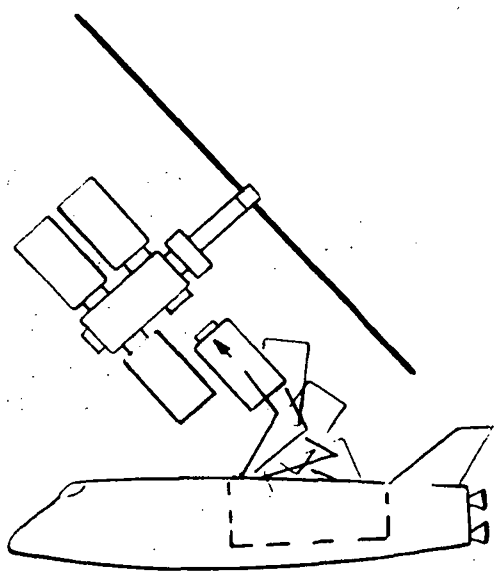


Figure 1-4. Stationkeeping Concept

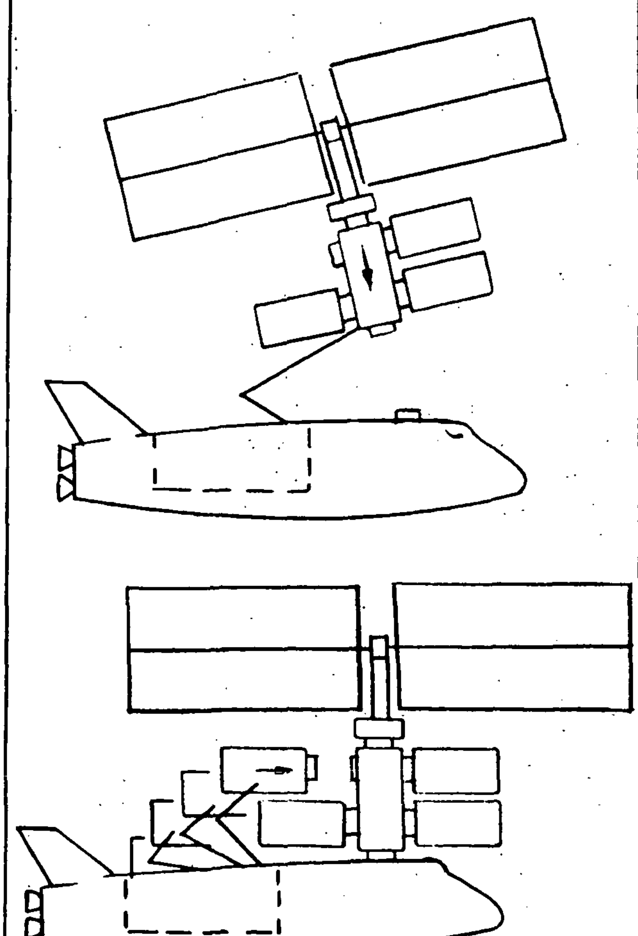


Figure 1-5. Dual Berth Concept

The manipulator docking system has more mission capability than direct docking. For example, by changing the end tool from a docking interface to a controlled release mechanism, cargo and satellites can be deployed and spin-stabilized at a safe distance from the active vehicle. Direct docking systems are limited in this respect without employing extensive kitting.

The option of whether or not to provide manual control or automatic/remote control of the docking maneuver is decided by (1) whether or not the vehicles are manned, and (2) if manned, whether it is more practical to arrange the spacecraft configuration to use man's capabilities or (3) whether it is more practical to install a system that can do the job with man acting only as a monitor with override capability from a remote location.

If the two docking vehicles are unmanned, there is no question that the maneuver will be automatic/remote-controlled. In this case, the question is one of determining which vehicle carries the largest share of automatic/remote-controlled systems. If operational requirements permit, it may be more practical to design one vehicle to be completely passive with the exception of attitude hold capability.

If one vehicle is manned and the other is not, the purpose of docking with the unmanned vehicle must be examined to determine if it can be completely passive. If, for example, the unmanned vehicle is to provide supplies, it might actually provide logistics rescue of the crew in a disabled manned vehicle if provided with an automatic/remote control of the docking maneuver.

If both docking vehicles are manned, tradeoffs (2) and (3) previously mentioned must be considered as to whether they should have automatic/remote control or manual control of the docking maneuver. It is without question that both vehicles should have control capability to act as the active vehicle in case the other is disabled; however, one or the other should be passive during the maneuver to prevent "out-of-phase" control. If one of the manned vehicles is too large to be precisely maneuvered, then the rescue requirement cannot be applied.

A man is required somewhere in the control loop regardless of whether the docking maneuver is flown by automatic/remote control or manually. Both modes will require sensing of velocity and alignment. The man can use direct-visual or video-visual information and alignment targets. The automatic/remote system with manual override would require electronically derived velocity and position data with a preference for video-visual backup and alignment targets. The major advantage in using automatic/remote control is that the man and equipment required to furnish his environment can be placed where weight and space can best be afforded. The major advantage in providing manual control of the docking maneuver is that the full utilization of man's capability as a nonlinear, fully adaptive, self-contained servocontrol system alleviates the hardware control system complexity.

When the requirements and procedures were being developed, two of the possible alternatives were eliminated. The manipulator berthing of an unmanned element to an unmanned element was eliminated in that the viable concepts do not lend themselves to totally automatic matings. Present designs all utilize man-in-the-loop operations, where man is directly in control of the system. The concept could be performed by remote control utilizing a command and data link between the unmanned element with the manipulator and a remote site; however, this is only an extension of the manned concept with the addition of a communications link to the remote site, whereby the controller would operate a manipulator control console and view the operation via a television link. Because of the present manipulator design concepts, the viability of this type operation is considered to be remote for near term operations and is therefore not persued further in this text.

With elimination of the extension-retraction device and the unmanned manipulator, requirements and procedures for the following concepts were developed:

Direct dock--both elements manned
Direct dock--both elements unmanned
Direct dock--one element manned, one unamnned
Manipulator berth--both elements manned
Manipulator berth--one element manned, one unmanned

1.4 DESIGN CONCEPT MODELS

Applicability of the mating concepts to the array of study elements required that a series of hardware design models be selected or developed for each mating function. The model was considered valid when it was compatible with the procedures, requirements, and study element designs. Where a model would not suffice for any one of the three filters it was revised, or discarded and another model generated. If no model could be developed, the concept was considered invalid.

MATING PORT

In the past, mating ports have been designed around a specific gender (male or female). With the variety of vehicles that future spacecraft must mate with, it becomes desirable for dockings to be accomplished without the limitation imposed by male and female docking mechanisms. If the EOS orbiter were the only logistics vehicle in the program, then male-female concepts would be acceptable. However, once a tug vehicle or other logistics vehicle which may be required to mate with the EOS orbiter as well as other program elements is included in the program, an androgynous design,multiple ports, or docking adapters are required. Therefore, a neuter (or androgynous) docking system that allows space vehicles with similar or identical docking hardware to dock has been selected for the mating port docking model. In addition to the androgynous requirement, several other criteria that are considered primary design requirements on the mating port were identified. These are listed as follows:

1. Provide an unobstructed clearance within the confines of the mating port for routine crew and cargo transfer. This clearance shall be available without the removal of mating mechanisms.

2. Be applicable to a wide variety of spacecraft configurations and mass properties. In this sense the mating port should be capable of attenuating large ranges of impact energy and be capable of positioning the spacecraft to allow structural interconnection between vehicles.

3. Provide a structural and dynamic attachment between elements capable of withstanding maneuvering or attitude control loads applied by logistics vehicles.

4. Provide area for utilities interconnections of both permanent and temporary type.

5. Provide a sealed interface after mating to afford a shirtsleeve environment for crew transfer.

6. Have inherent or built-in redundancy.

7. Provide the capability of being maintained in a shirtsleeve environment.

The initial screening of the concepts utilizing these criteria (see Figure 1-6) resulted in the elimination of all noted candidates with the exception of the following:

Multiple probe and drogue
Multiple forks
Ring and cone
Square frame

Two of the concepts have discrete multiple bumpers and the other two have a continuous bumper. All designs can effectively absorb energy, attenuate impact, and effect a stable mate. However, a fundamental difference in the geometry associated with capture latching is evident. During impact situations involving large misalignments and lateral velocities, initial contact will occur on only one or two bumper elements of the multiple bumper arrangements. Consequently, the bumper elements will be deflected, outward on one spacecraft and inward on the other. This situation adversely changes the geometry of the capture interface on each spacecraft, thus inhibiting capture latch performance. Compensation by increased lateral stiffness will increase loads on the mechanism (DS-520). The continuous bumper designs maintain a constant geometry capture interface and therefore may offer somewhat better performance. With manipulator berthing, this problem is alleviated because of the low impact energy to be absorbed during the berth.

The multiple forks concept can be eliminated from the list because of its close similarity with the multiple probe and drogue concept and because the multiple probe and drogue is essentially a proven design (Apollo derivative).

Table 1-1 presents a qualitative comparison of the three remaining design concepts. As a result of this cursory evaluation, no one concept was considered significantly better than any other. For purposes of the mating activity analysis, the ring and core was chosen as the baseline design concept model primarily because it would be maintained in a shirtsleeve environment and multiple external rotational mating was feasible.

For the remainder of the mating study, the ring and cone was selected as a baseline because of two qualities that make it a slightly favored candidate for universal applications. These are that the ring and cone can be maintained in a shirtsleeve environment with a smaller tunnel than the other two concepts and the ring and cone provides for multiple interval rotational oriented mating.

The requirement for shirtsleeve maintenance requires that mechanisms be installed within the tunnel. The ring/cone mechanism, when installed within the docking tunnel, dedicates an annular volume only slightly wider than the design lateral misalignment. This increases the tunnel diameter over that required for the minimum clear passageway by approximately one foot. The width of the annular space required for installation of the other mechanisms, including necessary clearance during engagement, would be at least twice the design lateral misalignment, increasing the tunnel outside diameter by at least one foot as compared to the ring and cone installation. The effects of increasing the outer diameter of a mating port results in a reduction of the overall diameter of modules that can be accommodated in the 15-foot diameter EOS cargo bay with side-mounted docking ports and a corresponding reduction in spacing between attached appendage modules (Figure 1-7).

Rotational oriented mating provides added design simplicity for manipulator utilization and affords more clearance when docking vehicles where appendage interference is critical. Figure 1-8 illustrates these effects.

Figure 1-9 shows the general configuration of a ring and core docking port. The illustration shows a neuter configuration where the active port engages a passive port. The active port can engage another active port thereby satisfying the androgynous requirement. The active port contains the attenuation system, the alignment wedges and alignment wedge guides, while the passive port has alignment guides only. The alignment wedges act as fingers that are tapered so that the approaching ring's alignment guide will mesh with it. The intermeshing, tapered wedges and guides provide radial and angular indexing capability and final alignment. The active ring contains independently operating, automatic capture and rigidizing latches. The latches are tripped upon contact of the two berthing rings. The latches provide the pull-down and clamping force necessary to accomplish the final sealing and structural continuity between the two modules. For module separation, the berthing latches are individually power released and automatically reset for the next berthing engagement.

Sealing of the interface is accomplished with dual seals on the face of the active ring. The passive port ring provides the berthing seal surface. The seals are the only components of the design that are not accessible in a shirtsleeve environment. Consequently, the active ports shall be placed on the vehicles that are returnable to ground such that the seals can be inspected and replaced if necessary.

The minimum docking port OD identified in individual element studies where side docking ports were required was 84 inches (DS-242). This allows approximately 60 inches ID for utilities interconnects and hatches. The minimum requirements for crew access and work space in the inter-element passageway was identified in the crew and cargo transfer activity analysis as a 48-inch diameter. The minimum hatch size was also identified in the analysis of these two activities as a 41-inch diameter. Thus, an 84-inch OD docking concept is compatible with crew and cargo transfer requirements.

Although the ring and cone was used as the model for the mating activity analysis, the requirements and constraints identified are equally applicable to similar docking concepts. This is especially significant because a more detailed peripheral trade study was conducted on four docking concepts, (1) the ring and cone, (2) square frame, (3) multiple probe and drogue, and (4) the international concept. This trade is presented in Appendix A, Trade A8. Weight and cost were considered to be the primary factors in the A8 trade and the resultant preferred approach was the square frame.

Table 1-1. Mating Port Evaluation

Factors	Concepts		
	Multiple Probe/Drogue	Ring/Cone	Square Frame
Technology	Apollo derivative	Present	Present
C/O Maintenance	Shirtsleeve with excessively large tunnel	Shirtsleeve	Shirtsleeve with excessively large tunnel
Safety	Acceptable	Better - contact (not capture) with the ring will occur even if lateral misalignment is exceeded.	Same as ring/cone
Reliability	Acceptable	Best-capture latch-engagement and release/retraction can be made redundant with fewer additional components because mechanism performs as a single unit.	Best--same as ring/cone
Commonality	Equivalent	Equivalent	Equivalent
Relative Cost	Medium	Highest	Medium
Weight	Lowest	Highest	Medium
Rotational Oriented Docking	180° intervals	As required	180° intervals

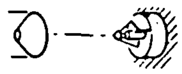
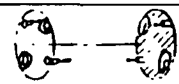
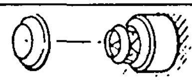
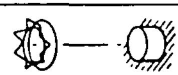
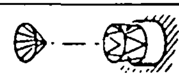
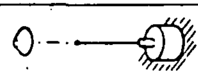
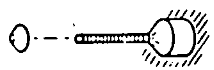
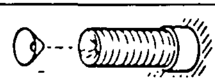
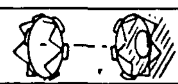
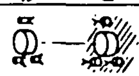
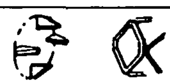
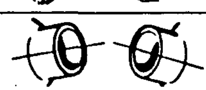
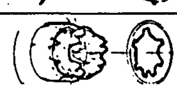
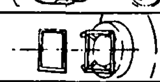
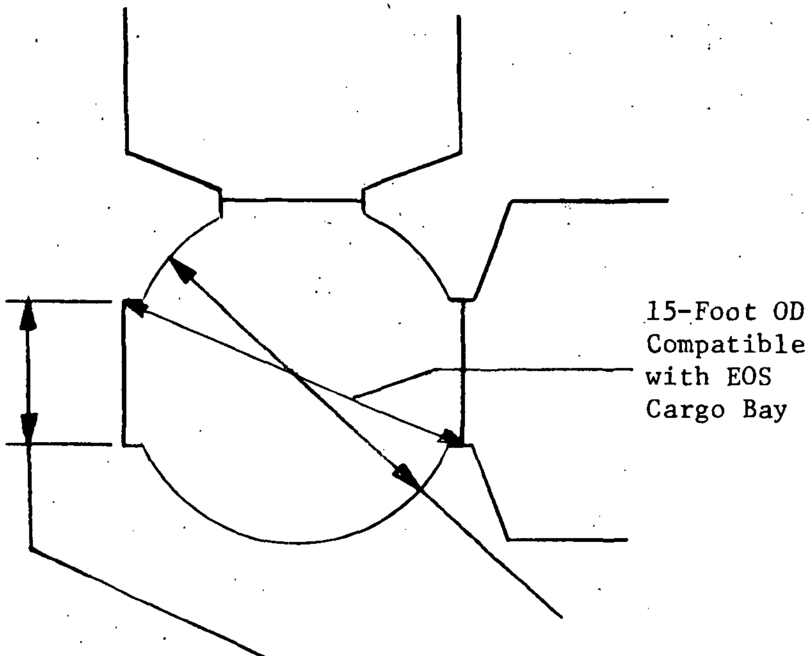
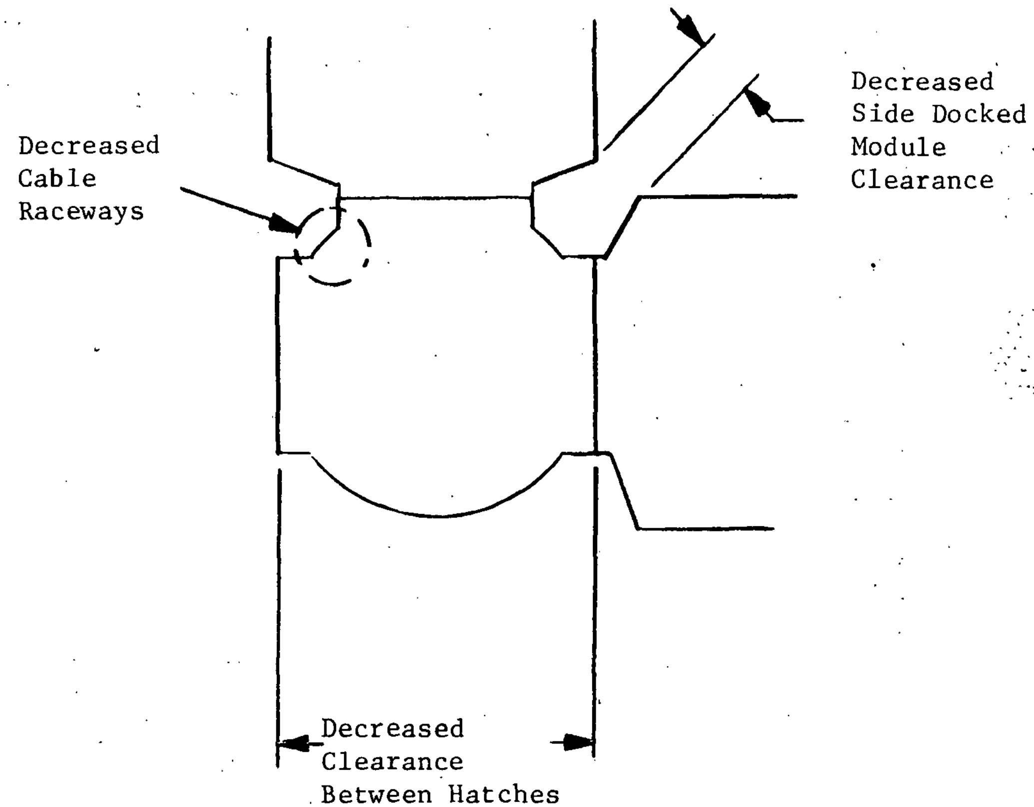
Concepts		60 in. Dia Opening	No Remov Parts	App to Variety Vehicles	Capable to be Made Androgynous	Dynamic Stability	Maintenance in Shirtsleeve Environment	Inherent Redundancy
APOLLO PROBE & DROGUE		√	--	√	--	√	√	√
MULTIPLE PROBE & DROGUE		√	√	√	√	√	√	?
CYLINDER AND CONE		√	√	√	--	√	√	√
GEMINI TUNNEL AND CONE		√	√	√	--	√	--	√
CONE AND RING		√	--	√	--	√	√	√
STEM AND CABLE		√	--	√	--	√	√	--
INFLATABLE PROBE		√	--	√	--	√	--	--
INFLATABLE TUNNEL		√	√	√	--	--	--	--
NASA RING AND RING		√	√	√	√	√	--	√
MULTIPLE FORKS		√	√	√	√	√	√	?
MULTIPLE PROBE/RING		√	√	√	--	√	--	√
CYLINDER TO CYLINDER		√	√	--	√	√	√	√
RING AND CONE		√	√	√	√	√	√	√
SQUARE FRAME		√	√	√	√	√	√	√

Figure 1-6. Mating Port Concept Options



Mating Port OD (Inches)	Module OD (Feet)
60	14.2
80	13.4
100	12.7
120	11.2

MATING PORT -- MODULE OD RELATIONSHIP



AFFECTS OF INCREASING MATING PORT OD

Figure 1-7. Effects of Increased Docking Port OD on Modules with Side Mating Ports

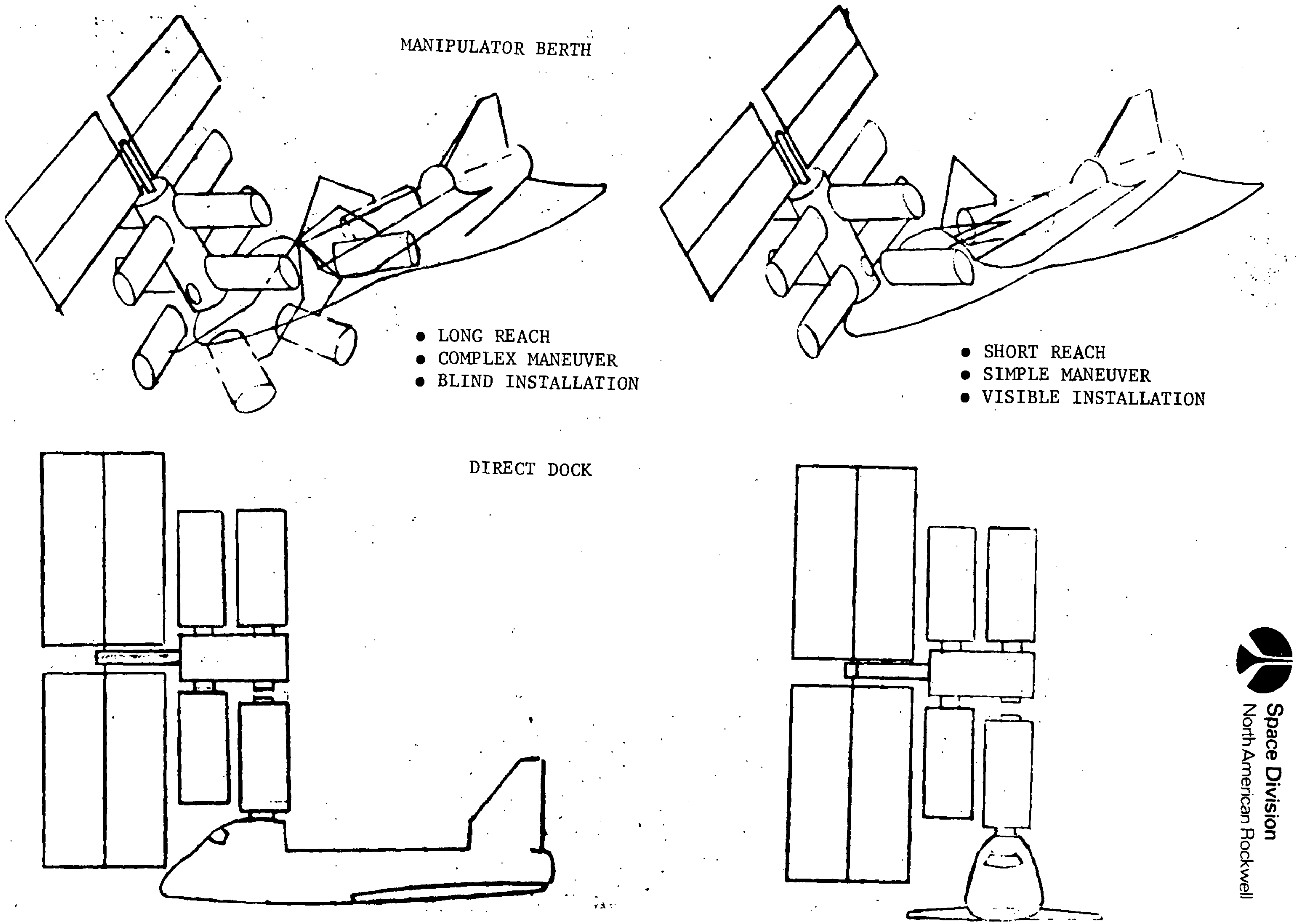


Figure 1-8. Rotational Oriented Mating Advantages

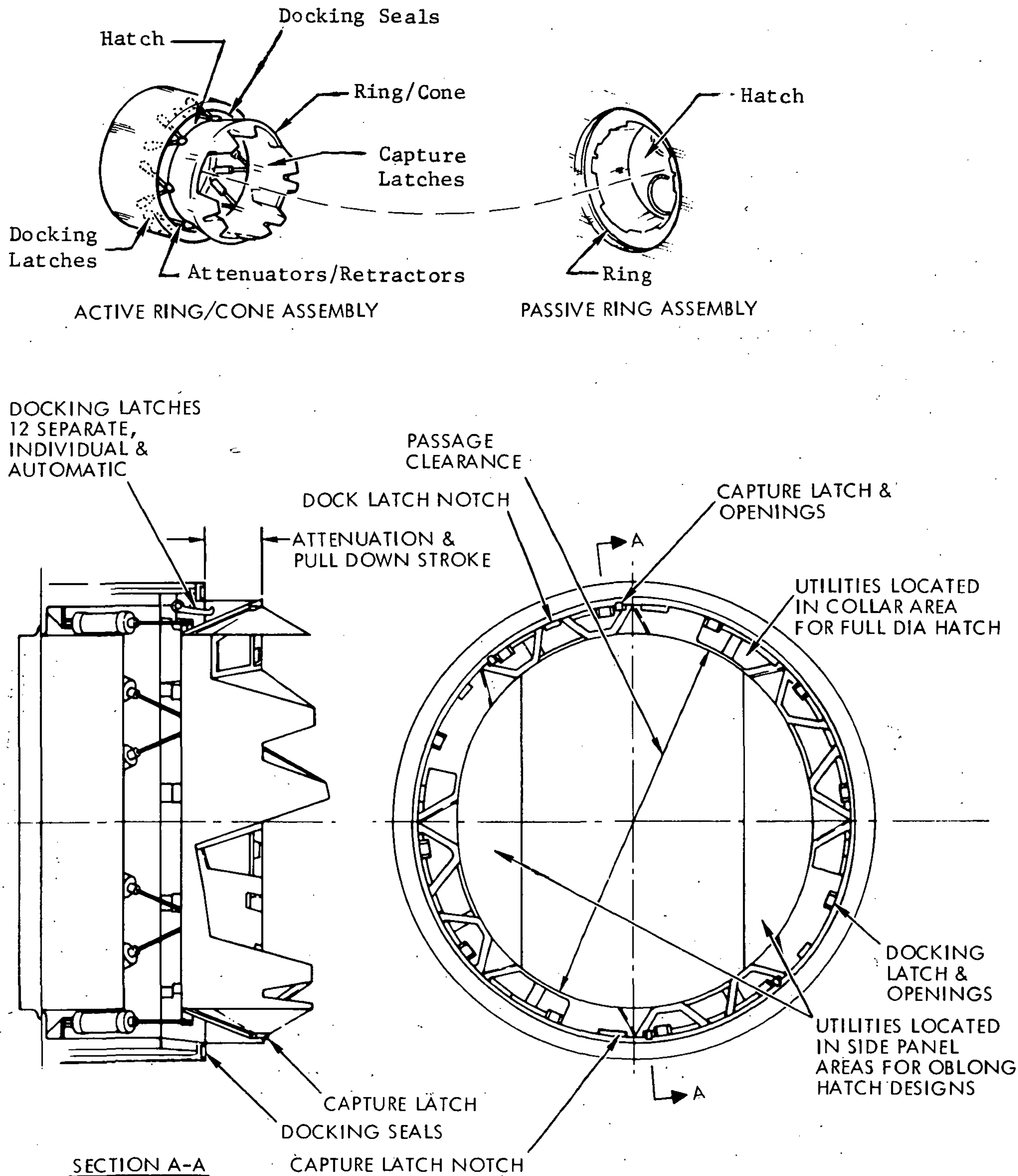


Figure 1-9. Mating Port Model

This mating port design appears viable for all of the study elements except for small satellites. It would be impractical to penalize these satellites with a docking concept that actually could be bigger and heavier than the satellite itself. An adapter such as a probe and drogue device similar to the Apollo concept (Figure 1-10) or an extension (retraction concept) could be installed in kit form in the "standardized" docking port of logistics vehicles for satellite mating operations. The primary difficulty with this concept is the attachment of the adapter to the logistics vehicle docking port. Installation on the EOS or ground based tugs is relatively simple but installation on a space based tug would require either IVA (manned tug), EVA, or a special holding port (drogue receptacle) on the EOS or an orbital facility such as the MSS.

The IVA concept could be as essential as the current Apollo approach which requires installation and removal of the device. EVA would require a secondary exit from the logistics vehicle. The drogue receptacle holding port would permit attachment and removal/storage via direct docking operations. The attenuation system of the probe and drogue would be sized for the low-energy dockings such that the ring/cone would not have to be overly sensitive. To secure the mate, the pull-down system of the probe/drogue would be used. The ring/cone could be retained in the pull-down position throughout the docking, or in the expanded position and pulled down after effecting the capture.

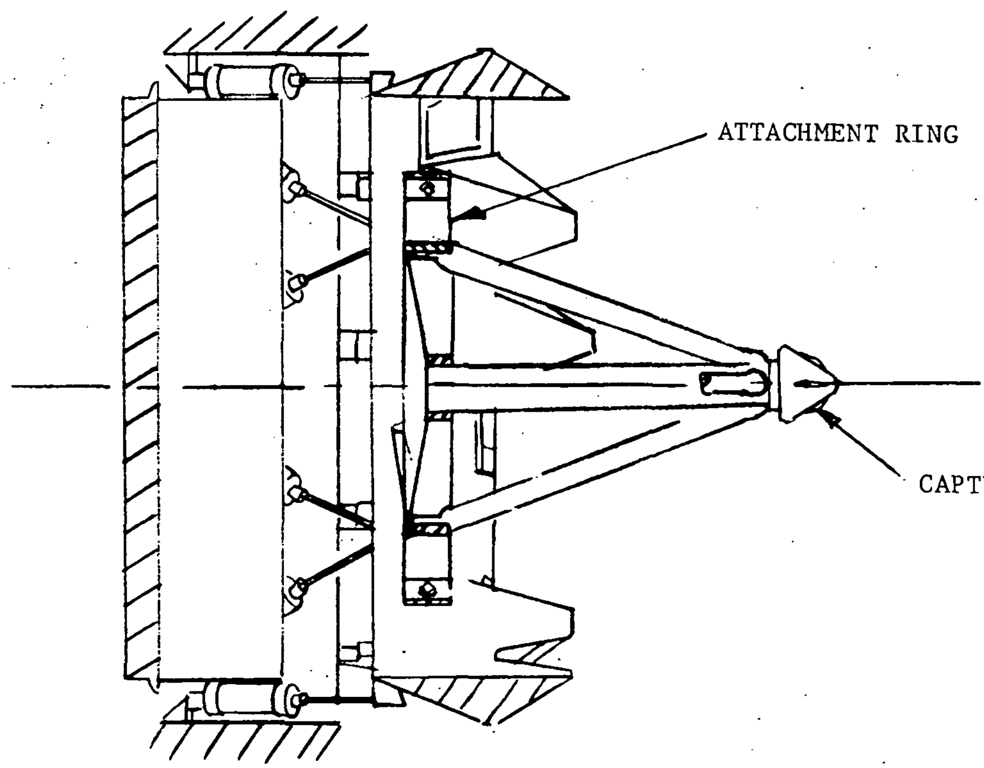


Figure 1-10. Ring Design with Apollo Probe Attached

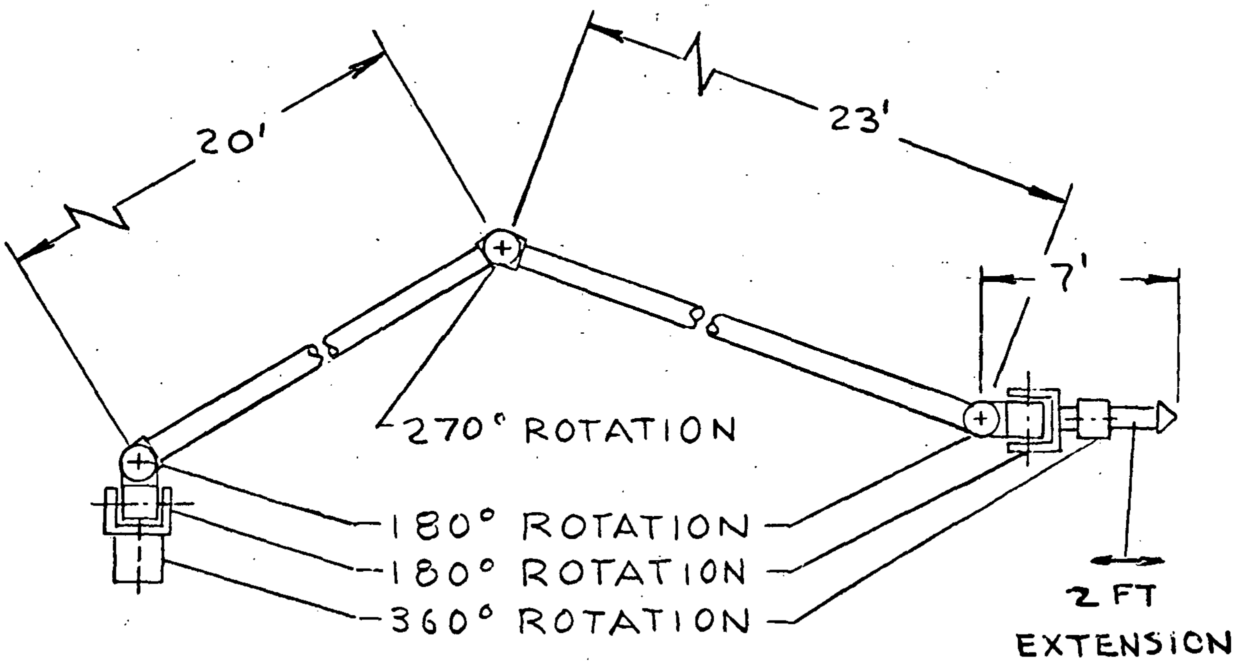
MANIPULATOR

Figure 1-11 depicts the manipulator design utilized for the study model. The design incorporates a seven-axis arrangement which allows the upper arm and forearm links to be positioned and operated in essentially any desired plane. During docking the seven-axis system can control all degrees of relative motion between the vehicles.

The manipulator can be directly controlled manually; it can be computer controlled; or it can be remotely controlled. The assembly consists of upper and lower structural elements, pivot joint actuators, and the wrist mechanism. The arm carries a remote control TV camera and spotlight mounted near the terminal end of the arm. Dual torque motors are provided and designed such that the failure of one motor does not prevent drive by the other.

Two generic types of end effectors have been identified: (1) claw concept and (2) probe concept. Figure 1-12 illustrates one claw concept which is designed to envelop a square bar attached to a payload ... and clamp onto it. The bar is itself enclosed in a conical recess which serves both as a guide to assist the claw in capturing the bar and as a guard and scuff plate for element protection. Figure 1-13 illustrates the probe concept which is modeled after the Apollo probe and drogue docking latch principle. The probe is guided into the receptacle by a pyramidal shaped cone and makes an initial capture to prevent disengagement. Final expansion of the probe secures the engagement.

The manipulator concept is readily adaptable to mating operations between the EOS orbiter and satellites with virtually no penalties on either the EOS orbiter or satellites. However, mating operations between tugs and satellites with a manipulator have operational constraints. A fully automated mating between two stationkeeping elements via a manipulator is a marginal concept. It is considered mandatory that a man be in the control loop. Remote control via RF link (including TV) are required for unmanned tug - satellite operations.



TORQUES AND FORCES

- Shoulder--Up/Down and Rotate: 500 ft-lb
- Elbow--Up/Down: 300 ft-lb
- Wrist--Up/Down and Right/Left: 200 ft-lb
- Wrist--Rotate: 200 ft-lb
- Wrist--Extend: 100 ft-lb

Figure 1-11. Manipulator Configuration

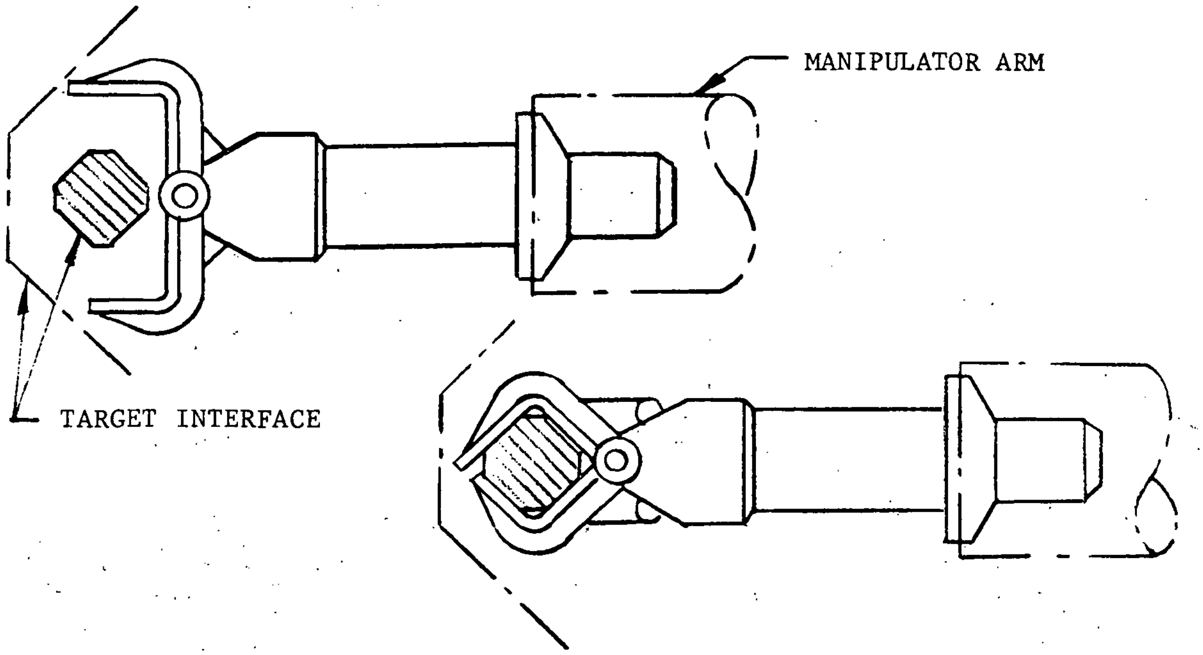


Figure 1-12. Claw End Effector

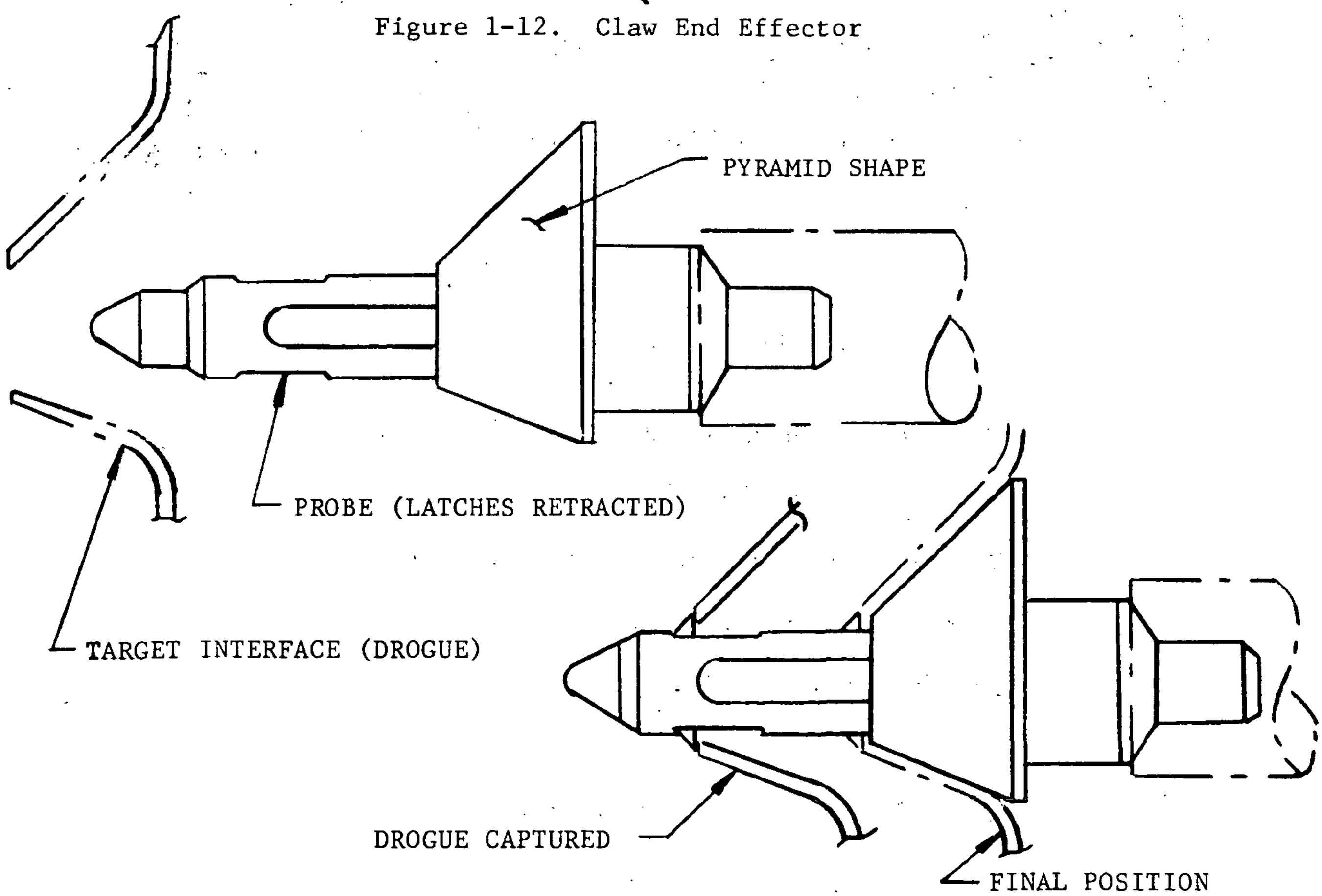


Figure 1-13. Probe End Effector

ALIGNMENT AND RANGE/RANGE RATE DETERMINATION AIDS

Because both visual alignment concepts and laser radar systems are considered viable candidates with the selection possibly dependent on the mating method (direct dock or manipulation), models have been developed for both options. The visual alignment concept would probably be the selected method for manipulator operations, whereas, for direct docking laser systems will be employed utilizing visual backup. The laser radar concept was selected as the preferred tracking system for rendezvous operations and since the mating operation begins at termination of rendezvous it would be natural to extend laser radar utilization to determine alignment and range and range rate criteria for the docking operations.

For manipulator operations, if the manipulator is automated (computerized), the alignment and range/range rate determination problem is associated only with the capture of a target vehicle. With a TV camera located at the terminal end of the manipulator transmitting pictures to the control center, alignment becomes a visual judgment task. The vehicle rates are nulled until a low limit cycle deadband is achieved between vehicles. The controller then needs only to direct the end effector into the capture receptacle making small corrections as the manipulator tip approaches the receptacle. The more difficult task may be to manipulate the associated joints such that manipulator arms do not come in contact with appendages of the target vehicle. With a second manipulator, this hazard can be reduced by strategically locating the second manipulator so that it's TV camera can view the working manipulator arms as illustrated in Figure 1-14.

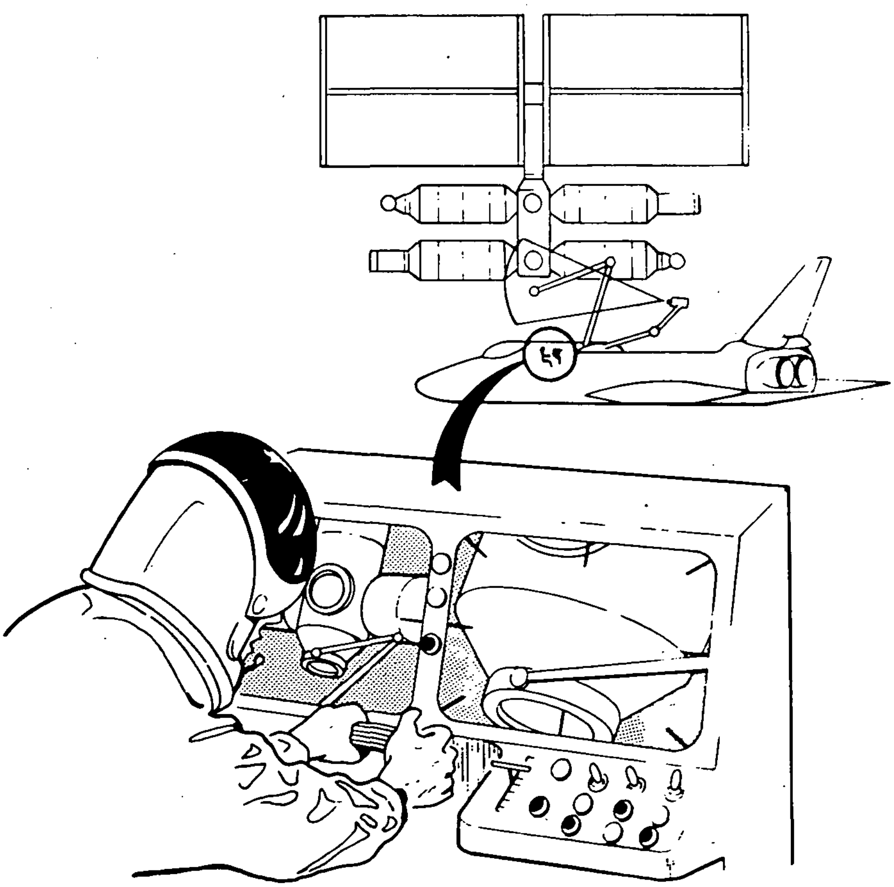


Figure 1-14. TV-Manipulator Interface

The allowable tolerance on separation distance during capture is relatively wide (±5 feet at a distance of 30 feet). A simplified manipulator simulation study was conducted by one contractor that demonstrated the capability of estimating separation distance by extending the manipulator close to (less than 10 feet) the stationkeeping element. This simulation also demonstrated the capability of nulling the relative velocity between elements to less than 0.1 foot/second by viewing and nulling the relative velocity between the manipulator end effector and the element to be captured. These results should not be misconstrued as the upper limit for capture. Other simulations have demonstrated that capture can be effected with relative velocities as high as 5 feet per second.

Direct docking alignment and range rate can be determined very accurately, when man is involved, using only visual aids. However, when docking two unmanned vehicles, visual techniques cannot be employed unless the vehicles are under full remote control. If remote control is utilized the control center (ground or another element) would be receiving a TV picture of the docking very similar to what would be seen by a pilot if the vehicle were manned. The control center would then remotely fly the vehicle into a hard dock.

With a laser radar system, fully automated dockings become a reality. The laser radar will provide precise information on the closing rates of vehicles, real time range data, and the angular alignment between vehicles. This data can be assimilated in a control system computer and resultant commands transmitted to the required thrusters such that a precision docking will be accomplished. During a direct docking, the laser radar on board the vehicle continuously measures the line-of-sight angles between the docking ports to a precision that will allow the respective vehicle to perform the necessary maneuver to null out the line-of-sight angles. The line-of-sight geometry is shown in Figure 1-15 (SD-531). The line-of-sight angles must be nulled usually to approximately +/-3 degrees, or less. Another measurement that is critical to a successful docking is the closure rate. Both the range rate and angle rates must be continuously and accurately measured so that the contact velocities can be carefully controlled prior to and at docking impact.

Before any docking attempt is made, the relative attitudes of both elements must be determined such that successive maneuvering can roughly align the opposing mating ports and the laser radar can acquire the docking target reflectors. A method has been conceived where relative attitude between vehicles, and the mating ports can be aligned utilizing a laser system (DS-268), The concept employs a search routine, whereby the active vehicle maneuvers around the passive target at some specified range. During the maneuvers the laser searches for a particular reflector pattern. When this pattern is recognized (minimum of three reflectors) and attitude determined, the vehicle moves to align the ports. Since the target is arbitarily oriented at a fixed attitude, reflectors must be located so as to be in view of the active vehicle laser beam from any position. If the payload is cylindrical in shape, with no interferring protrusions, the pattern might appear as shown in Figure 1-16. Reflector placement becomes more critical with an irregular-shaped vehicle or with vehicles with interferring protrusions such that multiple patterns must be developed and tailored for the particular configuration. This method of identifying passive laser reflectors and utilizing this knowledge to align the active vehicle along the payload docking port centerline for final approach

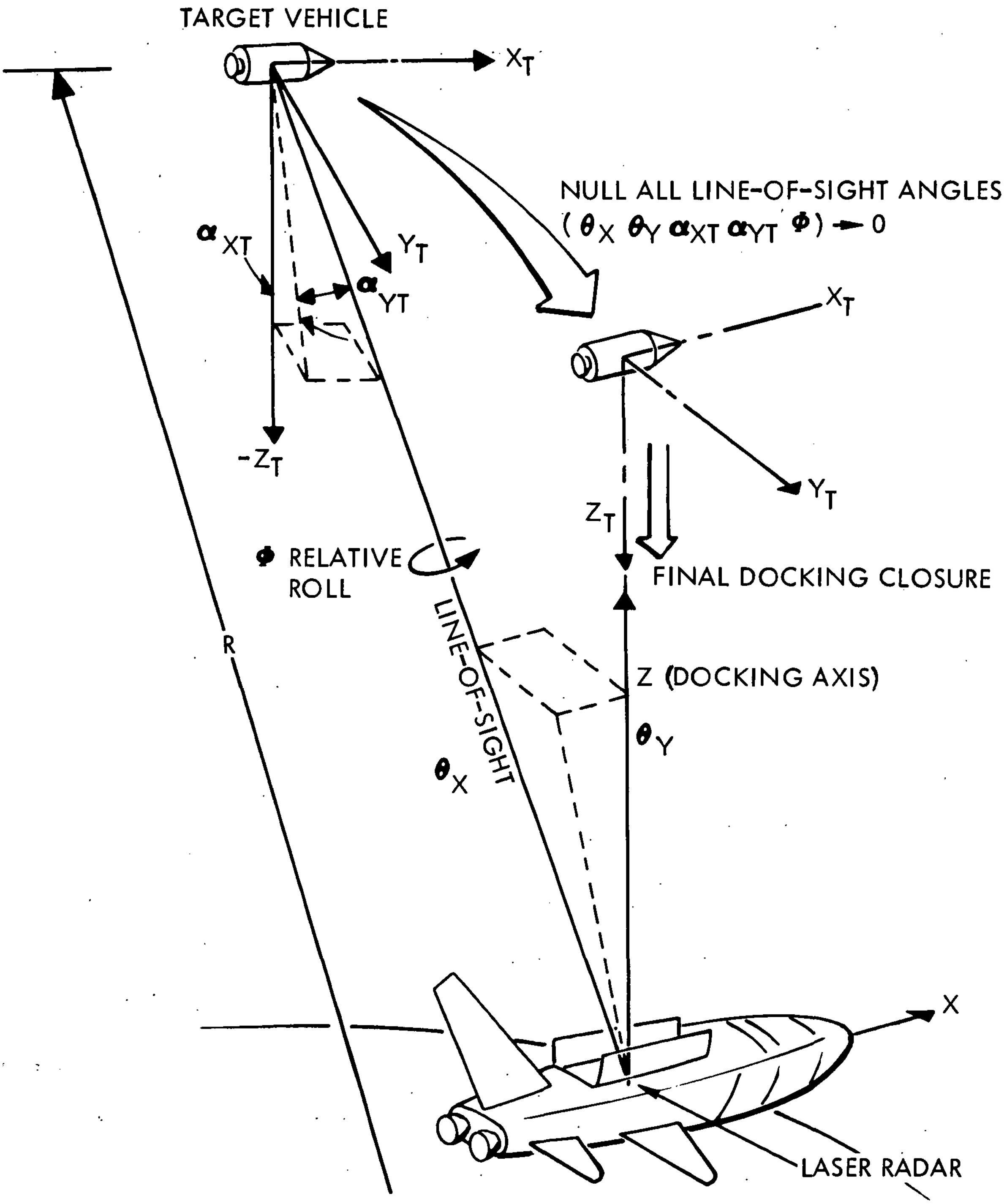


Figure 1-15. SCR Target Acquisition and Tracking

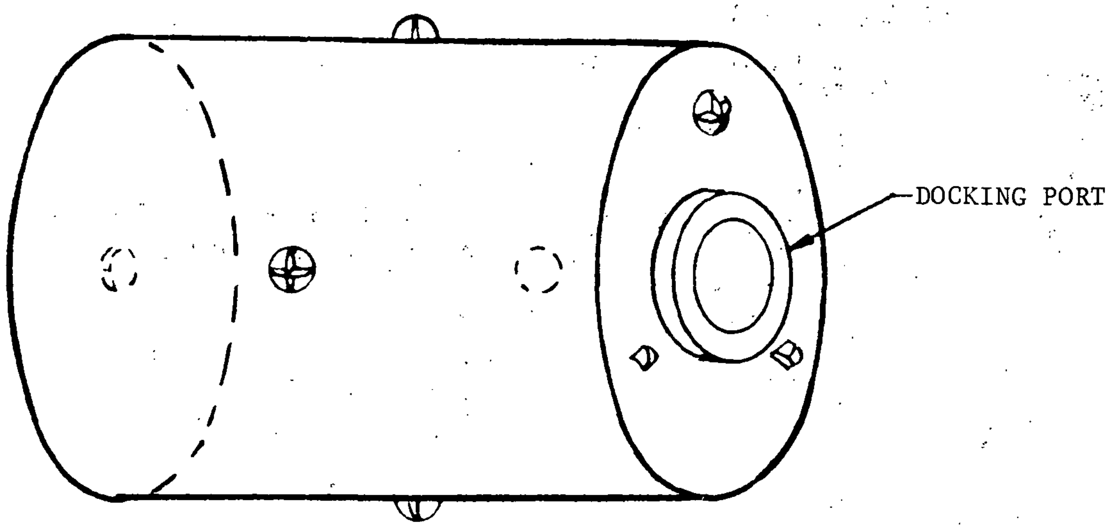


Figure 1-16. Payload Passive Reflector Geometry
for Attitude Determination and Mating Port Alignment

appears feasible. However, if a remote control center is available to transmit maneuvering commands to one or both vehicles, the attitude determination and initial alignment can be accomplished much more readilly and within the present technology utilizing a TV camera on the active vehicle. The camera could be remotely controlled to scan the vicinity of the active vehicle until it located the target vehicle. Whereupon, it would be locked on target. The relative position of the vehicles could be determined by reading the slew angle of the camera with respect to the active vehicle attitude. Relative attitude can be determined, either by directly viewing the target vehicle and it's appendages or by viewing an active light pattern on the target vehicle. The active or passive vehicle could then be commanded to assume an attitude that would align the docking ports such that the laser radar can quickly locate the reflectors that bound the mating port. Because this latter system is within present technology, and because it is highly likely that all unmanned vehicles in the future will have capability of accepting remote commands, this concept is selected for automated docking attitude determination.

The laser radar concept can utilize an active reflector system or it can utilize a passive reflector system. For this model, the passive system is selected in that the concept relies on less complexity and interfaces and because the docking criteria does not warrant the additional precision afforded by the active reflector concept. With this configuration, all the active components can be placed on one vehicle. Alignment, range, and range rate are determined automatically without an operator. Figure 1-15 is a diagram of the concept. The radar transmitter-receiver is used to determine the line-of-sight angle (θ_x, θ_y) to the target. In addition, the radar transmitter-receiver is used to determine the target orientation or relative target attitude (α_{xt}, α_{yt}) when the line-of-sight range between the vehicles is less than 1000 feet (DS-531). This is accomplished by measuring the range to each corner cube reflector, and the angular separation between the corner cube reflectors, then by using a unique set of geometric equations the relative attitude (α_{xt}, α_{yt}) of the target vehicle with respect to the line-of-sight between the two vehicles can be calculated. The relative roll angle (ϕ) will also be calculated using the same set of geometric equations.

A synchronously scanned transmitter-receiver is required to effectively search for and locate a target using a narrow laser beam. A scanning system is needed to rapidly scan the transmitted beam and the receiver field-of-view. A scan technique that steers or points a narrow laser beam synchronously with an equally narrow receiver field-of-view (FOV) will provide a laser radar system with maximum efficiency with regard to transmitter-receiver beam geometry. If the transmitted laser beam is larger than the receiver FOV all the laser energy outside the receiver FOV will be lost. If the transmitted laser beam is smaller than the receiver FOV, then the sky background noise and the receiver detector dark current noise will be larger, thus reducing the signal-to-noise ratio of the radar system.

There are various ways to implement the synchronous scan technique. This model uses a scheme whereby the transmitter-receiver is scanned electronically without the use of mechanical gimbals. A piezoelectrically driven mirror in the transmitter and an electromagnetic deflection coil in the receiver are the electric elements that control the transmitter-receiver scan (DS-531).

For a fully automatic docking, either vehicle can be the active element. It is not necessary for the vehicle with the laser radar to assume the active roll. Figure 1-17 illustrates this option for the docking of a module to a space station utilizing the EOS Orbiter as the active vehicle. This concept has the laser radar installed at the docking port end of the cargo module. This is the preferred location in that this location allows for the direct reading of docking port centerline misdistance (and provides the most commonality with respect to laser reflector location). If the laser radar is located within the EOS Orbiter, angular misalignment must be integrated with the geometry of the docking port location with respect to the laser radar location for miss distance determination. The concept has the laser radar data being directly read into the control computer. If however, the laser radar is located on the station, the radar data can be computed on board the station and control commands transmitted to the EOS Orbiter control computer or the data can be directly transmitted to the EOS orbiter control computer with it performing the computation.

The CCTV shown in the figure provides additional docking data (mating port configuration) to the crew or for an unmanned docking, the TV data can be transmitted to a remote control center.

Figure 1-18 shows the minimum interfaces within and between the vehicles and the interface with the remote control center for a fully automated system using a laser radar concept. Figure 1-19 shows the same relationship for a manned element mating with an unmanned element, and Figure 1-20 shows the concept utilized between two manned vehicles.

Figure 1-21 is a schematic of the laser radar concept. The estimated system performance characteristics for the system are summarized in Table 1-2.

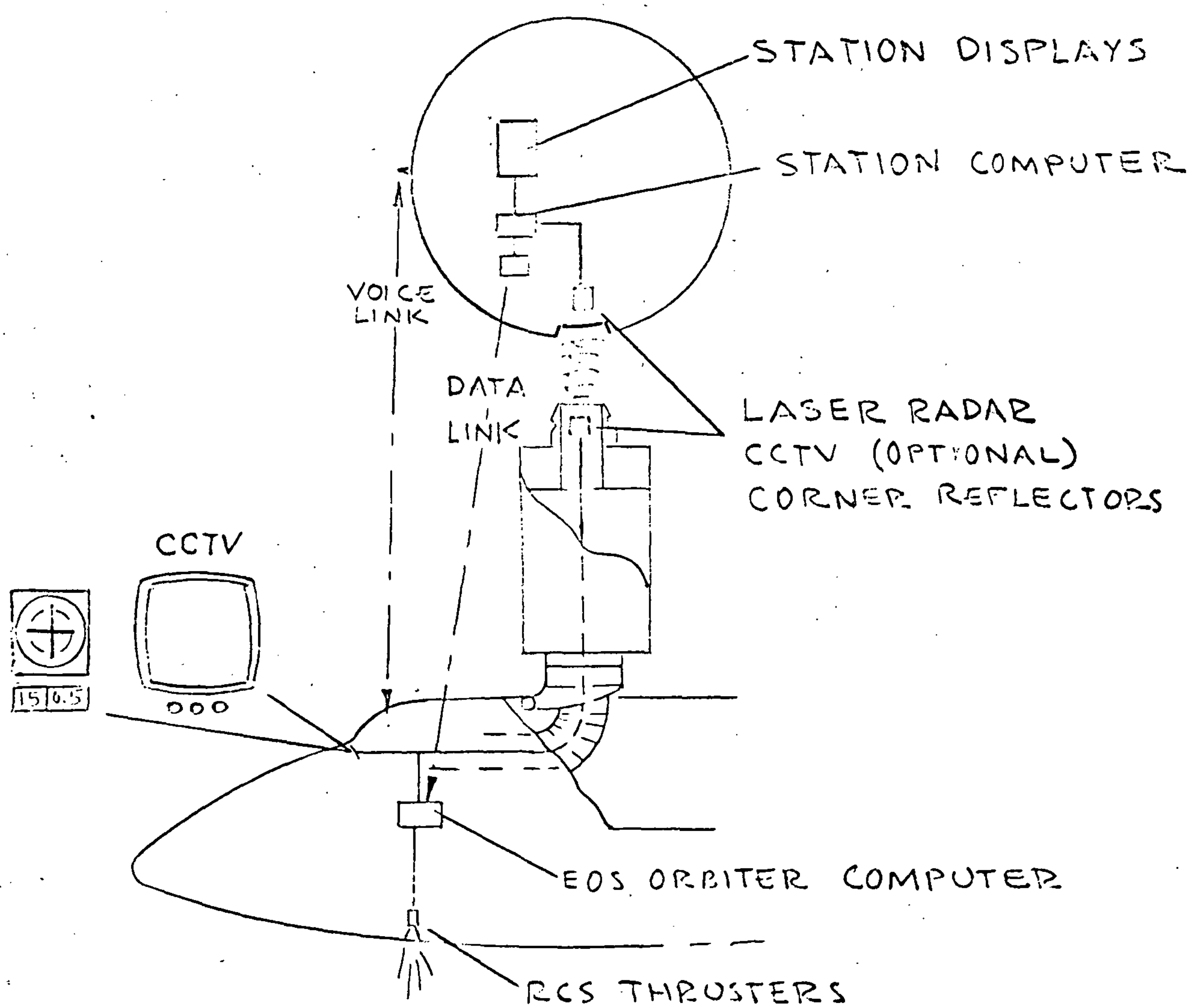


Figure 1-17. Automatic Docking Either Vehicle with Laser Radar

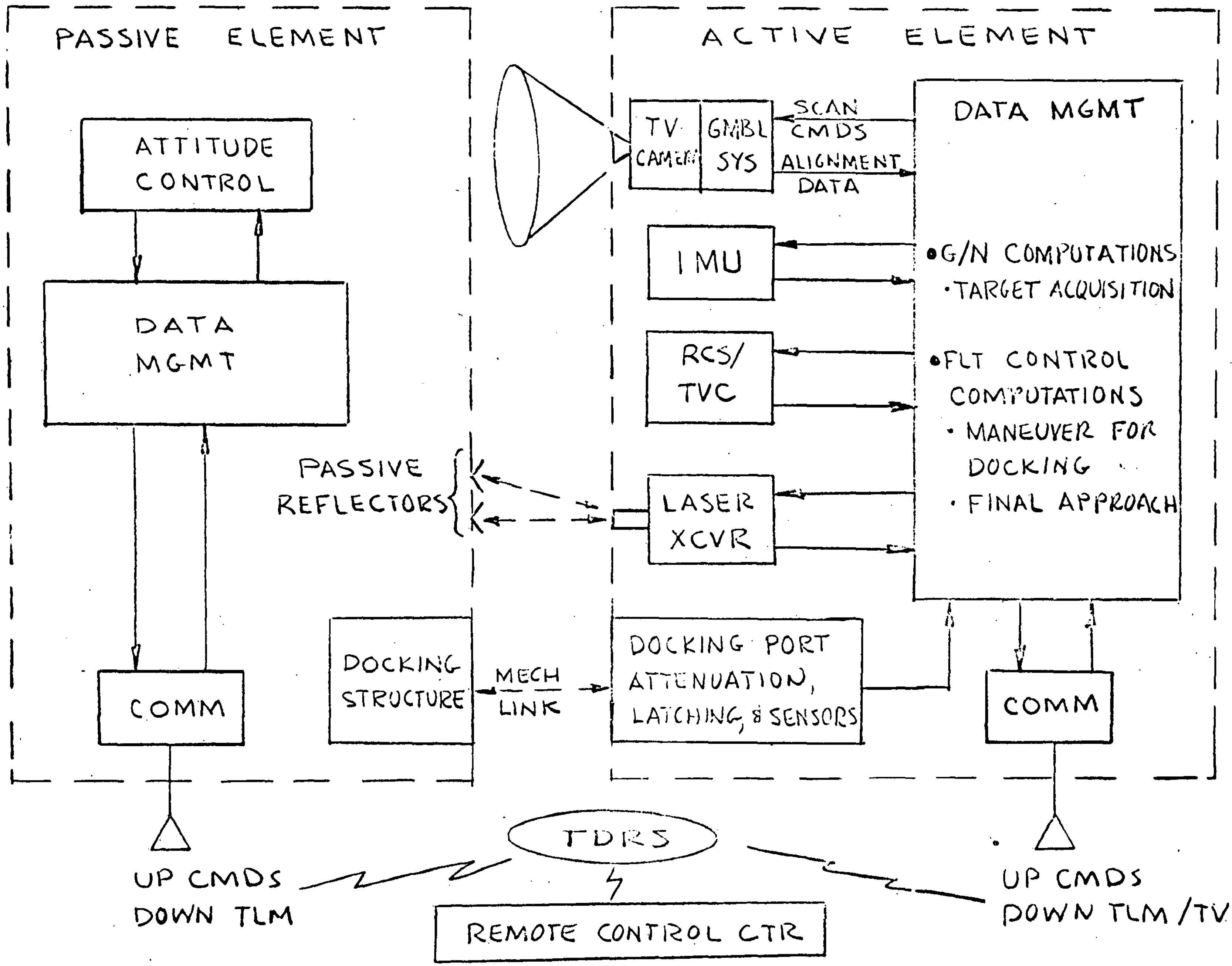


Figure 1-18. Automatic Docking System Interfaces

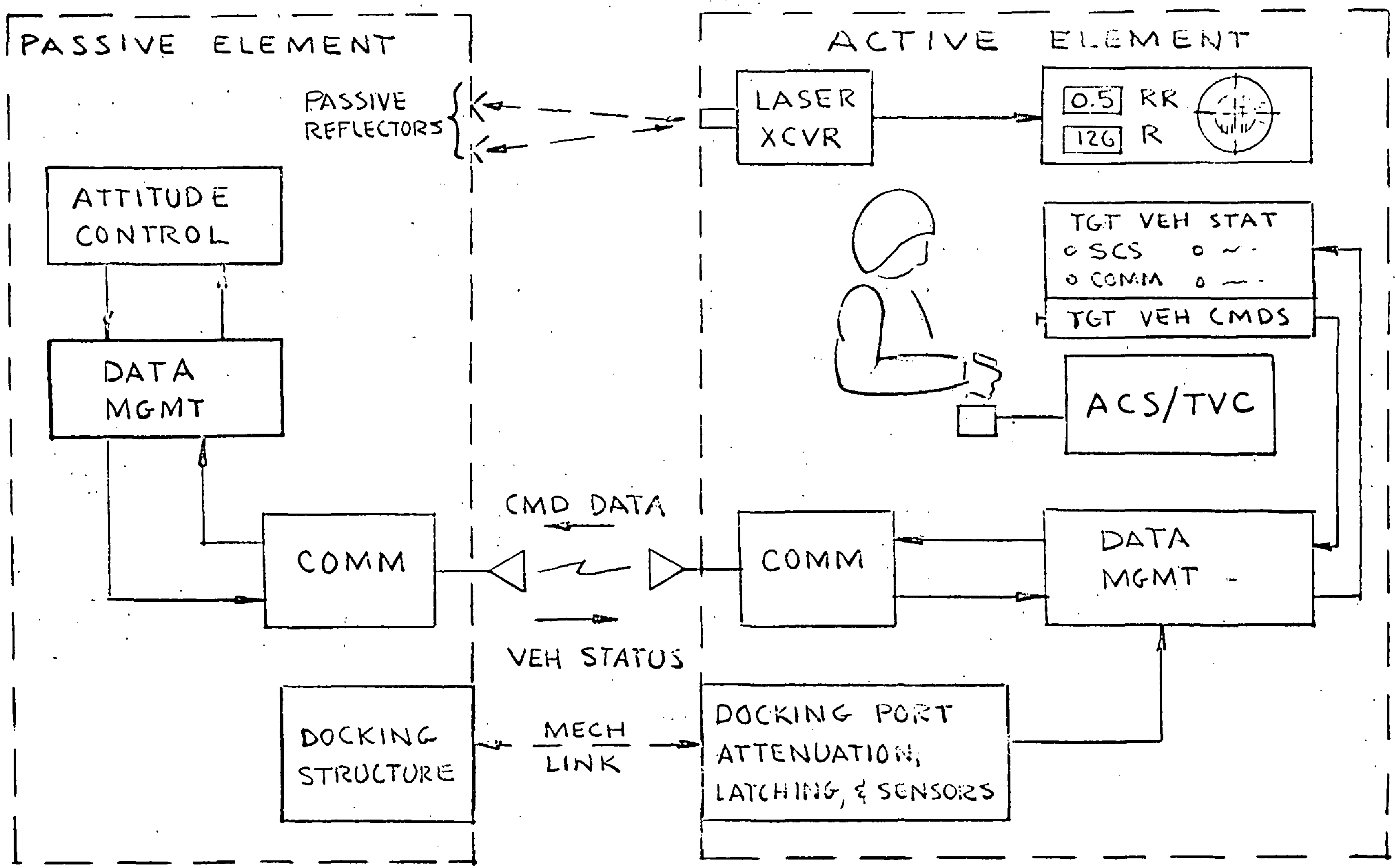


Figure 1-19. Direct Docking--Manned Element to Unmanned Element

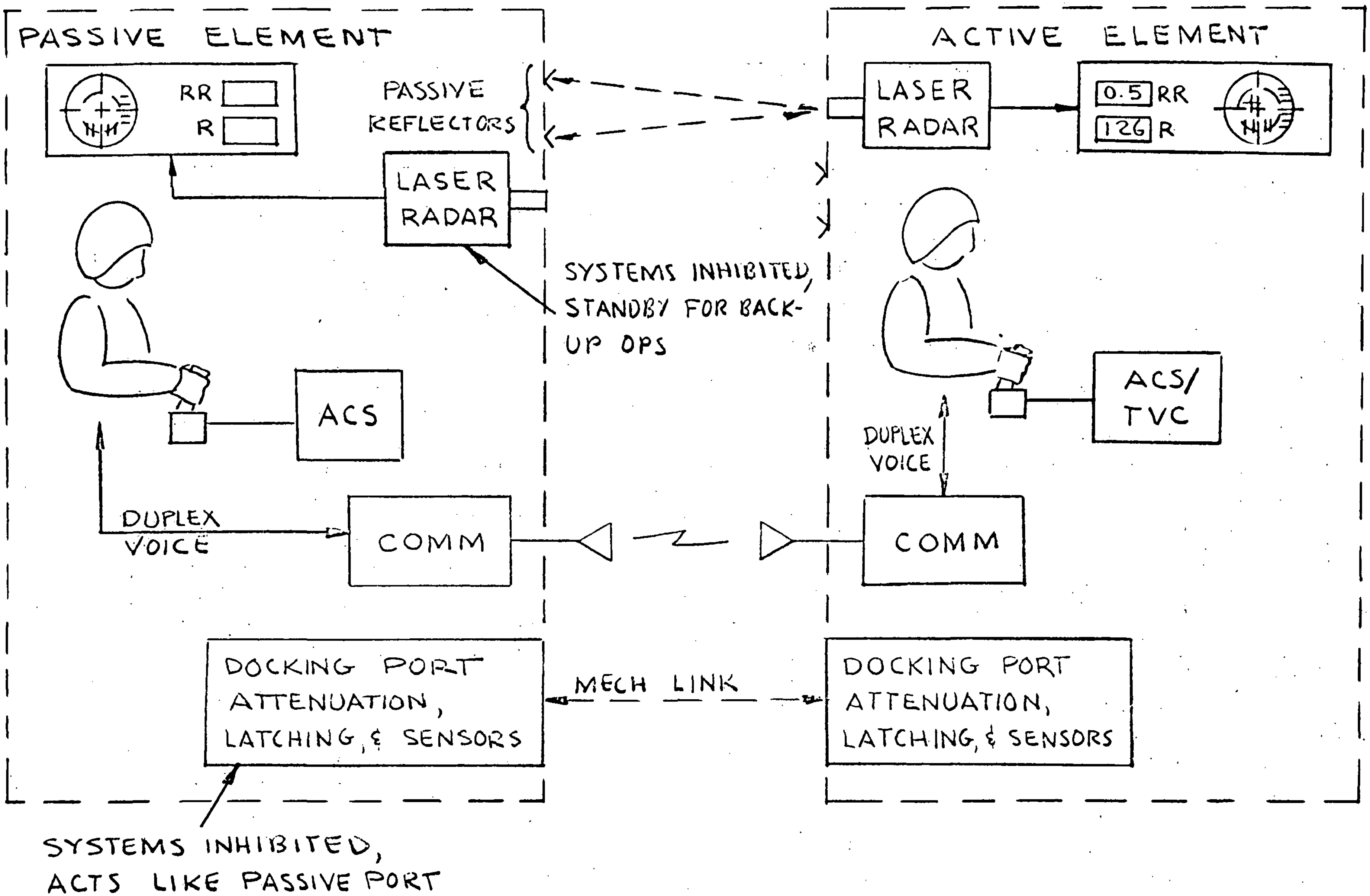


Figure 1-20. Direct Docking--Manned Element to Manned Element

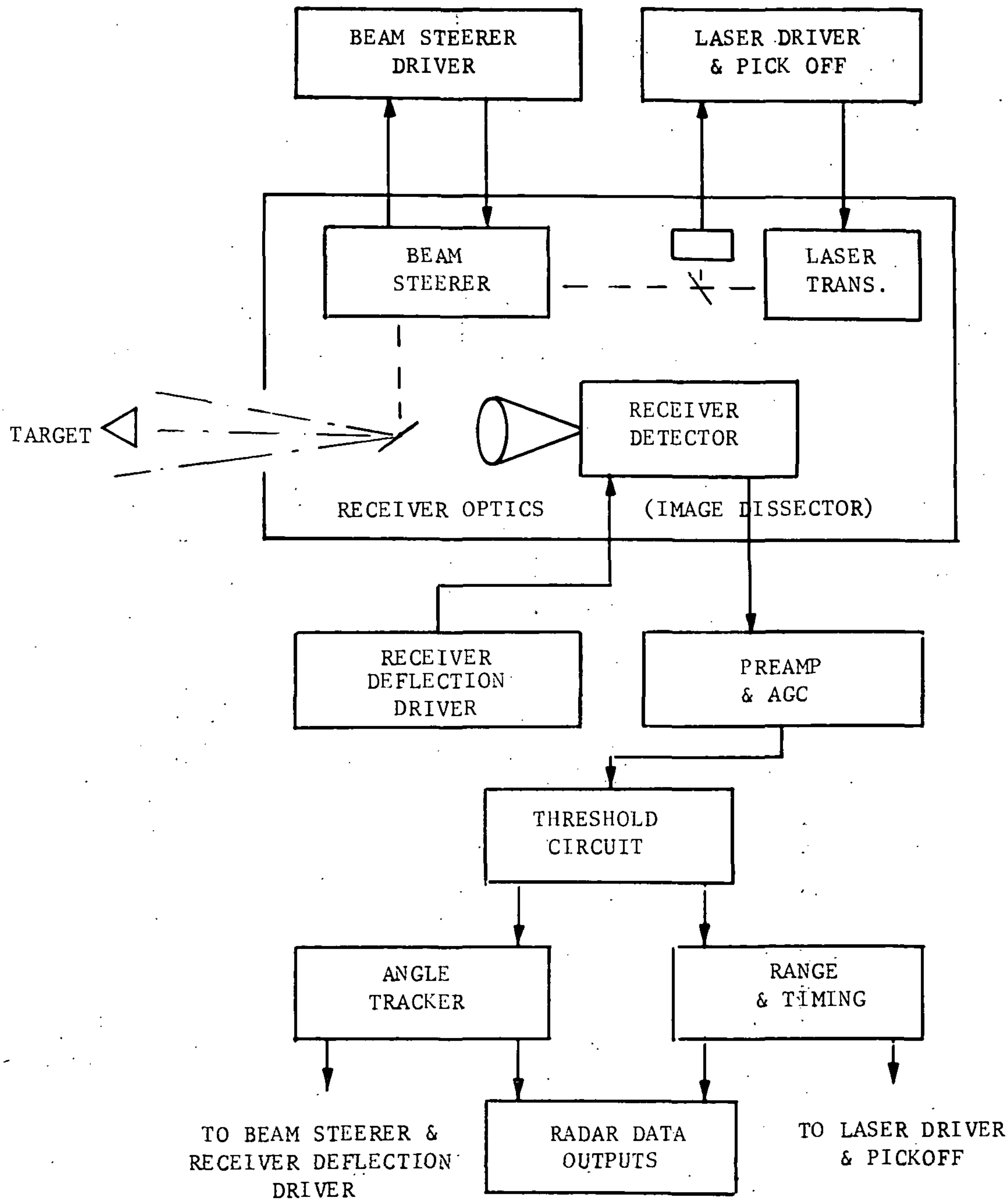


Figure 1-21. Scanning Laser Radar Basic Block Diagram

Table 1-2. Estimated System Performance Characteristics--Scanning Laser Radar

Parameter	Operating Range	Accuracy (3σ)
Range Slant range to target	Low Power Laser: 0-56 km (30 mi), GaAs Semiconductor (1.0 mw Avg. out) Medium Power Laser: 0-167 km (90 mi), Nd:YAG (1 wt Avg. out)	$\pm$0.02% of range or $\pm$10 cm whichever is greater
Range-Rate	0-1 km/sec	$\pm$1.0% of range-rate or $\pm$1.0 cm/sec whichever is greater
Angle Radar-to-target line-of-sight angles (θ_x, θ_y)	0 $\pm$ 15° without gimbals	
Relative target attitude Target-to-radar line-of-sight angles (α_{xT}, α_{YT})	0 $\pm$ 15° without gimbals (For SLR-3 configuration this is only measured when the range is less than 500-1000 feet.)	
Relative roll angle (ϕ)	0 $\pm$ 90° (Measured only at docking)	
Angle-Rate Acquisition Mode Radar-to-target LOS angle-rate ($\dot{\theta}_x$, $\dot{\theta}_y$)	For 1 KHz PRF** 0-0.025 deg/sec Worst case--target moving perpendicular to line scan 0-0.303 deg/sec Best case--target moving parallel to line scan	
Relative target attitude rate target to radar LOS angle-rate ($\dot{\alpha}_x T$, $\dot{\alpha}_y T$)	Same as above	
Relative roll angle-rate (ϕ)	Same as above	

The following series of models are concepts that can be utilized to satisfy utility interface requirements.

FLUID SEAL INTEGRITY

Prior to activation of fluid interfaces, seal integrity should be verified. Figure 1-22 is a design concept model that will satisfy this requirement.

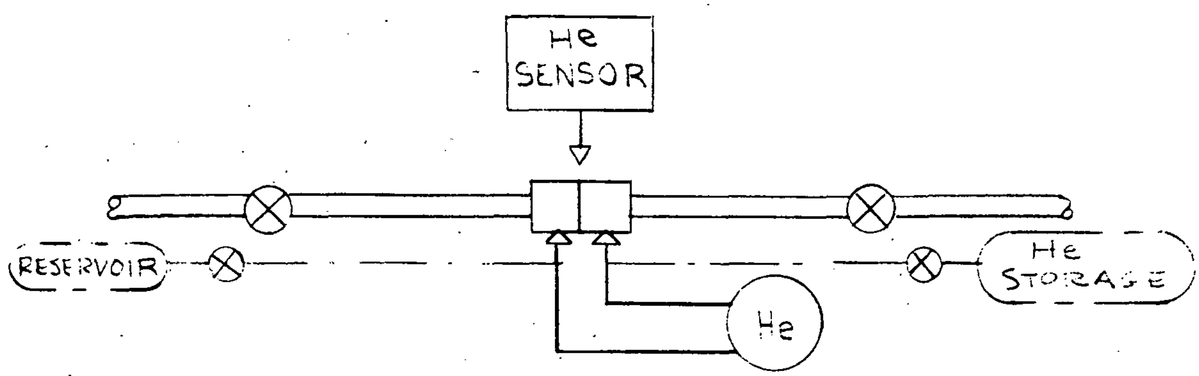


Figure 1-22. Fluid Interface Mate Verification

The helium bottle is attached at the interface connector and the mate verified by sensing helium leakage at the connector. The system can be temporary and installed and checked as each connection is made or the system can be permanent as shown by the phantom lines.

ELECTRICAL CONNECTOR MATE VERIFICATION

Prior to activating electrical interface circuits or closing deadface switches, proper mate of the interface connectors shall be verified. Figure 1-23 is a design concept model that will satisfy this requirement.

The concept essentially interconnects selected pins within a connector and a circuit continuity verification performed. The system interface can be located at any point prior to the deadface switch. Number and location of selected pins is dependent on connector size and design.

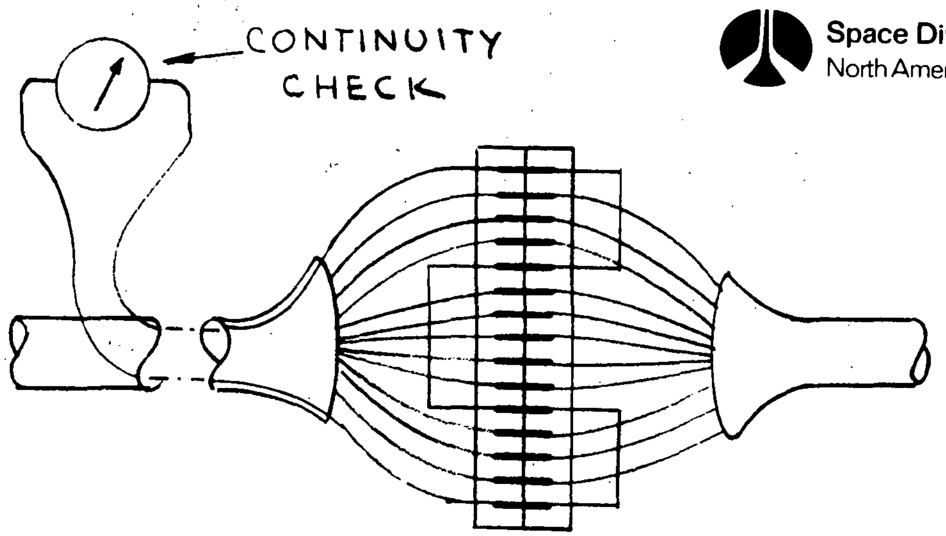


Figure 1-23. Electrical Connector Mate Verification

ELECTRICAL/FLUID LINE PROTECTION AND QUICK INTERFACE SEAL

Electrical cables and fluid lines that traverse crew and cargo passages shall be suitably enclosed or otherwise protected to minimize hazards to the crew and provide protection for the hardware. The interface between mated elements must be designed to be closed and sealed without performing a prolonged demating of interface connectors.

Figure 1-24 is a design concept model that will satisfy the foregoing requirement. This design is such that no cable or fluid line is exposed to damage within the passageway and the hatches can be sealed without demating the connectors. This design requires that the interfacing lines be connected utilizing short interconnect linkages. The design still requires that the interconnect linkages be removed before separation. However, this operation can be performed IVA or the hatch on the contaminated side of the interface can be sealed, the tunnel repressurized with clean air and the interfaces demated.

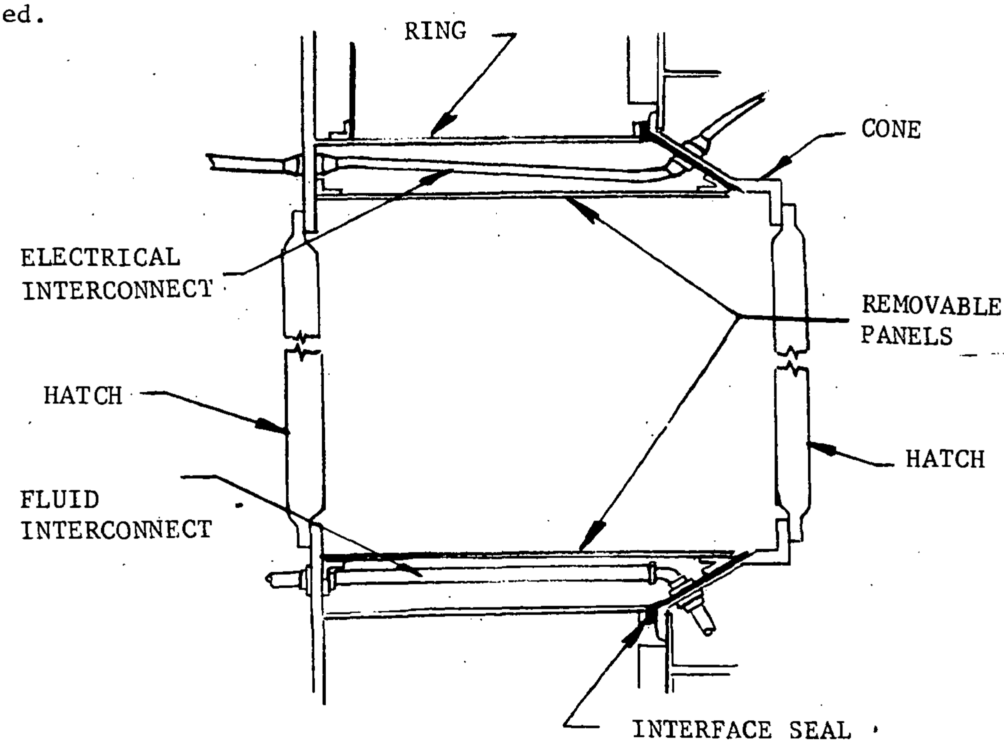


Figure 1-24. Electrical/Fluid Line Interface

COMMUNICATIONS

Figure 1-25 is a model of the RF communications in effect when mating various program elements. Manned vehicles will be conversing directly during dockings, passing information between vehicles over a duplex voice link. Unmanned vehicles require some type of remote control commands to assume particular attitudes or to activate particular equipment. Unmanned vehicles must also be statused before and during the mating activity to verify that subsystems are in accord with the mating operation. Remote control centers, such as ground control, can interface directly with orbiting elements during mating when the vehicles are in line-of-sight, however, since this cannot be guaranteed during all matings or for the full duration of the mating, this interface is not considered totally acceptable. Therefore, an interface that utilizes a system such as TDRS is required. An expansion of the communications concepts and the trade studies selecting the preferred concepts are documented in the communications section, part 3, Section 1.0. of this document.

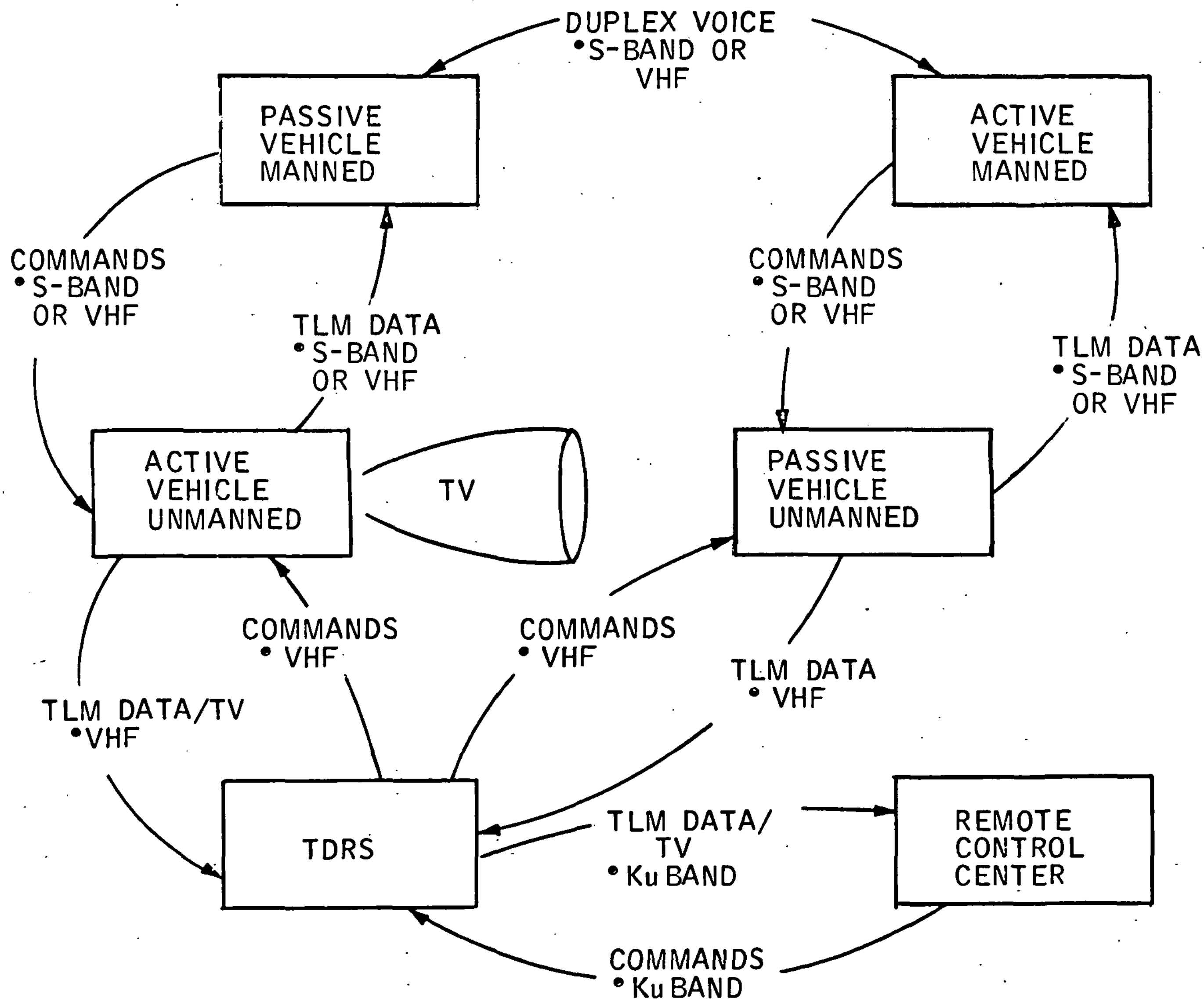


Figure 1-25. Mating Communications Interfaces

1.5 OPERATIONAL PROCEDURES

The development of operational procedures for mating required that a number of considerations be evaluated in order that each of the possible element pairs in the study would be applicable to at least one of the developed procedures.

There were three possible manned or unmanned element relationships. Both of the mating elements could be manned, one of the elements could be manned and the other unmanned, or both elements could be unmanned.

There were also three methods of performing the mating operation. The operation could be performed using the direct dock method, it could be performed using a special extension-retraction device, or it could be performed with a manipulator attached to one of the elements. The extension-retraction device was eliminated from the procedural development in that it was a simplified manipulator (single degree-of-freedom) and would not provide the procedural depth of a manipulator concept.

A simple matrix, Table 1-3, was prepared and the combinations analyzed to determine what type procedures needed to be developed.

Table 1-3. Possible Procedural Development Array

	Manned to Manned	Manned to Unmanned	Unmanned to Unmanned
Direct dock	X	X	X
Manipulator berth	X	X	X

The use of a manipulator for performing unmanned-to-unmanned berthing operations did not appear to be a viable option. Most manipulator designs were developed around force feedback concepts or with man-in-the-loop to at least perform override functions. Also, those elements that appear to be candidates for built-in manipulators were elements that would probably be manned. Therefore, it was ground ruled that manipulator berth of unmanned elements-to-unmanned elements would not be investigated.

The direct docking concept is performed with one element essentially performing a passive role in that it will probably only hold attitude while the other element performs the maneuvers necessary to accomplish the dock. Because only one element will be performing the active operations, particularly at final docking phases, and that element is the manned element of a manned-unmanned pair, the procedure for a manned-to-manned or manned-to-unmanned direct docking would be so very similar that these two procedures could be combined. If, however, the active element were the unmanned element of the pair, the unmanned to unmanned docking procedure would apply, but with the manned element providing the support rather than another remote site.

Finally, when the preliminary procedures for manipulator berthing of manned-to-manned elements and manned-to-unmanned elements were developed it was found that they too were very similar and, like the direct docking, could also be combined.

Therefore, three procedures were developed: (1) direct docking - manned elements to manned elements and manned elements to unmanned elements, (2) direct docking - unmanned elements to unmanned elements, and (3) manipulator berth - manned elements to manned elements and manned elements to unmanned elements.

Before preparing any procedure it was necessary to select a pair of elements to use as a model. By doing this, the procedure would not become so generic that it could fail to uncover detail ambiguities of specific elements that may affect design concepts or be sensitive to particular design requirements. Since the EOS orbiter could be mated with the full array of study elements, it was concluded that it be used in at least one of the procedures. The modular space station was the next element selected in that it presented the most stringent alignment problems with its variety of configurations during assembly, and because of its always-present interferring appendages that must be avoided during the mating operations. These two elements were utilized as the model for the manned direct docking concepts. Since the direct docking concept was to be evaluated against the manipulator berth concept it followed that the same elements should be utilized for the manipulator berth procedure as well, such that the procedural deltas would not be design oriented, but operationally oriented. For the unmanned element-to-element direct docking procedure, two candidate unmanned elements (space tug and detached research applications module) were selected. Table 1-4 shows the final operational procedures that were developed.

Table 1-4. Mating Procedures

	Manned to Manned	Manned to Unmanned	Unmanned to Manned
Direct dock	One procedure EOS orbiter to MSS		Space tug to DRAM
Manipulator berth	One procedure EOS orbiter to MSS		X

PROCEDURAL COMPARISON

The mating procedures include capture, attenuation of delta velocities or impact forces, structural alignment of the mated pair, and configuring of the interface between the elements for mated operations. The single manipulator procedure was extended to include the transfer of a module from an EOS orbiter cargo bay into a hard berth on the MSS so that these additional steps could be analyzed for any new requirements.

The three procedures are shown in detail in Appendix B. Figure 1-26 is a general comparison of a manipulator berth procedure with a direct docking procedure. The central balloons represent common procedures, whereas, the upper and lower balloons on the page represent procedural differences. The real difference between the procedures is that the manipulator procedure is a two-phase operation, involving a capture and transfer and mate, and the direct dock procedure performs capture at the mating port and effects the mate in essentially the same operation. The manipulator must null out the relative velocities between the vehicles after capture, whereas, with direct dock, impact energy is attenuated at capture.

PROCEDURES APPLICABILITY

Each procedure that was developed was reviewed for applicability to the feasible mating combinations. Refer to Appendix B for the results of these analyses in matrix form. The matrix has reduced the total element pairs by combining like elements such that the total element interfaces are reduced to 49.

It is possible to mate all element pairs using either the direct dock or manipulator berth approach. However, for this analysis it was assumed that manipulators would not be installed on all elements. Those elements that do not appear to be candidates for manipulators are the OIS, CPS, RNS, and OPD. The first three elements which are booster-type vehicles are not candidates for manipulators in that the secondary advantages gained by manipulators are not applicable to the type missions performed by these vehicles. The OPD is not a candidate in that manipulator operations involve a man-in-the-loop concept and the OPD is an unmanned element. All matings, however, could be performed utilizing manipulators if a third element with a manipulator is available to support the operation.

Therefore, of the 49 interfaces, mating is applicable to 42 of them. Manned direct docking can be utilized for all matings. Manipulator berth is applicable for all except CPS and RNS mating to an OPD because these are not manipulator elements and mate utilizing direct dock methods. Unmanned direct docking is applicable to all direct docking options where the possibility of an unmanned-to-unmanned docking exists (17 of the 42 mating interfaces).

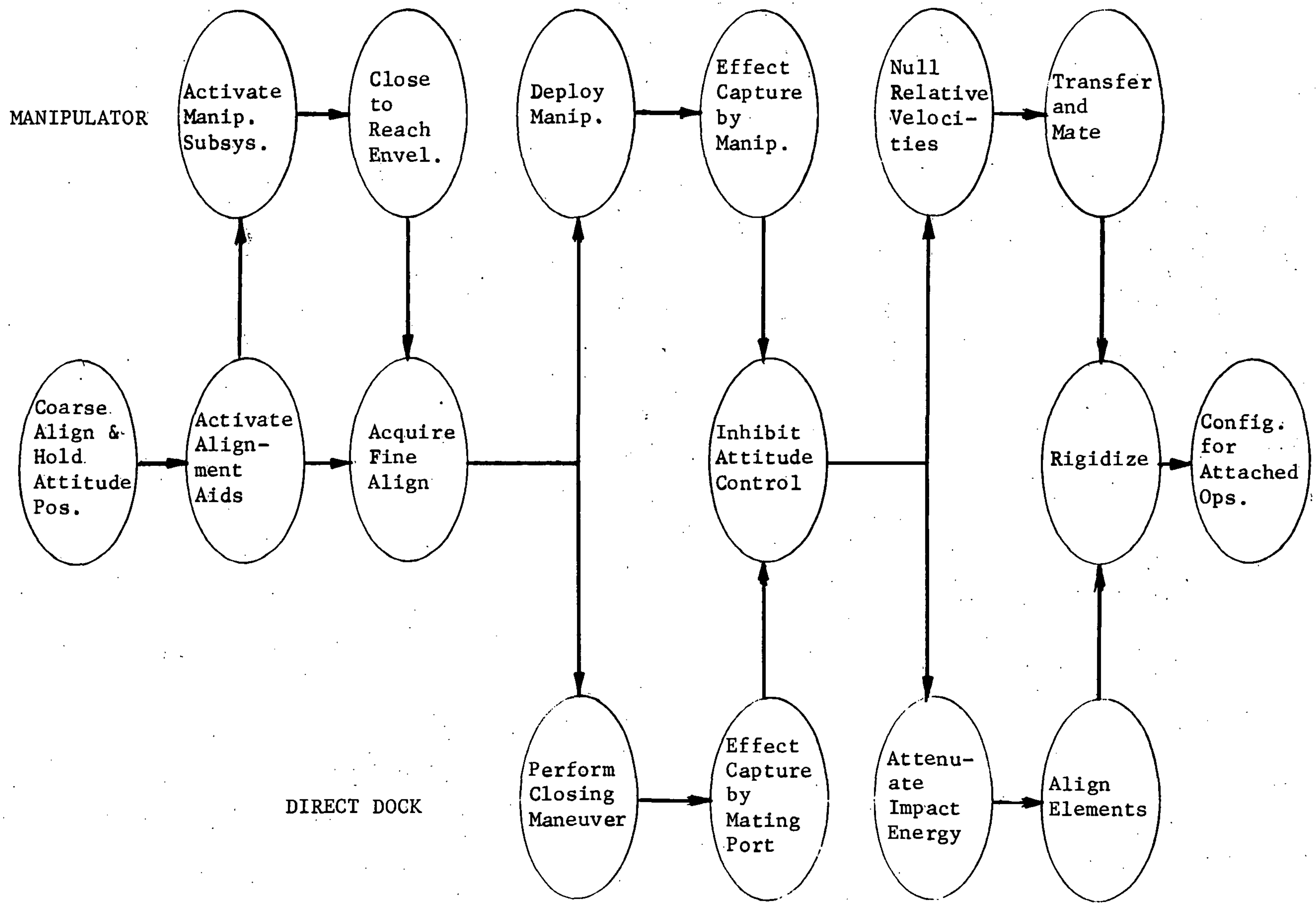


Figure 1-26. Procedure Comparison

1.6 FUNCTIONAL REQUIREMENTS

Functional requirements are presented in this section. These requirements enable the various conceptual approaches to mating to be further evaluated against the criteria that will be imposed on the concept or imposed by the concept itself. These requirements are applicable to any orbital operation mating activity involving either a direct dock concept or a manipulator berth concept. In most cases, the requirements are generic in that for any type mate they will apply. This is particularly true in the case of interface configuring for mated operations.

The columns on the right hand side of the requirement identify the approach and procedures to which the requirements are applicable. The numbers 1-1, 1-2, and 1-3 refer to the applicable mating procedure located in Appendix B.

	Related Procedure No.		
	Direct Man	Manip	Direct Auto
	1-1	1-2	1-3
1. All elements that are candidates for mating operations shall provide self-illumination. The extent of illumination shall be as follows:			
a. Orientation lights shall be provided to facilitate contact between mating elements for both daylight and night matings. The lighting shall provide the capability to identify the orientation of the illuminated vehicle at a minimum range of 1000 feet for elements of large size (greater than Apollo) and 200 feet (Apollo requirements) for elements of the Apollo size or smaller. 1000 feet is the maximum distance identified for the beginning of the translational docking maneuver. Visual attitude determination at this distance does not appear unrealistic and provides enough separation to perform maneuvers to roughly align the mating ports for the subsequent translational maneuver. Orientation lights shall be distinguishable from a star background at terminal rendezvous (1000 feet for Apollo spacecraft). Colored lighting or light patterns should be used to aid in visual acquisition and proper geometric orientation between the two vehicles. The lights should present a narrow beam output, be spectrally tailored to the most sensitive visual threshold, and probably utilize a flash (strobe) mode to aid in acquisition and conserve power (DS-523).	X	X	X
b. Lighting shall be provided to artifically illuminate the mating ports. The ports shall be illuminated to the extent that they can be inspected utilizing closed circuit television or optical aids at ranges of 20 feet to 100 feet (EOS orbiter/MSS docking), or direct visual at a range less than 20 feet (Apollo/LEM dockings). Although maximum utilization of sunlight for illumination during docking maneuvers is recommended, the possibility of interfering shadows and the requirement to dock at night will dictate artificial lighting for both direct visual and video visual systems.	X	X	X

Requirement	Related Procedure No. Direct Man 1-1	Related Procedure No. Manip 1-2	Related Procedure No. Direct Auto 1-3
c. Passive mating aids that require direct viewing (targets) shall be artifically illuminated. Illumination criteria is as follows: The aids shall stand out and not be obscured by other lighting on the vehicle (colored lighting is acceptable). The illumination does not blur characteristics of the aid (cross hairs). Active vehicle lighting does not cause reflections on the aids that will obscure characteristics. The aids can be utilized at distances up to 100 feet (see previous requirement).	X	X	
2. Protection of eyes and video visual system from reflected or high intensity light damage shall be provided. Glare or vidicon smear and image burn could cause momentary loss of visual cues at a critical moment and cause vehicle collision. Effort should be made to reduce or eliminate reflective surfaces in key areas where possible and vidicon tube design shall preclude smear and image burn. Orbital orientation during the docking maneuver can preclude direct sunlight damage.	X	X	X
3. Video visual systems (TV) shall adhere to the following criteria: Provide a minimum of 300 lines resolution at video monitor; provide a lens field of view limited to a maximum of 70 degrees to minimize distortion (reference: Remote Maneuvering Unit simulations). The video presentation to the pilot shall be the "fly to" convention. That is, the TV monitor will present a window of the spacecraft being "flown to" the target.	X	X	X

	Related Procedure No.		
	Direct Man	Manip	Direct Auto
	1-1	1-2	1-3
4. For direct docking, one vehicle must align its mating port with respect to the mating port of the other vehicle in both translation and rotation. For manipulator berthings, the same alignments are required; however, the function is accomplished utilizing manipulator control of the element. Alignment shall be as follows: lateral miss distance: +/- 6 inches pitch/yaw/roll misalignment: +/- 3 degrees Note: for rationale, see alignment analyses at end of section.	X	X	X
5. Alignment aids shall provide relative positional information between mating elements. The information provided shall be centerline miss distance and angular misalignment. Accuracy shall be as follows: automatic systems, such as laser radar: +/- 1 degree direct visual systems: knowledge to identify when the vehicles are off aligned with the mating port centerlines greater than 3 degrees Note: for rationale, see alignment analyses at end of section.	X	X	X
6. During direct docking alignment and closure to docking contact, a narrow attitude deadband ranging between 0.2 degree and 1 degree shall be maintained by the independent vehicles. The criticality of the limit cycle is dependent on the combined separation distances between the independent vehicles center-of-masses and the mating port interfaces. Note: for rationale, see alignment criteria at end of section.	X		X

	Related Procedure No.		
	Direct Man	Manip	Direct Auto
	1-1	1-2	1-3
7. Free-flying elements that are candidates for manipulator capture and berthing activities shall be capable of holding attitude and rate stabilization. The requirements that follow were the only parameters identified from the various contractor documents reviewed for this specific operation. The constraints are within vehicle capabilities. Attitude hold alignment: ±1.0 degree (DS-208) Rate stabilization: 0.05 deg/sec (DS-208)		X	
8. For inspection routines, the target vehicle shall maintain an attitude hold of ±5 degrees and a rate deadband no greater than 0.5 degrees/second. Standoff distance between the elements for the inspection will depend on the configuration of the elements, the inspection aids available, and the inspection detail required.	X	X	X
9. Range and range rate data shall be displayed during manned matings and be available to remote control centers during automated matings. Range Accuracy: automated systems such as laser radar: +/- 2 ft. direct visual for direct docking at ranges up to 25 ft.: +/- 25% berthing standoff position of 25 feet within +/- 5 ft. Range Rate Accuracy: < 0.1 fps Note: for rationale, see range-range rate analyses at end of section.	X	X	X
10. Electronic acquisition for automated docking maneuver control shall have remote backup for manual override of the docking operation. If the manual override is to continue the docking rather than abort the functions, visual capability must be provided through a video system to the remote control site.			X

Requirement	Related Procedure No. Direct Man 1-1	Related Procedure No. Manip 1-2	Related Procedure No. Direct Auto 1-3
11. Mechanical and/or computer aided multi-degree-of-freedom (manipulator) berthing systems shall be provided with manual override to prevent inadvertent contact, due to failure of the automated functions, with other parts of the active vehicle or with the vehicle being captured.		X	
12. Mating port shall be designed to the following criteria:			
a. The design shall be applicable to direct docking and manipulator berthing operations. The concept may be of a design that will perform one type of mating, but with an adapter added can perform the other type (i.e., the basic mechanism could be applicable to manipulator berthing, but with an adapter that provides shock attenuation features, the mechanism could be utilized for direct docking.)	X	X	X
b. All designs shall be inherently dynamically stable when fully engaged to an associated mating port.	X	X	X
c. All designs shall provide redundant features where active mechanisms are involved.	X	X	X
d. Both the active mating systems and the passive mating systems shall incorporate in their design the means to automatically reduce angular misalignment and lateral miss distance between the mating interfaces to permit initial capture on first structural connection (i.e., the capture mechanisms	X	X	X

	Related Procedure No. Direct Man 1-1	Manip 1-2	Direct Auto 1-3
shall be automatically triggered and self-locking). The duration of time between triggering and capture latch engagement shall be minimized to prevent the latch from missing if an element rebounds out of the mechanism. Reliable "fail safe" capture latching is considered to be a basic requirement. This means that a failure to capture at all latches either would not prevent a successful lock or would not prevent safe separation and another attempt at docking.			
e. A method of monitoring the status of capture mechanism (latch position) shall be provided. If latches are not properly engaged, subsequent maneuvers could damage the port or cause contact between the elements at other points on the vehicles.	X		X
f. The capture mechanism shall be capable of quick release and recycle to its initial state at any phase of the capture operation. Failure to attenuate an angular rotation of a captured vehicle may require rapid separation and maneuvering to avoid collision.	X	X	X
g. The mating port shall be capable of rotational oriented berthings of 180 degree intervals minimum, with 90 degree intervals or less preferred. These criteria are necessary in order to assure clearance of appendages for specific pairs and to provide a realistic handling of modules by a manipulator during berthing operation. Figure 1-8 illustrates these problems.	X	X	
h. The mating port shall be capable of successfully capturing and hard docking to an opposing mating port with a miss distance and misalignment tolerance as follows:	X	X	X

Requirement	Related Procedure No. Direct Man 1-1	Manip 1-2	Direct Auto 1-3
miss distance: +/-6 inches min misalignment (p,y,r): +/-4 degrees min Note: for rationale, see alignment analyses at end of section.			
i. Mating port design shall be capable of accommodating the full complex of study vehicles identified. Vehicle masses range between 15 slugs and 40,500 slugs. Note: See impact attenuation rationale at end of section.	X	X	X
13. All elements shall be designed with a common androgynous mating port system or with a passive system that mates with the androgynous system. The applicability of this requirement must be traded against a number of considerations for each vehicle independently. Some of these considerations are as follows: a. Weight - an androgynous mating port can weigh up to three times that of a passive port, 150 pounds versus 500 pounds (DS-237). b. Program simplicity - where all ports are androgynous, any element can be called upon to mate with another. c. Configuration - the configuration of some elements may not support a mating port the size of which was designed around a large vehicle (EOS orbiter, MSS, OPD, etc.). Small satellites would not utilize the same ports as these elements, unless an adapter is available. d. Element flexibility - if an element is to mate with other logistics elements, it would be a strong candidate for androgynous design; however, if it were to mate with only one logistics element and were androgynous, it may be overly designed. For example, if an	X	X	X

	Related Procedure No.		
	Direct Man	Manip	Direct Auto
	1-1	1-2	1-3
EOS orbiter were the only logistics vehicle being developed, then all vehicles that it mated with could be equipped with passive ports. However, if a tug and EOS orbiter are in the program and the tug and EOS orbiter are called upon to mate with some of the same orbiting elements, as well as each other, then the EOS orbiter and tug would require androgynous design or an adapter would have to be utilized for tug-EOS orbiter matings.			
e. Program time frame - an element that is to be developed far out in the program time frame would be a candidate for a passive design if the supporting elements developed in an early time frame were to be outfitted with androgynous systems.			
f. Safety - if a manned element were in need of a rescue craft, it would be highly desirable that any logistics vehicle in the area be capable of performing the operation rather than verifying a mating port match.			
14. Prior to contact between the mating interfaces, the relative closing rate (axial velocity) must be reduced to a velocity that is compatible with both vehicles structure and mating port energy absorption capabilities.	X		X
Except for the allowable longitudinal closing velocity with attenuation, the other data presented are ratioed from a baseline standard to provide an indication of expected values. For baseline models see the impact attenuation rationale at the end of this section.			
<u>Longitudinal Velocity</u> with attenuation - 0.2 fps to 0.5 fps without attenuation - 0.04 fps to 0.17 fps			
<u>Lateral Velocity</u> with attenuation - 0.09 fps to 0.5 fps without attenuation - 0.03 fps to 0.17 fps			

		Related Procedure No.		
		Direct Man	Manip	Direct Auto
		1-1	1-2	1-3
	<u>Angular Velocity</u> 0.06 d/s to 0.3 d/s Note: for rationale, see impact attenuation analyses at end of section.			
15.	Before capture of an element by a manipulator, the relative velocity between elements must be reduced to a level that is compatible with manipulator capabilities and vehicle configurations. Allowable relative velocity: less than 0.1 fps Note: for rationale, see relative velocity nulling analyses at end of section.		X	
16.	Residual attitude misalignments remaining after capture shall be corrected by the active vehicle prior to rigidizing. One method is to maneuver the active vehicle into alignment while the passive vehicle maintains attitude hold. This requires a pivoting capture interface. Another method is to inhibit the attitude hold feature of one vehicle and mechanically force the capture interface to move the vehicles into alignment. The berthing maneuver using the manipulator system is an example of this method.	X	X	X
17.	The mating interfaces shall be drawn together by the active vehicle mating system to remove residual attenuation stroke and seat the interfaces. The rate at which the vehicles are drawn together must be controlled to within the structural capability of the docking ports. If the vehicles are drawn together with a small angular misalignment, the docking ports make contact at a point. Further draw down will force the vehicles to rotate into alignment and attempt to overshoot. If rigidizing latches trigger on alignment of the interfaces, the attempted overshoot will generate high bending moments. Either	X	X	X

Requirement	Related Procedure No. Direct Man 1-1	Manip 1-2	Direct Auto 1-3
the rigidizing latches should be inhibited until overshoot dynamics cease, or the draw down forces should be reduced as draw down proceeds to prevent excessive angular rates during forced alignment.			
18. If, during berthing, one or the other vehicles is required to maintain attitude hold, the sum of the manipulator joint torque limits must not exceed the vehicle attitude control capability about any axis. If the torques do exceed the attitude hold control capability, then attitude hold as a requirement would not be valid in that the hold component would not be able to be maintained during manipulator operations.		X	
19. Propulsive venting (other than attitude control systems) of both vehicles shall be inhibited or controlled during the mating operations. The control of venting is not only necessary to prevent attitude control problems, but should also be avoided to prevent effluents from obscuring alignment aids. During mated operations venting must still be controlled, particularly venting of condensable gases to minimize exterior contamination of susceptible elements. However, if venting is necessary, it should be performed on an intermittent least-interference basis.	X	X	X
20. The mating interfaces shall be structurally connected either automatically or manually to provide the required intervehicular stiffness for combined vehicle maneuvering. The engaged and locked rigidizing latches shall be preloaded such that the fundamental bending/torsional mode of the mated pairs is determined by the primary structures	X	X	X

Requirement	Related Procedure No. Direct Man 1-1	Manip 1-2	Direct Auto 1-3
of the mated pairs, i.e., latch spring stiffness shall not affect vehicle control systems that depend on structural modes. Preloading shall protect against loads and moments from combined vehicle maneuvering opening the interface to the extent that pressure seal is lost.			
21. Mechanical radial position and roll indexing shall be provided at the mated interface to prevent interface slippage and damage to pressure seals during combined vehicle maneuvering.	X	X	X
22. After mating, the vehicle control systems of one of the elements shall be inhibited to permit combined vehicle maneuvering and prevent inadvertent control system activity which could result in vehicle control problems and possible plume impingement damage. For manipulator berth operations, the ACS of at least one element is inhibited after capture is verified. The design of the manipulator and its operational interfaces will determine if the ACS of both elements will be inhibited after capture such that relative velocity is nulled out independently by the manipulator or in conjunction with the ACS.	X	X	X
23. The capability to inspect, maintain, and manually recycle both capture and rigidizing latches in a shirtsleeve environment shall be provided.	X	X	
24. Pressure equalization capability and leak rate verification transducers shall be provided on each side of each docking interface hatch of any docking vehicle combination requiring shirtsleeve environment for manned mated operations.	X	X	

Requirement	Related Procedure No. Direct Man 1-1	Manip 1-2	Direct Auto 1-3
25. Throughout mating operations, the elements shall be capable of being separated upon command. This requirement naturally applies only after the interface between the elements has been properly isolated/sealed for safe separation or before the interface hatches have been opened. a. Separation shall involve reversing the mating functions in a controlled manner such that the docking interface is left in a condition to mate again (i.e., rigidizing latches shall be unlocked and recycled.) If this function can be designed such that the configuring can be accomplished after separation, this requirement is void. b. The separation system shall be capable of being inhibited after mating operations are secure and before the interface hatches are opened.	X	X	X
26. Throughout the docking maneuver the control systems of both vehicles shall be monitored for indications of control failures such as reaction jet "stuck-on" and "stuck-off" conditions. Inhibit switches and selectable jet logic may prevent vehicle dynamics from reaching catastrophic proportions and permit systems jettison and abort maneuvers without major vehicle damage. During post contact vehicle alignment and prior to rigidizing, vehicle jack-knifing or spinup can be particularly dangerous.	X	X	X
27. All electrical interfaces shall be deadfaced on both sides of the interface prior to being connected. The possibility of connecting "hot" connectors is very likely if deadfacing is not part of the interface design. Shorting a hot pin to the wall of a connector or to a ground pin in the mating receptable could cause a spark which may, in turn, create a fire if the atmosphere contains a combustible contaminant. Shorting the wrong pins together can also damage hardware in one or both of the elements.	X	X	X

	Related Procedure No.		
	Direct Man	Manip	Direct Auto
	1-1	1-2	1-3
28. Prior to activating electrical interface circuits or closing deadface switches, proper mate of the interface connectors shall be verified.	X	X	X
29. Prior to activiation of fluid interfaces, seal integrity should be verified. Deviation is not permitted where liquids or hazardous gases are involved. For non-hazardous gases, the lines can be activated individually with the interface integrity verified prior to activation of the next line. Leaking fluid lines can create a serious hazard in a zero-g environment whether the fluid is hazardous or not. By independently activating a line as it is connected, a failed interface can be quickly identified and repaired without disconnecting other interfaces.	X	X	
30. Interfacing assemblies that contain plugs, receptacles, and couplings shall be equipped with compatible guides such that alignment will be achieved prior to engagement of the connectors. Individual connectors and fluid couplings shall be provided with independent mechanical guides and indexing such that alignment is achieved prior to engagement of connector pins or fluid coupling interface seals.	X	X	X
31. Extension and connection of automatic utility interface connectors and couplings shall be delayed until after the mating rigidizing mechanism has engaged and locked up. Early extension may fail to mate the connectors if the interface is not properly aligned. If engagement does occur, torquing of the interface by rigidizing latches may damage the receptacles.	X	X	X
32. Manual interface connections shall be located, designed, and mounted such that a worker can mate the connectors in a pressurized suit or provisions shall be available to perform the task in shirtsleeve.	X	X	
33. Manual interconnects shall be located to permit visual inspection of the connection. Where possible, provisions should also be available to inspect connections made automatically.	X	X	

	Related Procedure No.		
	Direct Man 1-1	Manip 1-2	Direct Auto 1-3
34. Electrical cables and fluid lines that traverse crew and cargo passages shall be suitably enclosed or otherwise protected to minimize hazards to the crew and provide protection for the hardware. If it is necessary to route cables and wires through holes in metal partitions, the cables shall be protected from mechanical damage by installation of gromments or other acceptable means. Routing electrical cables along fluid lines or near high temperature sources shall be avoided (DS-509).	X	X	
35. Direct insertion or quick-disconnect connectors shall be used unless high pressures demand threaded connections.	X	X	
36. The tunnel leak rate between the mated elements shall be no greater than the leak rate of the hatch seals of the individual elements. This criterion is provided to prevent any strain being placed on the pressure supply system.	X	X	
37. A credible accident to, or a credible failure of an interface function or adjacent function shall not cause the loss of redundantly provided functions or compound the accident or failure by creating additional hazards (explosion, fire). In this sense, the following criteria apply: a. Hazardous fluid lines shall be barriered or physically separated from power wires and each other (O_2 lines shall be considered hazardous in interface areas (DS-208). b. Redundant fluid lines shall be separated a minimum of 45 degrees (DS-208). c. Redundant connectors shall be separated a minimum of 45 degrees (DS-208).	X	X	X

	Related Procedure No.		
	Direct Man	Manip	Direct Auto
	1-1	1-2	1-3
38. When electrical or fluid interfaces are to be mated between elements, a ground connection between the element structures shall be established to provide a consistent measured low impedance bond between the elements rather than rely on the mating interface for structural ground.	X	X	
39. The interface between mated elements must be designed to be closed and sealed without performing a prolonged demating of interface connectors. In case of a hazard in one element that can propagate to a mated element (i.e., fire, atmosphere contamination, depressurization, etc.), the interface between the elements must be capable of being rapidly sealed. Quick disconnect of connections is acceptable; however, since the period of propagation can be on the order of seconds, any required disconnections should be kept to a minimum.	X	X	X
40. All mating elements shall be equipped with RF communications systems. The minimum extent of the system shall be as follows:			
a. When mating unmanned elements to unmanned elements a ground communications link or a link with a manned orbiting remote control center shall be established. Critical operations between the elements will be monitored, real time. Where feasible, TV coverage should be available.	X		X
b. When mating manned elements to manned elements a duplex voice link between the elements shall be provided. Element status and voice command information must be transmitted between the elements.	X		X
c. When mating manned elements to unmanned elements, a data link shall be provided between the elements. The manned elements will continuously monitor and status the unmanned element and will transmit commands to the unmanned element.	X	X	

Item	Related Procedure No. Direct Man 1-1	Manip 1-2	Direct Auto 1-3
41. Before maneuvering an element attached to a manipulator, the engagement of the end effector in the element receptacle shall be verified. Verification can be performed by simulating the forces that will be applied to the end effector-receptacle during the subsequent maneuvers. Failure of the end effector-receptacle connection could result in escape of the element during subsequent maneuvers with possible collison between the elements.		X	

FUNCTIONAL REQUIREMENTS ANALYSES

The following paragraphs provide the rationale for those quantified functional requirements where extensive analyses is required. These rationale develop conclusions at a relatively gross level. They do not imply that the requirement has been optimized or that further analyses is not required when design proceeds. For example, energy attenuation criteria were analyzed assuming load paths directed through the centers of mass of both vehicles. The effects of large c.g. offsets, lateral velocity, angular and lateral misalignments and flexible body dynamics on attenuation can only be analyzed by developing digital math models of equations of motion, control systems, and docking system detail kinematics in six degrees of freedom of both vehicles. These data cannot be effectively generated until vehicle hardware designs have been more formulated.

Each rationale can pertain to several requirements (i.e., the alignment rationale includes criteria for direct docking and manipulator berthing covering both vehicle alignment and alignment aid accuracies).

Alignment

Alignment criteria for direct docking is dependent on three variables: (1) the capability of a docking port to accept a reasonable misalignment, (2) vehicle appendages that must be avoided during a direct docking, and (3) the ability to control the misalignment of two vehicles with the available alignment aids and control systems.

Present docking port technology is such that designs are available that can accept misalignments in pitch or yaw ranging up to 10 degrees and misalignments in roll ranging up to 180 degrees and lateral miss distances ranging up to 12 inches. Table 1-5 lists the design criteria identified from the studies conducted on various proposed program elements. Because these criteria are all within present docking port capabilities, it is not necessary to conduct analyses of various docking port designs,but only to develop a common alignment criteria that is applicable for all element pairs. It is sufficient to know that a design can be developed that will be compatible

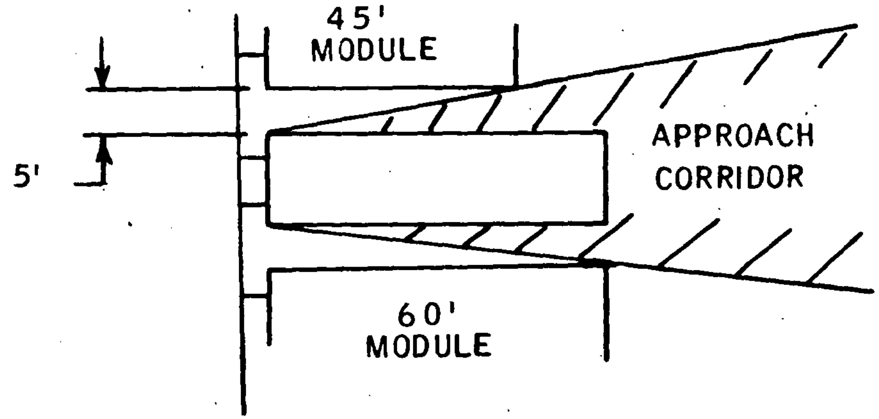
The most critical docking alignment tolerance occurs where appendage or adjacent module interference must be considered. Figure 1-27 illustrates this problem and identifies the associated allowable misalignment. It can be seen that with the identified spacing, maximum length module, and an off-center line approach of 1.0 foot in the plane of the modules, the maximum misalignment must be no greater than 3 degrees. This misalignment also includes any post-impact gyration which may result when misaligned vehicle mating ports collide.

The module spacing of 5 feet is the closest appendage spacing identified in this study. If spacing was larger, naturally misalignment can be larger. But, there is a point of diminishing returns. Control systems can be relaxed with larger misalignments, but mating ports become expensive if they must accept a very large misalignment. Because the identified misalignment for this module spacing does not drive control system design, the identified criteria is considered acceptable.

Table 1-5. Direct Docking Requirements

Parameters	Requirements											
	EOSS (203)	MSS (216)	EOS (218)	EOS (133)	EOS (140)	OPD (451)	RNS (326)	RNS (329)	TUG (252)	CPS (302)	RAM (155)	OLS (350B)
MAXIMUM VELOCITY/ ALIGNMENT DEVIATION												
Axial Velocity (FPS) (Closing Rate)	0.5	1.0	0.4	0.4	0.4	0.6	0.1	0.2	0.4	1.0	1.0	0.5
Radial Velocity (FPS) (Cross Axis Translation Rate)	0.3	0.25	0.25	0.15	0.15	0.15	0.1	0.3	0.3	0.5	0.3	0.3
Angular Velocity (DPS) (Change-in-Rate in Attitude)	0.5	0.5	0.1	0.1	0.1	0.3	0.2	0.5	0.5	0.5	0.5	0.5
Radial Alignment (In) (CTR Line Mis-Distance)	+/-5	+/-12	+/-6	+/-6	+/-6	+/-5	+/-5	+/-5	+/-12	+/-12	+/-12	+/-5
Angular Alignment (Deg) (R-P-Y Mis-Alignment)	+/-4	+/-5	+/-3	+/-3	+/-3	+/-4	+/-3	+/-4	+/-4	+/-5	+/-5	+/-4

*Roll Angular Velocity is 0.02 deg/sec.
NOTE: Numbers in column headings represent data sources listed in Appendix C.



MODULE LENGTH	℄ MISS DISTANCE		
	0	0.5'	1.0'
45'	≤ 6°	≤ 5°	≤ 5°
60'	≤ 4°	≤ 4°	≤ 3°

Note: Effects of vehicle manufacturing tolerances and mating port residual misalignment after rigidizing are minimal (5 foot space would be reduced 3 inches maximum).

Figure 1-27. Allowable Misalignment for Appendage Clearance

Finally alignment criteria is dependent upon the capability of a vehicle to hold alignment. Control can be affected by several variables (alignment aids available, distance of docking port to c.g., and cross-coupling that cause tolerances to approach or exceed limitations). Visual alignment systems that do not look through the center of the mating ports require that the data be integrated with the geometry of the docking port location and alignment sensor location. For the Apollo-LEM dockings, it was necessary to decrease the allowable designed tolerances when reading the alignment aids because of the off center location (DS536). Simulated manual dockings of a space station to a Saturn (S-II) vehicle utilizing out the window targets resulted in miss distances ranging generally around 0.5 foot with isolated cases out to 1.0 foot (DS236). With an automated system, such as a laser radar, the off center location can be displayed and the geometric parameters integrated within the reading thereby compensating for the additive misalignment. If alignment aids are designed such that vehicle geometry does not affect the readings, such as a system that views through the mating port, then this characteristic will not impose more critical alignment tolerances. An automated system such as a laser radar can determine alignment to an accuracy of +/-0.02 degrees in pitch and yaw, and +/-1.0 degrees in roll. Visual systems can determine when the alignment is off center greater than 3 degrees in either pitch,yaw, or roll.

The distance between the c.g. and the docking port limits the vehicle attitudes deadband. Figure 1-28 illustrates the mating port displacement as a result of various attitude hold criteria as it relates to distance between vehicle c.g. and the docking port. With a limit cycle deadband of 0.3 degree and a mating port located 40 feet from the c.g., displacement will be 2.52 inches. This in itself is well within mating port miss distance tolerances; however, when two elements are mating each with 40 foot separation distances between c.g., and their mating ports, the displacement becomes 5.04 inches which approaches the allowable limit. Vehicles with c.g. - mating port offsets of 40 feet, 60 feet, and greater, are included in the array of study elements. As a rule of thumb, these vehicles should design for attitude hold capability in the range of 0.2 degrees. For elements with relatively short distances between c.g. and mating port, this criteria can be relaxed. The 0.2 degree requirement will not be a driver for most elements in that other vehicle criteria (i.e., experiment and navigation) requires pointing characteristics that are more stringent. For those elements that have not identified altitude hold criteria, 0.2 degrees is well within present technology and should not impose any design difficulty, particularly since the hold component is required for only the short mating period.

Translation-rotation cross-coupling can produce the largest docking control errors (DS 562). There are two sources of such coupling. One is the result of imperfect arrangement of the RCS thrusters with respect to the vehicle center-of-mass such that translation thrusting also produces some applied moment on the vehicle. The other is due to the fact that the docking port is not located at the active vehicle center-of-mass, so that pure rotation produces relative translations at the docking port. The array of vehicle configurations proposed for the next two or three decades indicate that the feasibility of consistently locating control systems and docking ports around the center-of-mass is highly unlikely and simply would not, in some cases, be practical. Therefore, the selected control system for docking should be one

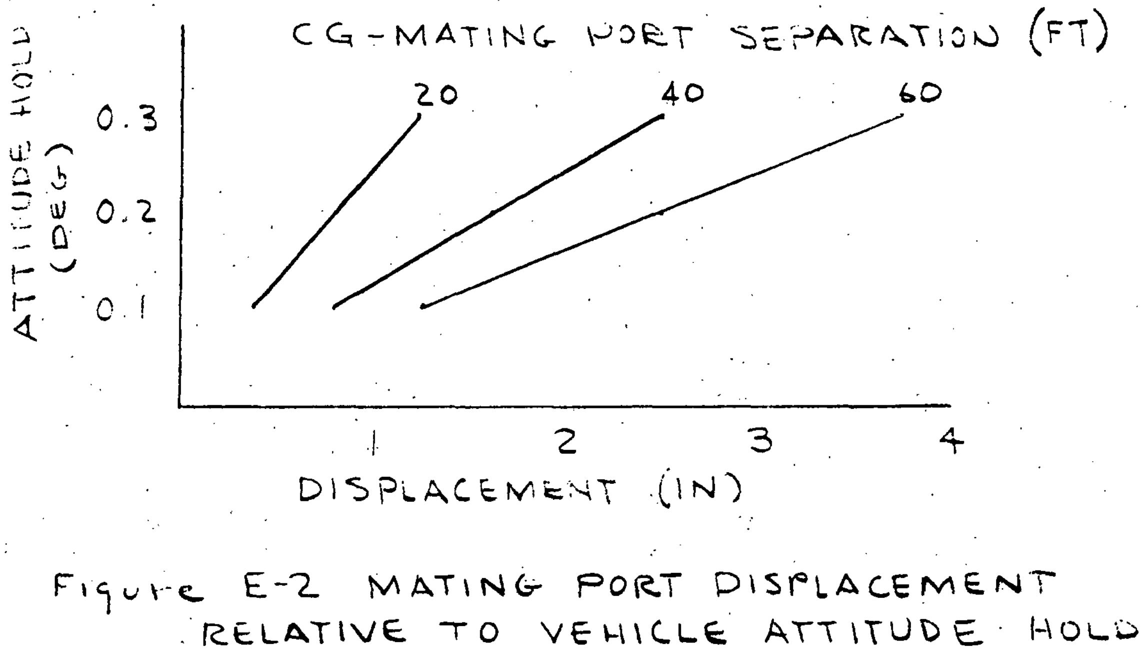


Figure 1-28. Mating Port Displacement Relative to Vehicle Attitude Hold

that can compensate for cross-coupling effects such as a system that automatically holds attitude during translation maneuvers. If this is accomplished, then the miss distance and misalignment at contact can be maintained well within tolerance. If on the other hand, this is not feasible, the tolerance buildup for manual dockings can be significantly larger. Simulated dockings showed that cross-coupled systems rated poorly relative to non-coupled systems (i.e., on a Cooper rating scale of 0 to 8, cross-coupling rated between 6 and 8, and non-coupled systems rated between 1.5 to 4.5 (DS 562). Because simulated runs with cross-coupling (space station - SII dockings) showed pointing errors at contact to generally be less than 1 degree with occasional excursions to 1.5 degrees (DS 236), and since the critical misalignment parameters are 4 degrees (appendage clearance), it is assumed that cross-coupled systems can safely be utilized if misalignment were the only consideration.

Summation

The various study contractors have identified misalignment allowances of between 3 degrees and 5 degrees (see Table 1-5). Because of the appendage alignment criteria, four degrees is considered the maximum allowable misalignment. Table 1-6 identifies the requirements for the various components that can affect alignment or alignment determination. The requirements tolerances for visual alignment aids (pitch, yaw, and roll) and automatic alignment aids for roll were strictly the acceptance of component characteristics since these capabilities were within acceptable limits. The visual aid tolerance is about the maximum allowable, particularly in pitch and yaw. The automatic alignment aids are more stringent in that these aids transmit information to a remote site for possible additional control. This closer tolerance provides controllers the capability to forecast approaching limits and make command corrections at optimum periods.

Because of the +/-1 degree alignment aids tolerance and the 4 degree maximum allowable misalignment, the following requirements are considered the design to criteria.

Vehicle control (p, y, r):	+/-3 degrees
Mating port allowable misalignment (p, y, r):	+/-4 degrees

Table 1-6. Alignment Component Criteria

COMPONENT	REQUIREMENT (degree)	CAPABILITY (degree)
Visual Alignment Aid (p, y, r)	≤ 3	≤ 3
Automatic Alignment Aid (p, y)	+/-1	+/-0.02
(r)	+/-1	+/-1
Vehicle Attitude Hold (limit cycle)	+/-0.2	< +/-0.2
Cross Coupling Effects	-	≤ 1.5

Allowable miss distance is a function of vehicle attitude hold (pointing capability) and capability of alignment aids to read displacement. A 6-inch miss distance was arbitrarily selected from the various requirements proposed by the study contractors (see Table 1-5). A 6-inch miss distance limitation should not be difficult to achieve. Simulated space station - S-II dockings using only visual aids and an allowable 1 foot deviation tolerance resulted in consistent contacts at less than a 6-inch displacement. With each vehicle of the mating pair holding a +/-0.2 pointing attitude, the 6-inch tolerance will not be exceeded until the distance between the combined centers-of-gravity exceeds 143 feet. From the identified pairs and the element configurations, this does not appear likely. Both visual aids and automatic systems can determine miss distance within this limit. With miss distances greater than 6-inches, some of the mating port design concepts become less viable, thus eliminating the selection of various candidates.

Impact Attenuation

Impact attenuation is primarily dependent on the equivalent mass of the docking vehicles, the closing velocity between the vehicles and the natural ability of the vehicle structures to absorb impact energy (spring constant). In general, active energy absorption requirements are determined by how much structural weight can be saved by devoting a smaller weight to an energy attenuation system. However, there is a point of diminishing returns. Attenuation system weight increases with the increase in absorbing stroke required to reduce structural load.

The relative motion (velocity at contact) between docking vehicles becomes the design criteria for the attenuation system and is best established by mean values plus the desired number of standard deviations of closing velocity as controlled by a trained pilot. Significant differences in spacecraft systems, c.g. location with respect to docking port, and docking system control will greatly affect docking dexterity or docking contact conditions.

Contact conditions are also a strong function of pilot training. Past history indicates that optimum docking systems are not developed where man/machine relationship parameters are defined without adequate simulation data available. However, some general criteria can be established which will enable study contractors and designers to concentrate their efforts within some fixed boundaries.

Figure 1-29 is a matrix of the mass equivalents for various mating pairs as identified by this study.

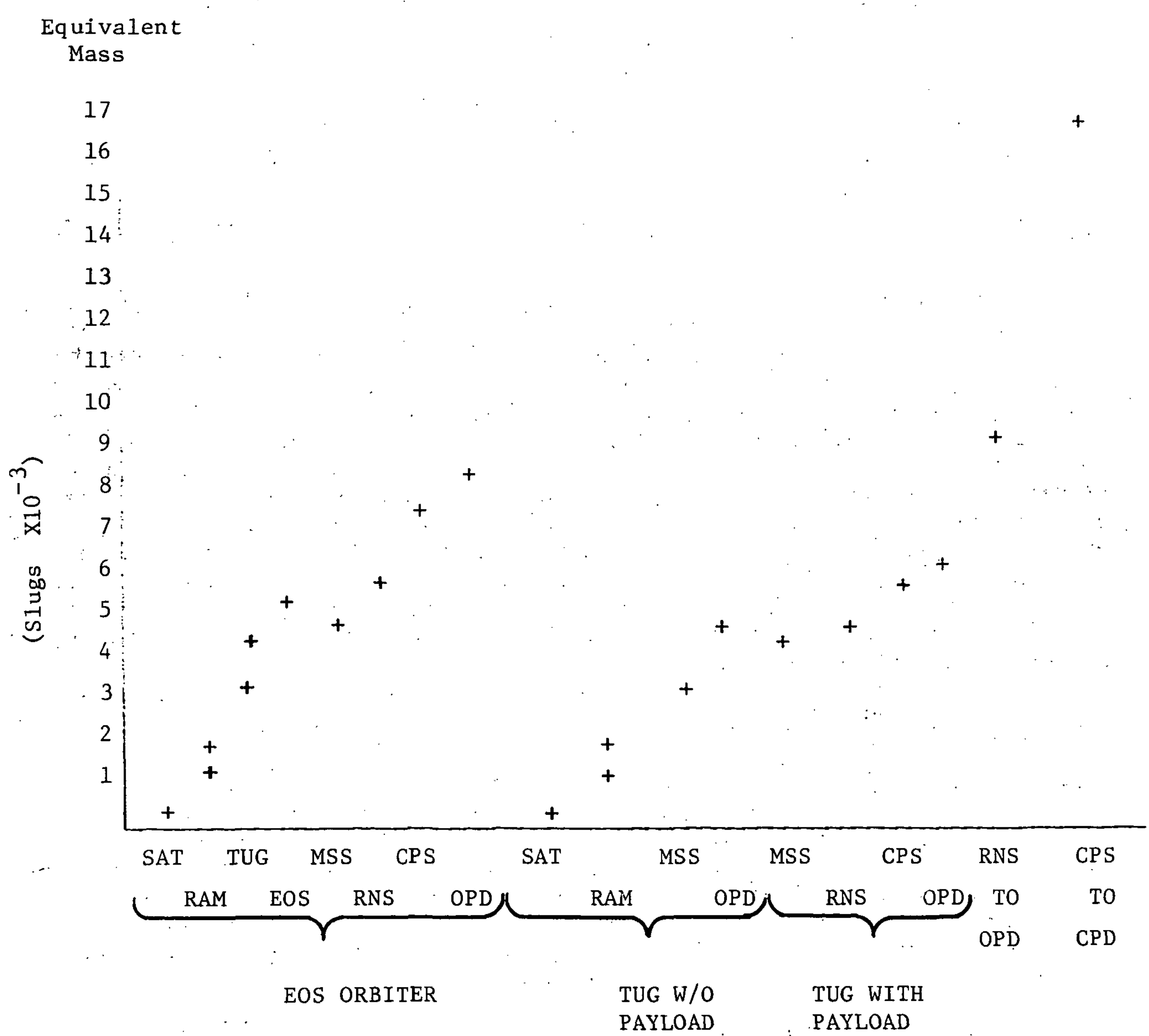


Figure 1-29. Mass Relationships

Figure 1-30 shows the resultant impact energy for various sized vehicles colliding in-line with their center of masses at various closing velocities. Figure 1-31 expands on these relationships by providing a matrix of the study element pairs that may be mated and the energy imparted by direct docking the vehicles at selected closing velocities. The matrix shows that a system that can absorb up to 800-foot pounds energy could be utilized for all the element pairs as long as the closing velocity was no greater than 0.3 feet/second. Experience indicates that the range of vehicle equivalent mass that a single attenuation system can handle without requiring a hardware modification is about 10 to 1. If we eliminated the CPS-OPD mating and the RNS-OPD mating, on the high side and the satellites, and possibly RAM matings on the low side, all of the other pairs could be fully accommodated by a single system that attenuated energy between 100-foot pounds and 400-foot pounds with closing velocities ranging between 0.3 fps and 0.4 fps. The CPS-OPD mating and the RNS-OPD mating could utilize a special attenuation system or be docked at a closing velocity less than 0.2 fps. The smaller masses (satellite matings) could possibly be accommodated by the single mating system if the capture latches can be made sensitive enough to react to low energy impact dockings and still be capable of capturing the massive vehicles.

Energy attenuation, regardless of the absorbing medium, requires a force applied over a distance. Figure 1-32 is an illustration of the force, as a function of stroke, required to arrest the relative motion of two spacecraft colliding at 0.4 fps in line with their mass centers. It is apparent that, if a working stroke of approximately one foot is provided, the loads on the mechanism will cause no significant design problems. However, as noted, these criteria reflect only direct dockings for vehicles impacting in line with their centers of mass. Additional criteria that affects attenuation design are large c.g. offsets, lateral velocity, angular and lateral misalignments, and flexible body dynamics. These criteria can be established accurately only by digital math models of equations of motion, control systems, and docking system detail kinematics in six degrees of freedom of both vehicles.

Allowable lateral and angular velocity requirements must be traded between vehicle control capabilities and mating port design capability ranges. The requirements determined herein are based on an EOS orbiter mating with another EOS orbiter. Requirements for this configuration are 0.15 fps allowable lateral velocity and 0.1 degree per second allowable angular velocity. Using this baseline, the rest of the mating pairs were ratioed relative to equivalent mass and are discussed subsequently.

With no attenuation system, allowable closing velocities are determined by the ability of the vehicle structures to absorb the impact energy. The variation of load with closing velocity is estimated using the axial stiffness characteristics of the structural shells. Figure 1-33 shows the capabilities of the modules of a modular space station to withstand loads without buckling for both pressurized and unpressurized conditions. These allowables are estimated based on a misaligned operation that introduces the load over a localized region of the interface. From Figure 1-33, it is seen that the

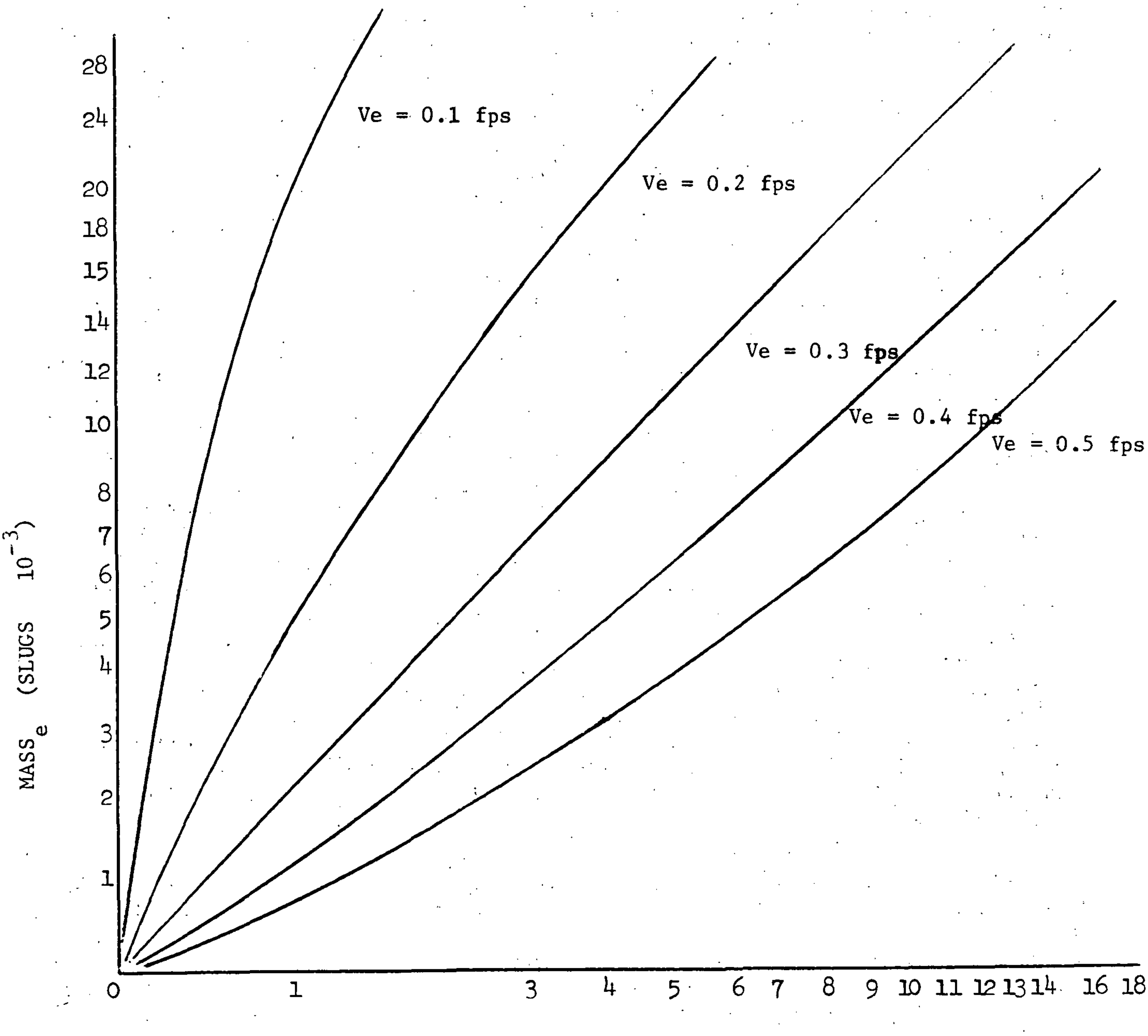


FIGURE 1-30. IMPACT ENERGY VS. EQUIVALENT MASS FOR VARIOUS CLOSING VELOCITIES

CLOSING VELOCITY FPS \ IMPACT ENERGY FT - LBS	–25	25–50	50–100	100–200	200–300	300–400	400–500	500–600	600–700	700–800	800–900	900–1000	1000–1100	1100–1200	1200–1300	1300–1400
0.5			TUG$_1$ - SAT EOS - SAT	TUG$_1$ - RAM	EOS - RAM		TUG$_1$ - MSS EOS - TUG	TUG$_2$ - RNS TUG$_2$ - MSS TUG$_1$ - OPD	TUG$_2$ - CPS EOS - RNS EOS - MSS EOS - EOS	TUG$_2$ - OPD TUG$_2$ - CPS		EOS - OPD EOS - CPS		RNS-OPD		
0.4		TUG$_1$ - SAT EOS - SAT		* TUG$_1$ - RAM EOS - RAM	TUG$_1$ - MSS EOS - TUG	TUG$_2$ - RNS TUG$_1$ - OPD TUG$_2$ - MSS EOS - MSS EOS - EOS	TUG$_2$ - OPD TUG$_2$ - CPS EOS - RNS	EOS - CPS	EOS - OPD	RNS-OPD						CPS-OPD
0.3	TUG$_1$ - SAT EOS - SAT		TUG$_1$ - RAM EOS - RAM	TUG$_2$ - RNS TUG$_2$ - MSS TUG$_1$ - MSS EOS - TUG	TUG$_2$ - OPD TUG$_2$ - CPS TUG$_1$ - OPD EOS - RNS EOS - MSS EOS - EOS	EOS-OPD EOS-CPS	RNS OPD			CPS-OPD						
0.2	TUG$_1$ - SAT EOS - SAT	TUG$_1$ - RAM EOS - RAM	TUG$_2$ - RNS TUG$_2$ - MSS TUG$_1$ - OPD TUG$_1$ - MSS EOS - MSS EOS - EOS EOS - TUG	RNS - OPD TUG$_2$ - OPD TUG$_2$ - CPS EOS - OPD EOS - CPS EOS - RNS		CPS-OPD										
0.1	TUG$_2$ - RNS TUG$_2$ - MSS TUG$_1$ - OPD TUG$_1$ - MSS TUG$_1$ - RAM TUG$_1$ - SAT EOS - MSS EOS - EOS EOS - TUG EOS - RAM EOS - SAT	RNS - OPD TUG - OPD TUG - CPS EOS - OPD EOS - CPS EOS - RNS	CPS - OPD													

TUG$_1$ = TUG WITHOUT PAYLOAD
TUG$_2$ = TUG WITH 65000 LB PAYLOAD

*Emphasized area represents the best fit for commonality. All element pairs can be direct dock with a system that attenuates 100 to 400 ft-lb impact energy if closing velocities are maintained at less than 0.4 fps.

Figure 1-31. Energy Attenuation Criteria for Direct Docking Various Element Pairs

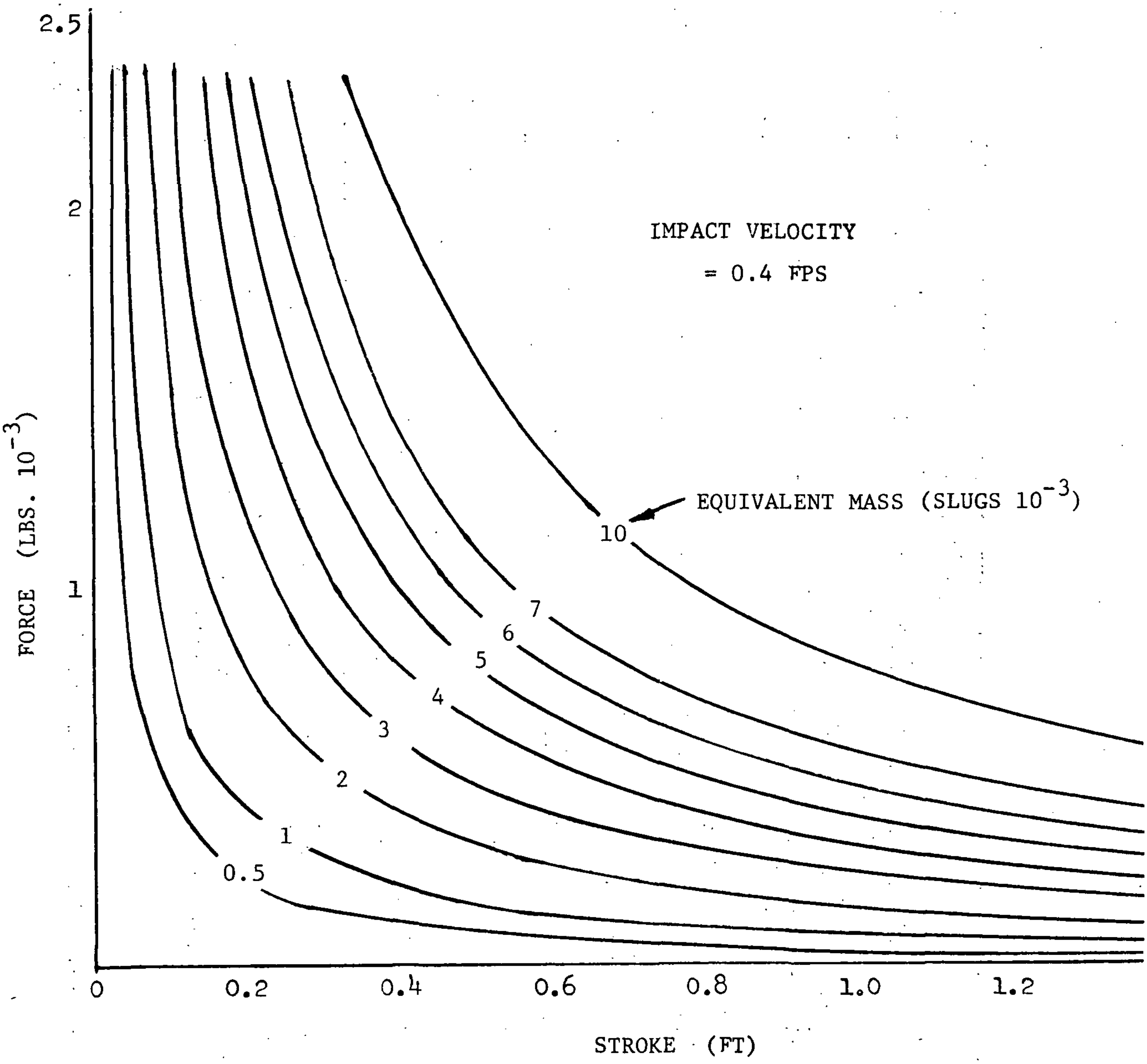


FIGURE 1-32. STROKE CRITERIA VERSUS ALLOWABLE FORCE

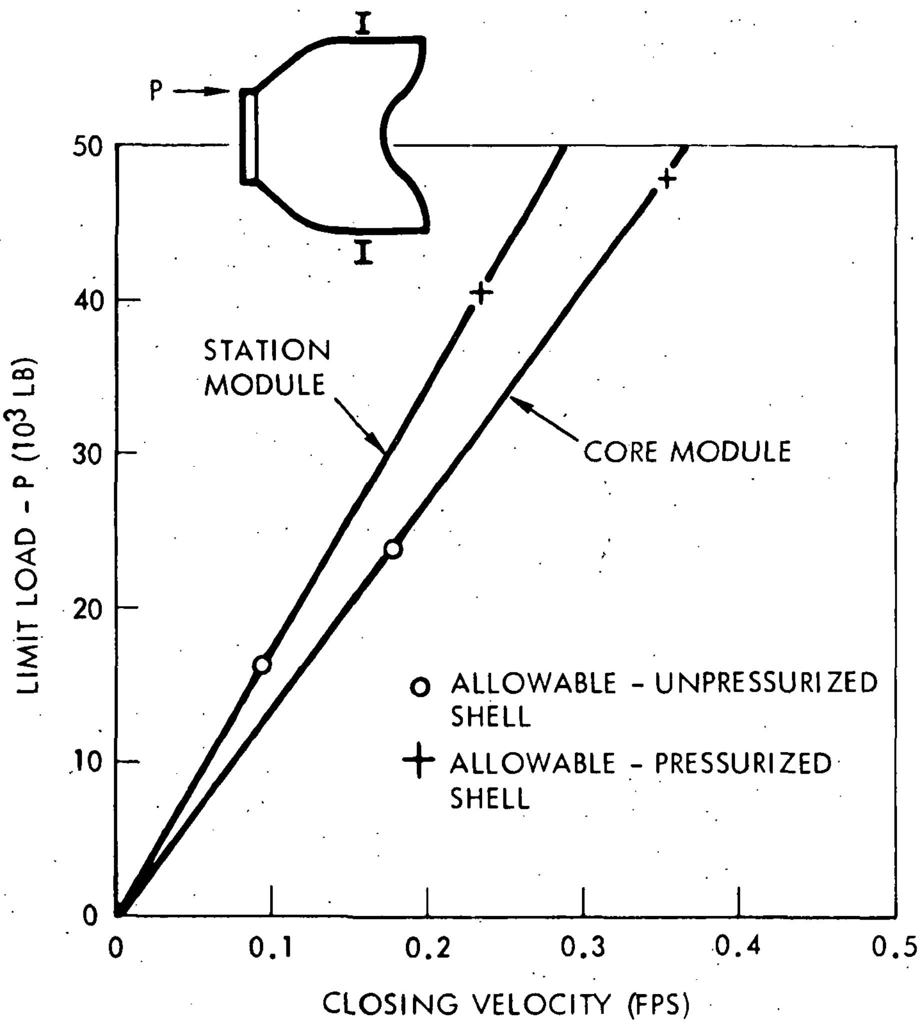


FIGURE 1-33. LOAD VERSUS CLOSING VELOCITY

velocities that will induce loadings equal to the structural capability are 0.095 fps and 0.235 fps for an unpressurized and pressurized common module, respectively, and 0.18 fps and 0.355 fps for the core module. All of these velocity capabilities are well above the 0.05 fps initial berthing impact condition allowed by space station design (DS-242). Using this design as a standard, the allowable impact velocities were ratioed for the various mating pairs relative their equivalent mass to determine the criteria for the various other element pairs.

Relative Velocity Nulling Rationale

Capture of a stationkeeping vehicle by another element using a manipulator requires that the relative velocity between the two elements be reduced to a level compatible with manipulator characteristics and subsequent control capabilities. The allowable velocity is dependent on the target vehicle mass, configuration, location of the capture receptacle, and the geometry of the manipulator arm at time of capture. These criteria define the torque required to null out the relative velocity and the allowable travel before contact between vehicles can occur or the manipulator full extension point is reached and the capture disengaged. In addition to these parameters, manipulator maneuverability and allowable capture miss distance tolerances will also dictate the maximum relative velocity.

Quantitative requirements limiting the relative velocity between the various mating pairs can be developed by providing a model of all the possible vehicle configurations that may be encountered in the next one or two decades, analyze their capabilities and configurations, and then impose requirements for a manipulator design. This requires, however, that much of the data be conjectural with the possibility of the driving criteria being subject to debate. Another method would be to utilize a model of a manipulator which has feasible design characteristics and identify the requirements that must be imposed on the vehicles. If these requirements are essentially within general vehicle capabilities, then the model would be considered valid. Because a preliminary manipulator design has been developed for EOS orbiter usage and the data is available (Reference: DS-570), this latter method was selected.

Figure 1-11 depicts the manipulator model that was utilized for the analyses and requirements development. This design may not be the selected configuration; however, the requirements were developed such that any design of similar properties would be capable of functioning with the study elements. This was achieved by never utilizing the manipulator design to its full capacity. For instance, all torque requirements were validated utilizing only one of the joints to apply resistive torques rather than analyzing the system with the three joints working in unison which, of course, would increase the manipulator model capabilities and in turn lessen the requirement tolerances. However, the requirements tolerances developed are within the present technology and should not impose any design difficulties.

Nulling out the relative velocity between vehicles essentially applies the same rules as direct docking impact attenuation. A stroke is applied over some distance absorbing kinetic energy in a controlled manner such that the vehicle structure or in the case of a manipulator the joints and arm structure, can absorb the impact shock. Because there is a limit to how strong the manipulator arms can be manufactured and still be reasonably lightweight, the stroke will be relatively long, especially when capturing large mass vehicles if the relative velocity is at all substantial. The manipulator model uses torquing motors located in each joint to apply controlled resistive forces to null out relative velocity. The resistive torque can be applied by any single joint with the other joints held rigid, or the torque can be compositely applied by all joints working in unison. Figures 1-34, 1-35, 1-36, and 1-37 identify the torque requirements for a manipulator utilizing only a single joint with a moment arm of a specified length to null out various relative velocities of vehicles of various mass sizes. The vehicle with the manipulator is considered to be holding attitude (infinitely large mass), thus the force that must be attenuated is that of the target vehicle.

The relative velocities considered were 0.05 fps, 0.1 fps, 0.2 fps and 0.3 fps. For these analyses, vehicle masses of 60 slugs, 1000 slugs, 2000 slugs, 4000 slugs, 10,000 slugs, 12,000 slugs, 28,000 slugs and 40,000 slugs were used which are the range of vehicle masses of the study elements. The manipulator end effector was considered to capture near the center of mass of the target vehicle and no additional moment arm was applied, except in the noted cases of Figures 1-34 and 1-35 which extend the moment arm to 100 feet, providing for the capture of an MSS at the end of an attached module. The vertical intersect lines represent the moment arm length (7 feet, 30 feet, and 50 feet) for each joint location (wrist, elbow, and shoulder, respectively) of the model manipulator. Assuming a maximum angular rotation of 45 degrees could be allowed at each joint during the capture operation, the maximum chord length for each joint independently applying the torque is approximately 5 feet, 23 feet, and 38 feet, respectively. The noted intersect points (diagonal lines) indicate the vehicle masses for noted velocities that can be nulled out by the single joint operating within a given chord length. Figure 1-38 graphically shows the results of these analyses. It can be seen that at a relative velocity of 0.05 fps, all of the elements identified can be brought under control within 5 feet by any of the individual joints. At 0.1 fps, all vehicles can also be controlled but the stroke length can be as great as 20 feet for the largest vehicle. At 0.2 foot/second all but the CPS and OPD can be controlled independently by either the elbow or shoulder joint. The larger vehicles (CPS and OPD) can fit within the 0.2 fps parameter if the large vehicles hold attitude and the manipulator vehicle (EOS orbiter) essentially goes passive. The manipulator will then be removing the kinetic energy of the smaller element. These criteria, however, are not the limiting factors. Large vehicles (RNS,CPS,OPD) and vehicles of complex configuration (MSS, OPD) pose the additional hazard of possible contact between vehicles because of the long stroke requirements and interfering appendages. Interference can occur only when the relative velocity is in the closing direction and can be avoided if at the time of capture, the vehicles are retreating from each other.

Retreating vehicles also provide the added safety factor that in case of failure to capture or failure to damp out the relative velocity will not result in a vehicle collision. If the direction of the relative velocity cannot be determined, then the stationkeeping position at time of capture must be such that the manipulator can null out the relative velocity no matter which direction it is applied.

Maintaining a positional attitude by one of the elements can create additional problems in that torques are applied by rocket engine impulses set up vibrations in an extended manipulator arm, particularly when extended with an attached load. The vibrations may be of an amplitude and frequency such that an uncontrollable situation results. This problem can be avoided by inhibiting reaction control systems and utilizing the manipulator torque capability to maintain a relative attitude between vehicles. The operation essentially has the vehicles inhibit engines at time of capture. At the same time the manipulator arm begins to reduce the relative velocity by extending its arm at a rate which will guarantee that the kinetic energy is absorbed before full extension is reached.

These criteria show that relative velocities of about 0.2 foot/second can be successfully nulled out by the manipulator model used in this study. An adequate margin of safety can be maintained between the elements during and upon completion of the "stroke" or arc of the target vehicle subsequent to capture.

The requirement for nulling the relative velocity is also dependent upon the slewing speed of the manipulator. One concept evaluated required a slew speed of the end segment of 0.5 fps to effect capture if initial separation were only 1.5 feet and the relative velocity between elements was 0.2 fps. If capture were limited to a 10-foot arc it must be accomplished within 50 seconds or the attempt aborted. Higher manipulator slew speeds and longer arcs would, of course, permit larger relative velocities between elements. (Capture at 5 fps relative velocities has been demonstrated in simulations.)

Summary

Simulations have shown that the relative velocity between vehicle centers of gravity can be reduced to less than 0.1 foot/second. These simulations were performed with no sensor other than the human eye and a TV camera viewing a stand-off cross for alignment and relative velocity determination. The procedure was to essentially maneuver the end effector with a TV camera mounted on it relatively close to the target vehicle (approximately 10 feet) and view the capture receptacle for any movement. When the relative velocity was trimmed by the pilot to the extent that no movement was apparent, the capture was effected. The relative velocity at capture during these runs was measured to be well below 0.1 fps and was not uncommon to be in the range of 0.03 fps. Thus, the recommended functional requirement for relative velocity between elements during manipulator capture operations is ≤ 0.1 fps. This value permits a low slew speed of the manipulator, a reasonable pre-capture arc of the target element, and/or a safe post-capture arc of the target element.

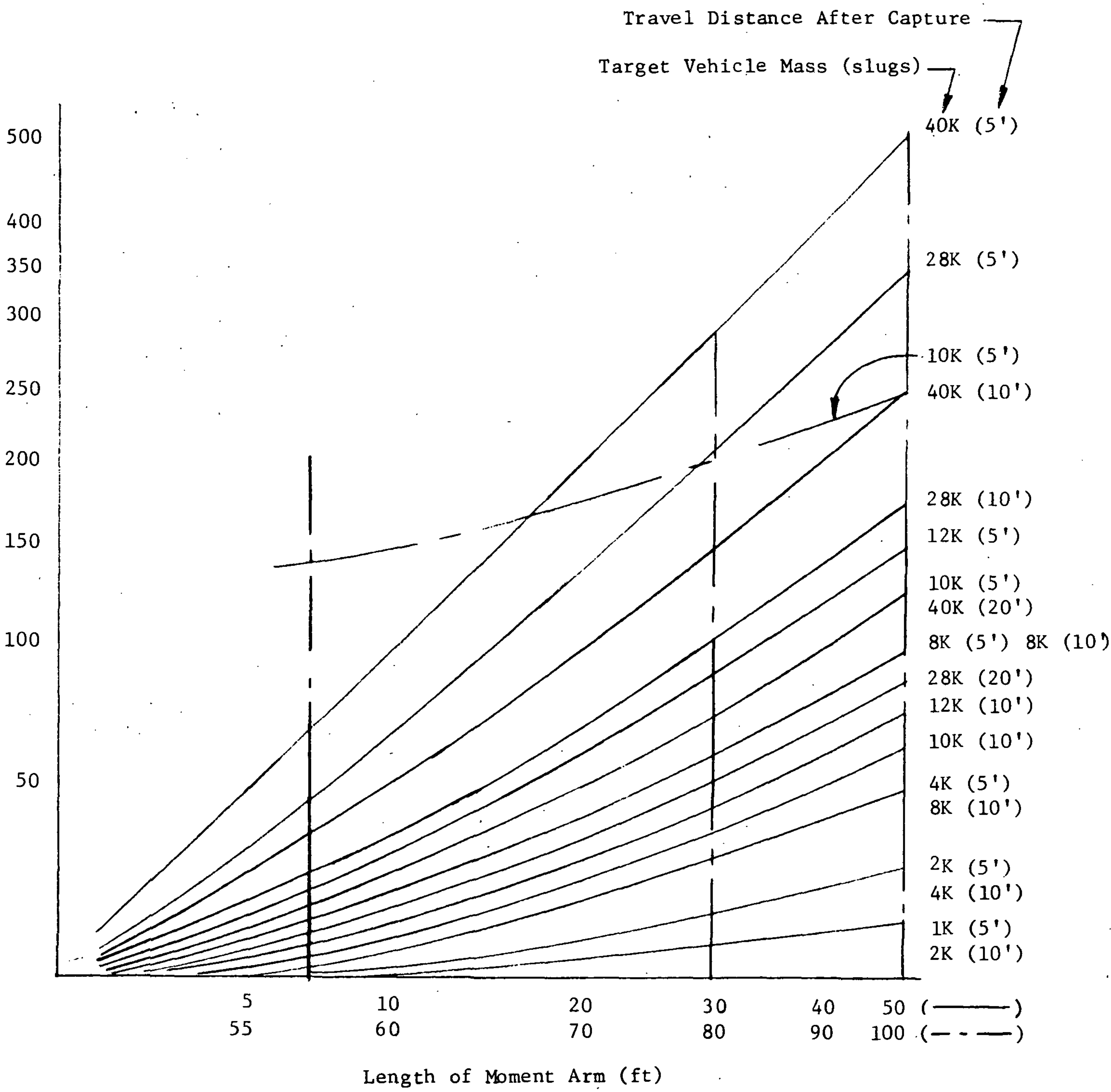


Figure 1-34. Torque/Stroke Requirements to Null Out a Relative Velocity of 0.05 FPS for Various Mass (slugs) Elements Relative to Moment Arm

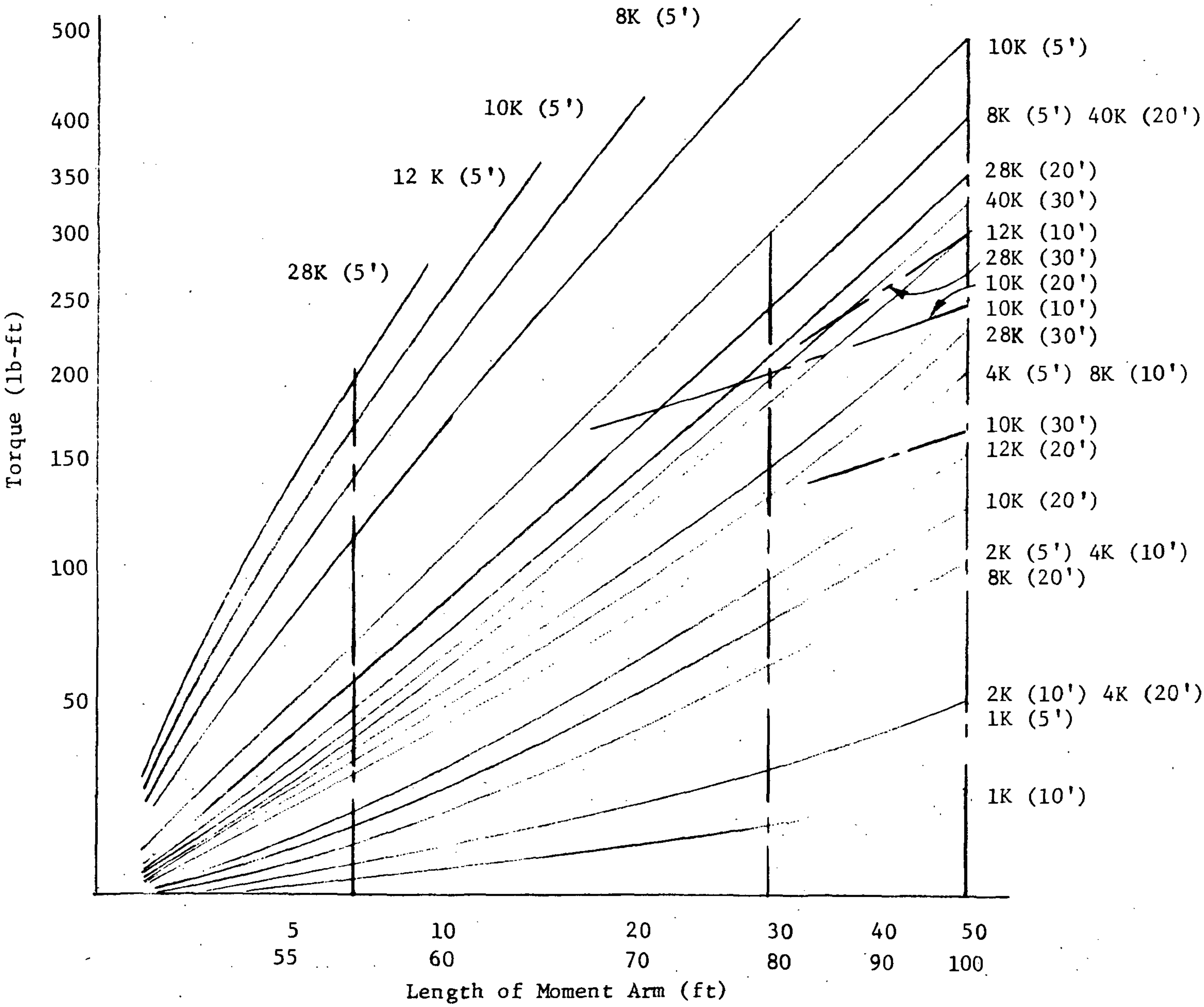


Figure 1-35. Torque/Stroke Requirements to Null Out a Relative Velocity of 0.1 FPS for Various Mass (slugs) Elements Relative to Moment Arm

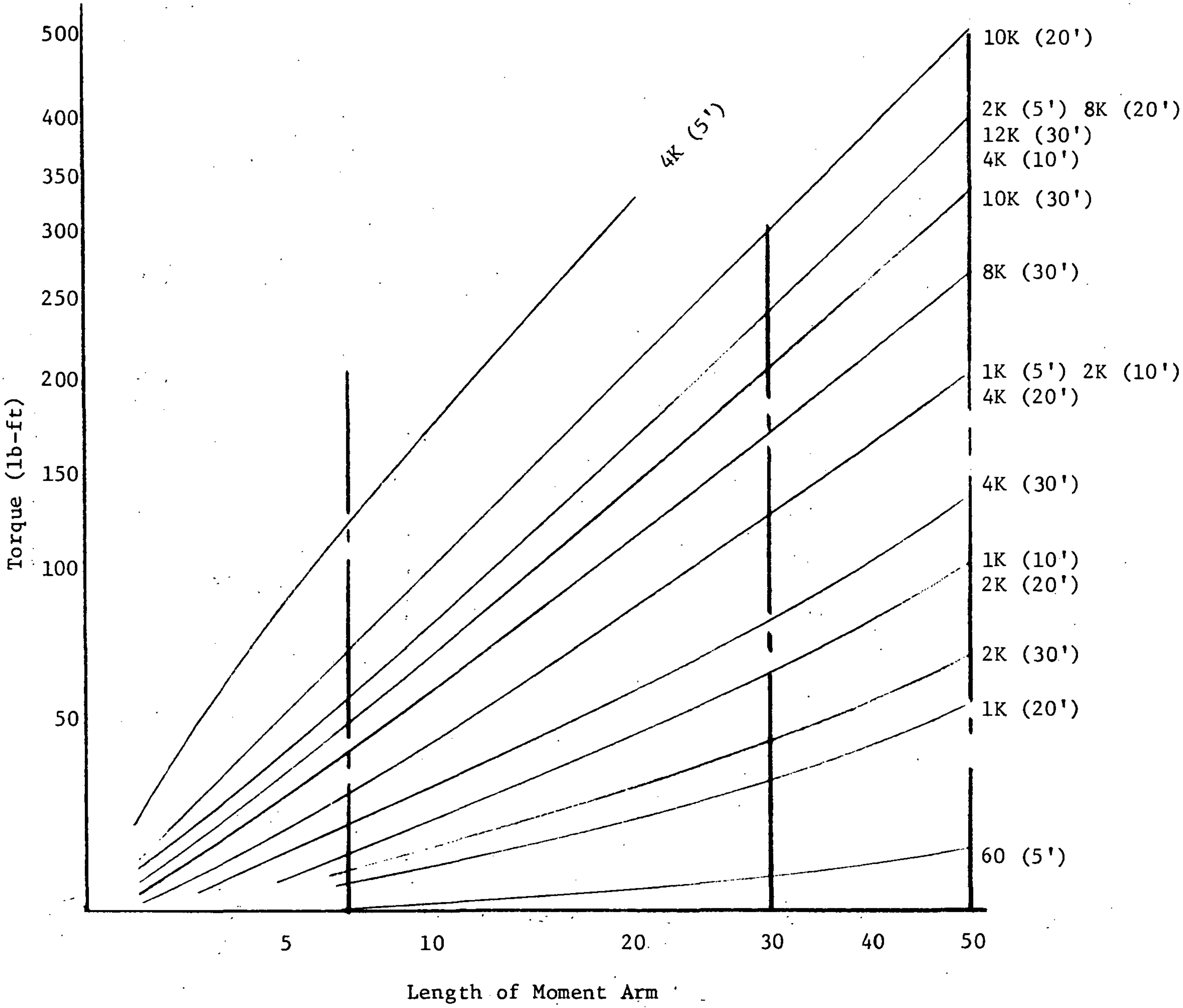


Figure 1-36. Torque/Stroke Requirements to Null Out a Relative Velocity of 0.2 FPS for Various Mass (slugs) Elements Relative to Moment Arm

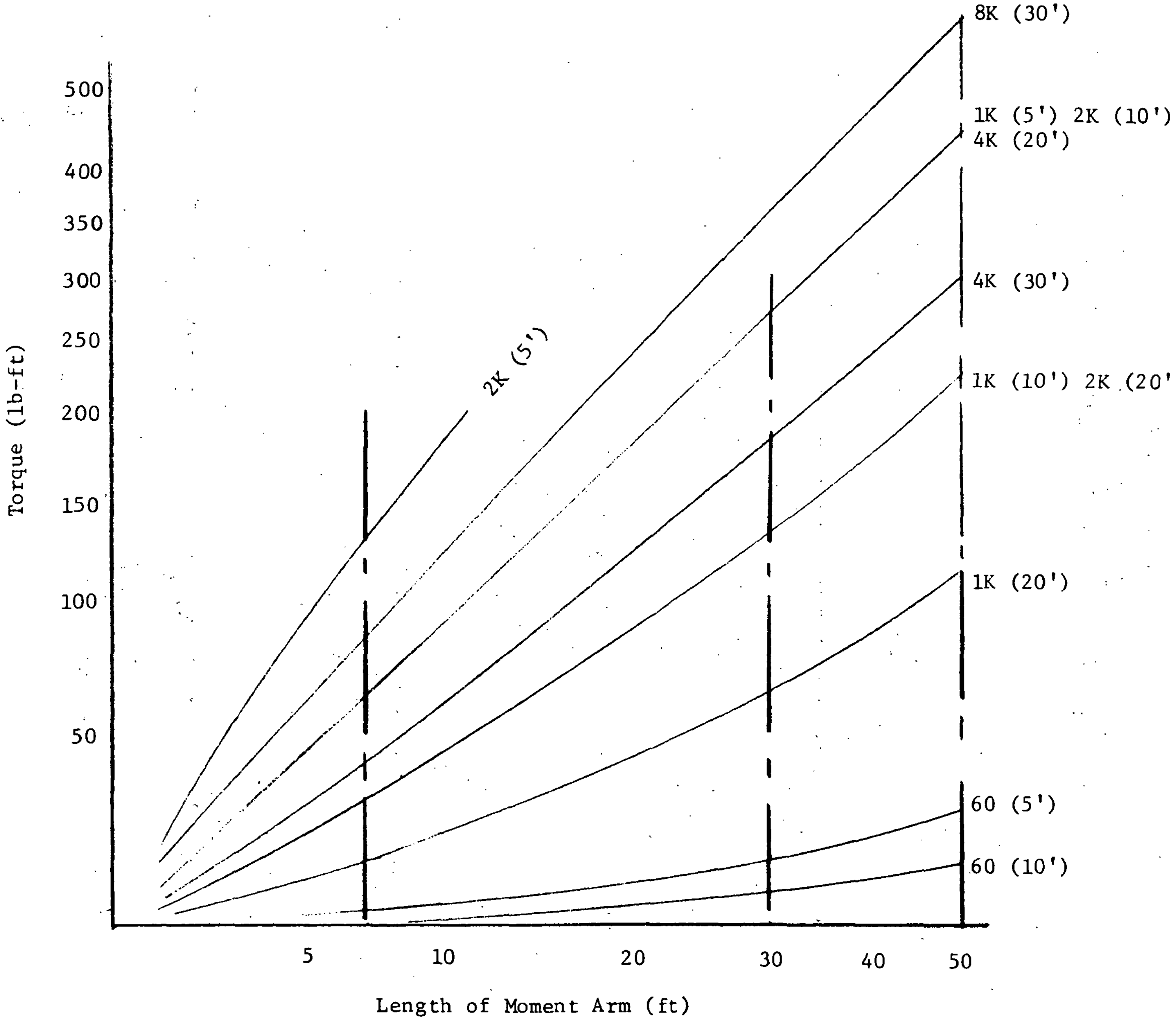


Figure 1-37. Torque/Stroke Requirements to Null Out a Relative Velocity of 0.3 FPS for Various Mass (slugs) Elements Relative to Moment Arm

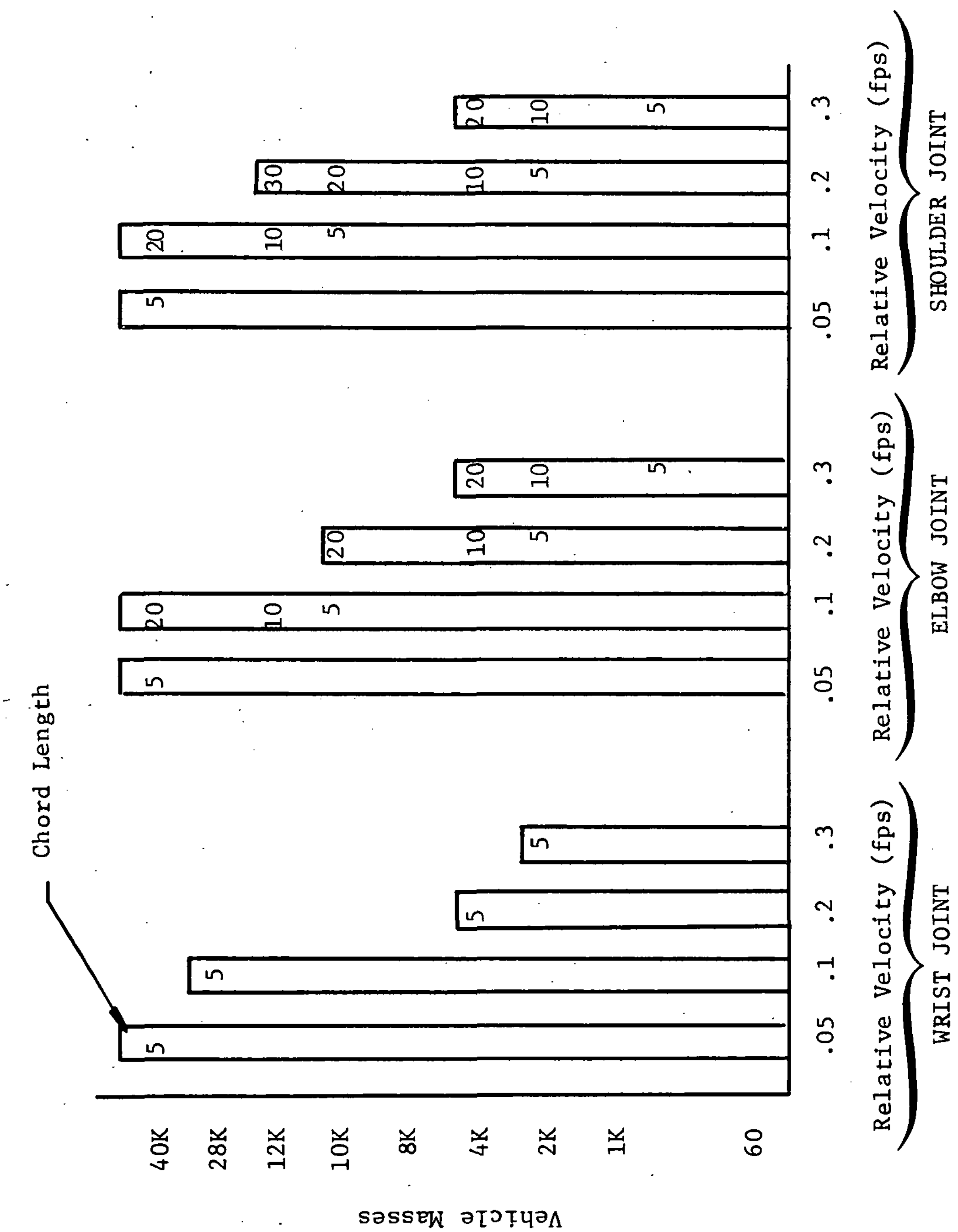


Figure 1-38. Individual Manipulator Joint Capabilities

Range Rate Accuracy Rationale

Range rate is required for automated dockings, manual dockings, and manipulator berth operations. Manipulator berth accuracy is the most stringent in that the maximum closing rate in some cases is less than 0.05 fps. But, because this rate is sensed within the manipulator itself, it does not impose an interface problem. Because it is solely an independent design, no tolerance is identified. Direct dockings on the other hand may require information to be transmitted between the closing vehicles. This information could be in the form of a rebounding radar signal, an RF transponded signal, or simply a target on the vehicle being measured by reading index lines as they cross a monitor grid.

As identified in the impact attenuation rationale, direct docking closing velocities can range between 0.2 and 0.4 fps. A system that enables the relative velocity to be determined within 0.1 fps will support this criteria and is within the range of both automated and visual aid techniques.

Sensors that provide closer tolerances will allow dockings to be achieved in a shorter time period because the closing rate can be increased relative to the rate knowledge.

Range Knowledge Rationale

Whereas range rate knowledge is a hard requirement and can be quantified, range knowledge for mating is not as defined. The need for range determination of some order is not in question, but the accuracy of the information is relatively subjective.

For automated mating systems, range information is required to provide the means to sense when to reduce the closing rate. Range also provides information to backup controllers for indexing the docking closing events and make, if necessary, overriding decisions at proper times. Range information makes possible the forecasting of points where tolerance limits will be exceeded. For example, if a vehicle alignment is slowly approaching the allowable misaligned limit, the controller can determine the point at which this misalignment will occur. It may be that the forecast would indicate the misalignment will not occur until after the mate was effected. Without range data, the controller would probably attempt to make the corrections immediately or abort the docking rather than awit until the limit is exceeded and possibly abort when the vehicles are very close together.

The accuracy of range data for unmanned dockings does not require extremely accurate sensing. A tolerance of about +/-2 feet is considered valid in that it provides the information to make decisions when the vehicles are relatively close together and is within automated system design capabilities; i.e., laser radar range accuracy is +/-0.02 percent of range or +/-10 cm, whichever is greater.

Manual direct docking range determination is far less critical. A trained pilot viewing the closing operation through a window or by TV can fairly accurately judge the range and incrementally increase or decrease the closing rate to achieve a controlled docking within the proper limits. The tolerance for this procedure is that the pilot will have the capability to determine range within +/-25 percent at a distance of 25 feet. This allows the pilot a fair separation distance for reducing the closing velocity to the required rate and not such a great distance that final closing is a prolonged event.

When capturing a vehicle utilizing a manipulator, range accuracy is not critical, but should be capable of being determined to within +/-5 feet when two vehicles are maintaining a stationkeeping position at a distance of from 25 to 40 feet. This particular range is based on a manipulator with a 50-foot reach. The +/-5 foot tolerance allows for capture of the largest vehicle at a relative velocity of 0.2 fps. If after capture, the vehicles were expected to move up to 20 feet, the manipulator capture point can be selected with the knowledge that the relative velocity will be nulled out before the two vehicles can collide or before full extension by the manipulator is reached.

FUNCTIONAL REQUIREMENTS BY ELEMENT PAIR

The following paragraphs reflect the requirements as they apply to the element pairs or the independent element of a pair. These paragraphs are numerically ordered following a one-to-one relationship with the requirements of the previous paragraphs, thereby providing an easy cross reference. Each requirement is identified by a key phrase and does not in most cases elaborate on the details or discuss the rationale. Details and rationale are contained in the previous paragraphs.

In order to reduce the volume of this section, the element pairs have not been directly identified. Instead, each element that a requirement is applicable to has been noted. By refering to Figure 1-1, the corresponding interfacing vehicles that the noted element can mate with can be identified. Ground rules that accompany the requirement provide the necessary information to qualify the associated element of the pair. The term target element refers to vehicles the noted applicable elements must mate with for a valid requirement. In most cases, the requirements are the same for all mating pairs, but there are some requirements that vary due to the mass relationship of the elements. In these cases the requirements have been ratioed using a baseline and the relative masses of the associated element pairs.

1. Illumination Criteria

Requirement: Illumination to visually determine element orientation at noted range.

Ground Rule: Applies when the target element is manned or target element is an unmanned logistics vehicle mating to an unmanned element.

Applicable Elements:

>1000 ft		>200 ft
EOS	RNS	TUG
MSS	OLS	DRAM
CPS	OPD	SAT

Requirement: Illumination to visually inspect target element mating port.

Ground Rule: Applies when the target element is manned or target element is an unmanned logistics vehicle mating to an unmanned element.

Applicable Elements:

EOS	CPS-CLS
Space Tug	RNS
MSS	OLS

Requirement: Illumination of alignment targets visible at a range greater than 100-feet.

Ground Rule: Applies when the target element is manned and utilizes direct visual alignment aids.

Applicable Elements:

EOS	SAT	RNS
TUG	RESUP MOD	OLS
DRAM	MSS	OPD
MSS ARAM	CPS	

2. Eye and video visual protection

Ground Rule: Applies when the noted applicable element is manned or monitoring operations with TV

Applicable Elements:

EOS	CPS-CLS	OLS
TUG	RNS	OPD

3. Video visual criteria

Requirement: TV monitors will provide 300 lines minimum resolution.

Requirement: TV cameras will have a 70-degree maximum field of view.

Ground Rule: Applies when a TV is used for mating alignment operations.

Applicable Elements:

EOS	MSS	RNS
TUG	CPS	OLS

4. Vehicle relative alignment

Requirement: Miss distance: +/-6 inches

Requirement: Misalignment: +/-3 degrees

Ground Rule: Applies when elements are performing a direct dock.

Applicable Elements: All element pairs except when one of the elements is a small satellite. Depending on the selected mating port design and alignment aid tolerances, the allowable miss distance can range up to +1-12 inches and be misaligned as much as +1-10 degrees. These wide tolerances are based on an Apollo probe/drogue design; one concept that appears feasible for satellite mating operations.

5. Alignment aids accuracy

Requirement: +/-1 degree

Ground Rule: Applies when alignment between elements is automatic

Applicable Elements: All element pairs.

Requirement: Knowledge of alignment within 3 degrees of mating port centerlines.

Ground Rule: Applies when alignment between elements utilize visual techniques.

Applicable Elements: All element pairs.

6. Element attitude deadband: <0.2 degrees

Ground Rule: Applies when elements are performing a direct dock

Applicable Elements: All element pairs

7. Stabilization requirements for elements to be captured by a manipulator.

Requirement: Attitude hold: +/-1 degree

Requirement: Rate stabilization: <0.05 degree/second

Ground Rule: Applies when the target element is equipped with a manipulator.

Applicable Elements:

EOS	SAT	RNS
TUG	RESUP MOD	OLS
MSS ARAM	MSS	OPD
DRAM	CPS	

8. Inspection Criteria

Requirement: Attitude hold: +/-5 degrees

Requirement: Rate stabilization: <0.5 degree/second

Ground Rule: Applies when the target vehicle is manned

Applicable Elements:

TUG	MSS	OLS
DRAM	CPS-CLS	OPD
SAT	RNS	

9. Range and range rate sensor accuracies

Requirement: Range accuracy +/-2 ft at <200 ft

Ground Rule: Applies when direct dock between elements is automatic

Applicable Elements: All element pairs

Requirement: Range accuracy +/-25% at <25 ft

Ground Rule: Applies when the noted element is manned and performing a manual dock with visual aids.

Applicable Elements:

EOS	MSS	RNS
Space Tug	CPS-CLS	OLS

Requirement: Range accuracy +/-5 ft at 25 ft

Ground Rule: Applies when the noted element is equipped with a manipulator.

Applicable Elements:

EOS	MSS
Space Tug	OLS

Requirement: Range rate accuracy knowledge within 0.1 foot/second.

Ground Rule: Applies when the elements are performing a direct dock.

Applicable Elements: All element pairs

Requirement: Relative velocity accuracy knowledge to recognize when relative velocity is less than 0.1 foot/second.

Ground Rule: Applies when the noted element is equipped with a manipulator.

Applicable Elements:

EOS	MSS
Space Tug	OLS

10. Automatic Docking Baseline

Requirement: Automatic docking systems will be equipped with backup systems or override controls.

Ground Rule: Applies when an automatic docking system design is applicable.

Applicable Elements: All element pairs

Requirement: Unmanned docking will be monitored by TV coverage to remote site.

Ground Rule: Applies when two unmanned vehicles are mating

Applicable Elements:

TUG	CPS	RNS

11. Automated manipulator control will be equipped with manual backup system.

    Ground Rule: Applies when the noted element is equipped with a manipulator.

    Applicable Elements:

EOS	MSS
Space Tug	OLS

12. Mating port criteria

    Requirement: Applicable to direct dock and manipulator berth

    Requirement: Dynamically stable

    Requirement: Inherent or built-in redundancy

    Requirement: Fail-safe capture

    Requirement: Capture status monitoring

    Requirement: Capture latch quick release capability

    Applicable Elements: All element pairs

    Requirement: Provide rotational oriented berthing

    Ground Rule: Applies when the target element is an MSS or OLS

    Applicable Elements:

EOS	MSS ARAM	RESUP MOD
SPACE TUG	MSS DRAM	

Requirement: Accept miss distance of +/-6 inches

Requirement: Accept misalignment of +/-4 degrees

Applicable Elements: All element pairs except when one of the elements is a small satellite. The singular model for satellite direct docking identified was the Apollo probe/drogue system mounted on a ring/cone design. This particular hybrid design allows a miss distance of +/-12 inches and a misalignment of +/-10 degrees.

Requirement: Mating ports capable of attenuating impact energy at time of capture, see Table 1-7.

Applicable Elements: All element pairs

13. Androgynous designed mating port

The selection of an androgynous system is dependent on various criteria. See equivalent requirement in the functional requirements section for these criteria.

14. Direct docking closing velocity

Requirement: See Table 1-8

Applicable Elements: All element paris

15. Relative velocity for manipulator capture

Requirement: 0.1 foot/second

Ground Rule: Applies when a manipulator mate is applicable

EOS	MSS
TUG	OLS

16. After capture, residual misalignments must be corrected

Applicable Elements: All element pairs

17. After capture at the mating port, the elements must be drawn together to rigidize the interfaces.

Applicable Elements: All element pairs

Table 1-7. Equivalent Mass of Mating Pairs (Slugs)

	EOS	TUG	EOS DRAM	MSS RAM	SAT	RESUP MOD	MSS	CPS	RNS	OLS	OPD
EOS	5000	4100	1600	-	60	8000	4500	7400	5600	4500	8000
TUG	4100	2500	-	3100	60	6000	3100	5600	4500	3100	6000
EOS DRAM	1650	-	-	-	-	-	-	-	-	-	-
MSS RAM	4500	3100	-	-	-	-	4500	-	-	-	-
SAT	60	60	-	-	-	-	-	-	-	-	-
RESUP MOD	8000	6000	-	-	-	-	4500	7600	6000	-	8000
MSS	4500	3100	-	4500	-	4500	4500	-	-	-	-
CPS	7400	5600	-	-	-	7600	-	7600	-	6000	10500
RNS	5600	4500	-	-	-	6000	-	-	6000	5000	9500
OLS	4500	3100	-	-	-	-	-	6000	5000	4500	-
OPD	8000	6000	-	-	-	8000	-	16500	9500	-	8000

Equivalent mass of each element pair is based on the selected element models shown in Appendix C.

Table 1-8. Direct Docking Closing Velocity Requirements

ELEMENT PAIRS	REQUIREMENT				
	LONGITUDINAL (FPS)		LATERAL (FPS)		ANGULAR
	W ATTEN	W/O ATTEN	W ATTEN	W/O ATTEN	(DEG/SEC)
EOS - EOS	0.3	0.05	0.15	0.05	0.1
EOS - RET TUG	0.3	0.07	0.2	0.07	0.15
EOS - SPACE TUG	0.3	0.06	0.18	0.06	0.12
EOS - DRAM	0.4	0.12	0.4	0.12	0.3
EOS - SAT	0.5	*	0.5	*	*
EOS - EO RESUP MOD	0.2	0.03	0.09	0.03	0.06
EOS - MSS	0.3	0.05	0.16	0.05	0.1
EOS - CPS/CLS	0.2	0.035	0.1	0.035	0.065
EOS - RNS	0.2	0.04	0.13	0.04	0.085
EOS - OLS	0.3	0.05	0.15	0.05	0.1
EOS - OPD	0.2	0.03	0.09	0.03	0.06
TUG - TUG	0.4	0.1	0.3	0.1	0.2
TUG - RAM	0.3	0.08	0.2	0.08	0.16
TUG - SAT	0.5	*	0.5	*	*
TUG - EO RESUP MOD	0.2	0.04	0.12	0.04	0.08
TUG - MSS	0.3	0.08	0.2	0.08	0.16
TUG - CPS/OIS & CLS	0.2	0.04	0.13	0.04	0.085
TUG - RNS	0.3	0.05	0.16	0.05	0.1
TUG - OLS	0.3	0.08	0.2	0.08	0.16
TUG - OPD	0.2	0.04	0.12	0.04	0.08
MSS - RAM MSS - EO RESUP MOD MSS - MSS MOD	0.3	0.05	0.16	0.05	0.1
CPS/CLS - CPS/CLS	0.2	0.035	0.1	0.035	0.065
CPS/CLS - EO RESUP MOD	0.2	0.035	0.1	0.035	0.065
CPS/CLS - OLS	0.2	0.04	0.12	0.04	0.08
CPS/CLS - OPD	0.15	0.015	0.045	0.015	0.03
RNS - RNS	0.2	0.04	0.12	0.04	0.08
RNS - EO RESUP MOD	0.2	0.04	0.12	0.04	0.08
RNS - OLS	0.3	0.05	0.15	0.05	0.1
RNS - OPD	0.2	0.025	0.075	0.025	0.05
OLS - OLS	0.3	0.05	0.16	0.05	0.1
OPD - EO RESUP MOD	0.2	0.03	0.09	0.03	0.06
OPD - OPD	0.2	0.03	0.09	0.03	0.06

*IMPACT VELOCITY BETWEEN AN ELEMENT AND A SATELLITE DEPENDS ON SUCH CRITERIA AS SENSITIVITY OF CAPTURE LATCHES, REBOUND PARAMETERS, STRUCTURAL SPRING CONSTANT, AND ACCELERATION RESTRICTIONS.

18. Manipulator torque controlled within the limits of vehicle attitude control capability.

    Ground Rule: Applies when a manipulator is on noted element

EOS	MSS
Space Tug	OLS

19. Inhibit propulsive venting

    Applicable Elements: All element pairs

20. Intervehicle rigidizing

    Applicable Elements: All element pairs

21. Mating port position and roll indexing

    Applicable Elements: All element pairs

22. ACS inhibit subsequent to mate

    Ground Rule: Applies when both elements are equipped with ACS

    Applicable Elements: The ACS of the following elements is always inhibited at mate.

DRAM	SAT	OPD

    Inhibiting ACS on the following elements is selective and will depend on the mating pair and the optimum control, longivity of mate, least plume impingement, etc.:

EOS	CPS	MSS
TUG	RND	OLS

23. Capability to inspect and maintain mating port active hardware in a shirtsleeve environment in orbit.

    Ground Rules: Applies when elements are capable of being manned and remain in orbit for long durations.

    Applicable Elements:

Space Tug	Resup Mod	RNS
DRAM	MSS	OLS
MSS ARAM	CPS-CLS	OPD

24. Pressure equalization on both sides of hatch

Ground Rule: Applies when crew transfer between elements is required.

Applicable Elements:

EOS	Resup Mod	OLS
Space Tug	MSS	OPD
DRAM	CPS-CLS	
RAM	RNS	

25. Throughout mating operations the elements shall be capable of being separated upon command.

Applicable Elements: All element pairs

26. Control System Monitoring

Applicable Elements:

EOS	MSS	OLS
TUG	CPS	OPS
DRAM	RNS	SAT

27. Electrical Interface Deadfacing

Ground Rule: Applies to element pairs where an electrical interface between the elements will exist after mating.

Applicable Elements: All element pairs

28. Electrical Interface Mate Verification

Ground Rule: Applies to element pairs where an electrical interface between the elements will exist after mating.

Applicable Elements: All element pairs

29. Fluid Seal Integrity Verification

Ground Rule: Applies to element pairs where a fluid interface between the elements will exist after mating.

Applicable Elements: All element pairs

30. Connectors and Couplings Equipped with Alignment Guides

Ground Rule: Applies to element pairs where electrical or fluid interfaces between elements exist after mating.

Applicable Elements: All element pairs

31. Automatic Connections Delayed Until after Rigidizing

Ground Rule: Applies to element pairs where electrical or fluid interfaces between elements will be made automatically.

Applicable Elements:

EOS	ARAM	RNS
TUG	SAT	OLS
DRAM	CPS	OLS

32. All Manual Connections Designed for IVA Mating

Ground Rule: Applies to element pairs where electrical or fluid interfaces exist between elements after mating and at least one of the elements of the mated pair is manned.

Applicable Elements: All element pairs

33. Visual Inspection of Electrical/Fluid Interconnects

Ground Rule: Applies to element pairs where electrical or fluid interfaces exist between elements after mating.

Applicable Elements: All element pairs

34. Interface Lines and Cables Protection

Ground Rule: Applies to element pairs where electrical or fluid interfaces exist between elements after mating.

35. Direct Insertion or Quick Disconnect Connectors Required

Ground Rule: Applies to element pairs where interface connections will be manually made.

Applicable Elements: All element pairs

36. Controlled Tunnel Leak Rate

Ground Rule: Applies when crew transfer is required between the mated pair.

Applicable Elements:

EOS	Resup Mod	OLS
Space Tug	MSS	OPD
DRAM	CPS-CLS	
MSS ARAM	RNS	

37. Redundant Interface Protection

Ground Rule: Applies where redundant interfaces between elements exist.

Applicable Elements: All element pairs

38. Electrical interface grounding

Ground Rule: Applies to element pairs where electrical or fluid interfaces exist between elements after mating.

Applicable Elements: All element pairs

39. Rapid interface sealing

Ground Rule: Applies when crew transfer is required between the mated pair.

Applicable Elements:

EOS	RESUP MOD	OLS
SPACE TUG	MSS	OPD
DRAM	CPS-CLS	
MSS ARAM	RNS	

40. RF communications

Requirement: Duplex voice

Ground Rule: Applies when two manned elements mate

Applicable Elements:

EOS	CPS-CLS	OPD
SPACE TUG	RNS	
MSS	OLS	

Requirement: TV to remote site

Ground Rule: Applies when two unmanned elements mate with TV on logistics element

Applicable Elements:

TUG	CPS	RNS

Requirement: Telemetry data link

Ground Rule: Applies when one mating element is unmanned or both elements unmanned.

Applicable Elements:

EOS	MSS	OPD
TUG	CPS	
DRAM	RNS	
SAT	OLS	

Requirement: Command data link

Ground Rule: Applies when one mating element is unmanned or both elements unmanned.

Applicable Elements:

EOS	MSS	OPD
TUG	CPS	
DRAM	RNS	
SAT	OLS	

41. Manipulator end effector engagement verification

Ground Rule: Applies to elements with manipulators

Applicable Elements:

EOS	MSS
SPACE TUG	OLS

1.7 DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

Two generic approaches to mating have been considered, direct dock and manipulator berthing. Direct dock includes manual and automatic techniques. Manipulator berthing is applicable to manned operations only. If a manipulator is in the program, automatic direct dock will still be required at least for the unmanned-to-unmanned vehicle matings. If direct dock alone were considered, the conceptual design evaluation would be to select between automated techniques and manual techniques. If manual techniques were selected, automated concepts would still be required for the unmanned-to-unmanned vehicle matings. Therefore, the only singular concept that is valid for all element pair matings is an automated direct dock approach. No matter what is preferred, this one concept must at least be developed for the unmanned-to-unmanned vehicle matings.

PREFERRED APPROACH SELECTION

This analysis will be devoted to selecting either direct dock or manipulator berthing to perform the mating activity. It has already been mentioned that if manipulator berthing is selected, direct dock will not be eliminated because of the unmanned mating requirements, therefore, the analyses will be to determine if a manipulator should be developed for the mating activity.

Table 1-9 compares direct dock and manipulator berthing against a series of factors as they relate to the mating activity only.

Technology

The Apollo program has proven that the manual approach to direct dock can be successfully employed. Manual direct docks were made with both manned (LEM) and unmanned (S-IVB) elements. This technique is considered state-of-the-art.

Automatic direct dock techniques have been employed in the Russian space program. The difficulty in this task rests with the development of the sensors required to determine relative alignment, range, and range rate between the vehicles and integrating this data with the vehicle control system.

Manipulators are new to space. They are made up of numerous mechanisms that will be exposed to the space environment. They will be required to make long reaches, capture large complex vehicles as well as small compact vehicles, and maneuver them in a controlled manner without being attached to a stable base. The system will have to be integrated with vehicle control systems and man.

Table 1-9. Mating Concept Comparison

Factors \ Concepts	Direct Dock		Manipulator Berthing
	Manual	Automatic	
Technology	Preferred - state of the art	Acceptable - technology available	Least preferred - new to space
Checkout Maintenance	Preferred - least and less complex parts	Acceptable - with active elements on vehicles that can be manned or returned to ground	Least preferred - requires ground maintenance
Safety	Acceptable	Acceptable	Acceptable
Reliability	Preferred - least parts	Acceptable - with redundant sensors	Acceptable - with redundant arms
Commonality	Acceptable - still requires automatic docking	Preferred - commonality across all element pairs	Least preferred - requires direct docking and manipulator techniques
Relative Cost			
Initial	Least cost	Medium cost	Highest cost
Long term	Least cost	Medium cost	Medium cost
Operational/Design Complexity	Preferred - less operations, least complex hardware	Acceptable - least operations, complex hardware	Least preferred - most operations, complex hardware
Interfaces			
Power	Low	Medium	High
ISS	Low	High	High
ACS	None additional	Complex	Simple
Crew	Vehicle pilot	None required	Vehicle pilot and/or manipulator controller
Near-Term Bias	Preferred	Acceptable	Least preferred
Far-Term Bias	Preferred	Preferred	Acceptable

Checkout/Maintenance

Elements that return to ground periodically can be easily maintained whether the concept is direct dock or manipulator. However, if the elements must be maintained in orbit their maintenance is a rather complex problem. With a manned element, docking mechanisms can be inspected and maintained in a shirt-sleeve environment, whereas, manipulators will require EVA maintenance. Unmanned elements will require EVA maintenance. The task would be to limit active systems on unmanned elements that do not periodically return to ground or a space hanger for maintenance. The manipulator would have to be of an IFRU (in-flight replacement unit) or the vehicle equipped with the element would have to return to earth for maintenance. EVA maintenance of a manipulator does not appear to be within the present state of the art. Sensor replacement or simple plug-in devices are feasible, but, torquing motors, clutch mechanisms, cables, and structural arms do not lend themselves to designs that are EVA repairable and still be suitable to the space environment.

Safety

A comparison of the direct docking system with that of a manipulator system does not show any strong reasons for preferring one system over another. Both approaches show the same criticality, with the potential of causing vehicle damage. The manipulator concept exhibits more modes for causing damage (capture then berth). If control of either the manipulator or of one of the vehicles is lost at a crucial phase, damage is quite likely because of the large volume swept by the manipulator envelope. The direct docking concept, on the other hand, has the one relatively severe risk, that of a control system failure when the two vehicles are close to each other which can result in inadvertent contact and damage (DS-526). The higher contact velocity of this system (up to 0.5 fps) compared to the manipulator system (less than 0.1 fps) could be expected to result in both less reaction time for corrective action and more damage.

Reliability

When comparing a direct dock concept and a manipulator berth concept in terms of reliability, the factors to be considered are the reliability of the direct docking capture and attenuation system and the manipulator arm mechanisms. Impact attenuation systems and capture systems will be exposed to a space environment in a passive state for long periods of time and still must be ready to perform multiple dockings when called upon. If the manipulator is also going to be exposed to these conditions, there is no doubt that the direct docking concept would be the more reliable simply due to the larger number of failure possibilities exhibited by a manipulator. If two manipulators are available for use, the reliability naturally increases. However, it is questionable if it would ever increase to that of a direct docking system. On the other hand, if the manipulator is periodically returned to earth for inspection and maintenance, its reliability factor could surpass that of impact attenuation systems that remain unattended in earth orbit.

The reliability of a manual direct docking versus an automated system gives preference to the manned operation because of the added hardware required for the automatic concept.

This study weights the manual approach the most reliable, the automatic concept somewhat less reliable, and the manipulator the least reliable. However, if the manipulator concept is designed for periodic returns to earth for maintenance and if the vehicle is equipped with redundant manipulators it becomes more viable, reliability wise, perhaps even surpassing the direct dock concepts.

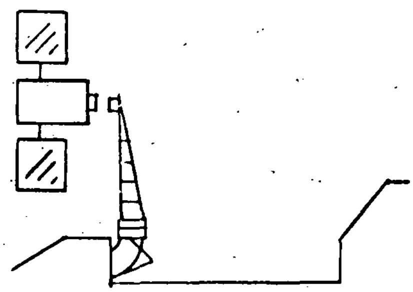
Commonality

The direct automatic dock concept provides the highest commonality between elements because the approach can be utilized across the full array of mating pairs. The manual approach and manipulator approach do not eliminate the need for an automated system. The manual direct docking is relatively similar to automatic docking and is therefore rated only slightly less common. The manipulator approach is an entirely different concept and is rated least common.

A further consideration that must be evaluated is the effect of direct docking with small satellites. Manipulators can perform this mating task with relative ease and minimal design impact to the satellite. Common direct docking ports, on the other hand, are not adaptable to all satellite designs. The large size of the common docking port (7 feet or greater) would be difficult and impractical to install on all satellites. Adapters can be installed (see Figure 1-10) on the logistics vehicle that can be made compatible with satellites. Another option is to employ a hybrid concept such as shown in Figure 1-39. The hardback scheme rotates the capture mechanism out of the cargo bay. The EOS (configuration shown) then flies the extended capture mechanism into the satellite to effect the mate. After capture, the mechanism with the satellite is folded back into the cargo bay. The telescoping probe design has the EOS stationkeep and align the probe with the satellite mating receptacle. The probe is extended, engages and captures the satellite and is retracted. The clamp assembly concept has the EOS maneuver close enough to the satellite so that it can be clamped onto by the capture mechanism. The clamp assembly can engage the satellite externally as shown or it can grasp a special capture device designed into the element. However, none of these options appear to offer the flexibility of the manipulator concept and none of the options, except possibly the telescoping probe, offers a universal solution.

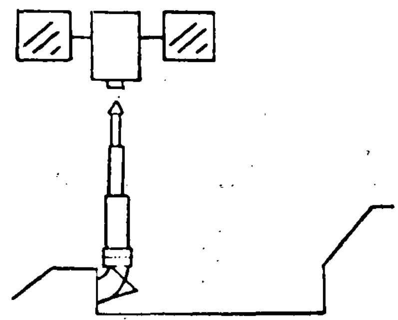
Relative Cost

Relative costs must consider both the initial investment and the long term investment and associated operational costs. Considering initial costs only, the direct dock approach is favored. But, over the long term the costs tend to favor the direct docking approach less. Perhaps not to the extent that the manipulator is a definite asset, but to where a detailed cost analyses would be required to define a preference. If we assumed that for direct docking, the attenuation systems were relegated to the logistics vehicles, EOS orbiter, space based tug, and ground based tug, then the costs of the interfacing element mating ports



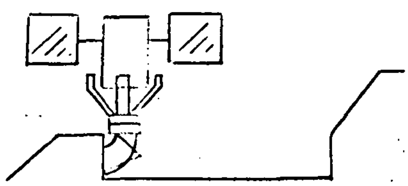
HARDBACK

- Probe or Magnetic Interface
- Rotates 90° Out of Bay
- Not Viable on TUG
- Provisions for Despining Satellites



TELESCOPING PROBE

- Probe Interface
- Viable on TUG
- Single Degree of Freedom Manipulator
- Provisions for Despining Satellites



CLAMP ASSEMBLY

- Engages Internal or External Surface of Satellite or other Retainer
- Viable for Space TUG
- Provisions for Despining Satellite, although the Operation is Close to Logistics Vehicle

Figure 1-39. Direct Dockings Concepts for Mating to Small Satellites would not essentially change if a manipulator were utilized because most of the other vehicle elements could be equipped with the lighter passive ports which are more equivalent in weight to a berthing port. The modular assembled vehicles and logistics resupply modules, however, have a definite cost savings when a manipulator is utilized in that only one mating port is required on a module rather than one on each end as required with direct docking systems. This cost and weight savings is considerable for the MSS. With a manipulator in the program, satellites can be designed without mating ports, thereby reducing their costs and perhaps increasing flexibility. Finally with a manipulator available, multiple payloads can be retrieved, whereas with a direct docking approach this would be difficult to incorporate into the design. But the ever present maintenance cost of a manipulator system is expensive. There is a maintenance cost associated with attenuation systems, but this appears to be considerably less than that associated with a manipulator and its related hardware.

The ratings for the systems are as follows.

Initial costs - manual direct dock is least cost, automatic direct dock is somewhat more expensive, however, because it has to be developed for the unmanned mating pairs, its inclusion into manned elements would not be that great, because the design development, test, and engineering would already be paid for. The manipulator system would be the highest cost.

Long term costs - It appears that the cost relationship for the initial costs would remain about the same for the long term costs, with the manipulator becoming somewhat more competitive.

Operational/Design Complexity

Direct docking requires vehicle alignment, a controlled closing rate between vehicles until capture is effected, and the attenuation of the impact energy. The manipulator berth involves vehicle alignment, reduction of the relative velocity between vehicles, extension of the manipulator and capture of the target vehicle, nulling of the relative velocities, and transposition and berth of the captured vehicle. It can be seen that direct dock has the least operations, but the complexity of the operations is less apparent. Vehicle alignment for direct docking is more critical than is required for a manipulator capture operation. Reduction of the relative velocity between vehicles to effect capture with the manipulator can be a time consuming operation, however, the controlled closing velocity to effect a direct dock places more strain on the pilot. Attenuation of the direct dock impact energy is not considered a difficult operation, nor is nulling of vehicle relative velocities, although the sensors and computer interfaces required by the manipulator to perform this operation are considered complex. The transposition and berth of the captured vehicle is considered an automated task and is equivalent to the relative velocity nulling task.

The automated docking is less complex in that no man is involved, except as a backup observer with the capability to override the operation. However, this override interface and the automated systems are more complex than the manual direct dock, and probably equivalent to the complexity of the automated manipulator relative velocity nulling, and transposition and berth operation.

Therefore, manual direct docking is considered the least complex with automated direct dock and manipulator berthing about equivalent.

Near-Term Program Preference

The results of this analysis indicate that for the mating activity alone, manual direct dock is the preferred approach, automatic direct dock would be the second choice, and manipulator berthing the least preferred. But because automatic direct docking must be developed for the unmanned mating pairs the utilization of an automated system for manned vehicles is considered a viable equivalent to the manual approach.

Far-Term Program Preference

The results of the analysis do not indicate any clear-cut benefits gained by selecting a manipulator berthing concept over the direct dock option when considering only the mating activity. The relative cost appears to be more competitive over the long term for a manipulator berthing option, but the other factors do not essentially change. It may be that experience and training with manipulators could prove that the approach is a very effective, reliable, and safe concept such that these factors will outweight the cost and the noncommonality issues. However, this analysis cannot accurately forecast this and therefore recommends the automatic direct dock concept which should be a well-developed technology within the next few years.

CONCLUSION

An overall evaluation of the comparison factors tends to favor the direct dock approach. But, because an automatic direct docking concept must be developed for mating unmanned elements to unmanned elements, it is recommended that for commonality this approach be the primary mating mode for all element pairs. It is also recommended that when a manned element is involved, manual override capability be provided.

The one prime driver for selection of the manipulator is mating operations between logistics vehicles and satellites. However, design alternates to the manipulator concept are available (Figure 1-39) that can effectively perform this mating task. It is recommended that this type of concept be developed for adapting to the direct docking design when required.

SYNERGISTIC INFLUENCES

As previously indicated, the mating activity alone cannot justify the use of a manipulator. Even matings with satellites can utilize a special device (see Figure 1-39) that is more cost effective than a manipulator design.

Other interfacing activities indicate that a manipulator could enhance their operations. The orbital assembly activity can be broadened with a manipulator in the program. Rather than do all assembly operations using direct dock techniques, a manipulator allows in-place structural assembly, thus permitting more complex configurational designs. However, the orbital assembly activity in general prefers the direct dock concept based on presently identified configurations and required operations. This preference is primarily the result of needing manipulators capable of reaching out 100 feet or greater to effectively perform some of the necessary assembly operations. Analyses of EOS payload deployment and retraction interfacing activities indicated a preference for the pivotal mechanism concept which is compatible with the automatic direct docking concept. However, development of the manipulator concept was also recommended for handling of multiple payloads. EOS programmatic considerations - cost, schedule, traffic model - will dictate the final selection. Possibilities include (1) one deployment/retraction concept as basic, the other a kit installation, (2) provisions for both concepts to be interchanged, or (3) inclusion of the alternate concepts in alternate orbiters.

Separation operations could also be enhanced if a manipulator were used but jet translation was selected as the baseline because of the negligible delta requirements to the basic element systems.

Thus, no one activity can either identify the requirement for or justify the cost of development of a manipulator as the preferred approach. But when all activities are considered, it is highly desirable to include a manipulator in the overall EOS development program. Therefore, it is recommended that all elements consider both manipulator and non-manipulator operations in conjunction with EOS interfaces during their definition phase.

DESIGN INFLUENCES

Incorporation of an automatic direct docking concept on all elements imposes additional hardware on manned elements that could mate using manual direct docking techniques. This additional hardware includes a laser radar transceiver as well as associated computer interfaces. Costs for development of this concept will exceed the manual direct docking development costs, but because the system must be developed for unmanned-to-unmanned matings, development costs can be programmatically shared. The automatic docking system requires that all vehicles be equipped with passive reflectors. Manual backup systems (EOS orbiter) that do not incorporate an independent visual alignment scheme will require that the active vehicle and associated vehicle be equipped with compatible visual alignment aids (Apollo derivative). Direct docking (automatic or manual) also requires at least one of the interfacing elements of all docking pairs be equipped with an active impact attenuation capability. With manipulators, this hardware is not necessary, however, as noted in the text, some element pair combinations will still exist where direct docking and the associated impact attenuation hardware will be required even with manipulators in the program. Direct docking requires that elements be capable of holding a relatively tight deadband in some cases (0.2 degrees) and can control a closing velocity between elements within a prescribed range (0.2 fps to 0.4 fps). But, if a manipulator is selected, other criteria on the same order will be required (i.e., relative velocity controlled to less than 0.1 fps and attitude deadbands on the order of +/-1 degree and a rate stabilization in the range of 0.05 degrees per second). Probably none of these vehicle control parameters will be drivers in that other requirements on most vehicles will dictate tighter or equivalent tolerances.

Table 1-10 identifies the hardware for each noted element based on the preferred conceptual approach for mating the various element pairs. The manipulator hardware is included as well as automatic direct dock and manual direct dock backup hardware for the EOS orbiter and applicable elements that mate with the EOS orbiter. Mating ports designed for direct dock can be used for berthing (manipulator approach) with no design modification. The following paragraphs are a synopsis of why each piece of hardware was selected for the identified element.

Mating Port: The elements with active attenuation are the logistics vehicles and the space stations (MSS and OLS), all other elements can be equipped with passive mating ports. Where two mating ports are indicated for an element, it infers that one will be on each end of the element. Note 2 refers to individual assembly criteria where two modules of an assembly must be mated; one of the elements must be equipped with an attenuation device. However, in none of the noted cases do the elements require an attenuation system for other elements mating to them except for the MSS which requires attenuation to support the MSS detached RAM. The satellites (note 1) are not configurationally defined, those that will be directly docked can be equipped with passive docking ports.

Laser Radar Transceiver: The laser radar transceiver is allocated to all logistics vehicles because these vehicles must perform automated dockings. The MSS is equipped with a laser radar to support MSS detached RAM's if they free fly into dock and also to provide a backup capability for docking with the logistics vehicles.

Laser Radar Reflectors: The laser radar reflectors are required on all elements to support those vehicles with laser radars. Some of the elements, for example, the EOS orbiter, are equipped with reflectors to provide a backup docking capability with another element.

Direct Visual Alignment Scope: The requirement for a direct visual alignment system is imposed only on the EOS orbiter because it is the only vehicle recommended for direct manual backup capability. Other logistics vehicles that may be manned can perform direct manual dockings using the laser alignment systems which should be effectively developed by the early EOS orbiter missions.

Visual Alignment Targets: Targets are required on all elements, as noted, to support the EOS orbiter backup visual alignment system.

TV Camera: TV to the remote control center is required to support rough alignment of unmanned mating pairs, for inspection of mating ports, and possibly for the EOS orbiter backup visual alignment system. The TV camera is allocated only to the logistics vehicles.

Translation Capability: All of the logistics vehicles require translation capability to accomplish the dock. The MSS supported detached RAM (note 3) requires translation capability if it is to free fly and direct dock to the MSS without the support of a logistics vehicle.

Manipulator: As previously indicated a manipulator is recommended for installation on the EOS orbiter.

Manipulator End Effector Receptacle: A manipulator end effector receptacle must be installed on all elements the EOS orbiter mates with, thus allowing it the option of manipulator berthing or direct docking to effect the mate.

Table 1-10. Mating Hardware Preference

Hardware	Element													
	EOS	UN-MAN TUG	MAN TUG	EOS DRAM	MSS ARAM	MSS DRAM	RET RESUP SAT	EO RESUP MOD	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD
Mating port (w/attenuator)	1	1	1	-	-	-	Note (1)	1	Note (2)	Note (2)	Note (2)	Note (2)	Note (2)	Note (2)
(w/o attenuator)	-	-	-	1	2	2		1						
Laser radar transceiver	-	√	√	-	-	-	-	-	√	√	√	√	√	-
Passive laser radar reflectors	√	√	√	√	√	√	Note (1)	√	√	√	√	√	√	√
Direct visual alignment scope	√	-	-	-	-	-	-	-	-	-	-	-	-	-
Visual aligment targets	-	√	√	√	√	√	√	√	√	√	√	√	√	√
TV camera	-	√	-	-	-	-	-	-	-	√	√	√	-	-
Translation capability	√	√	√	-	-	Note (3)	-	-	-	√	√	√	-	-
Manipulator	√	-	-	-	-	-	-	-	-	-	-	-	-	-
Manipulator end effector receptacle	√	√	√	√	√	√	√	√	√	√	√	√	√	√

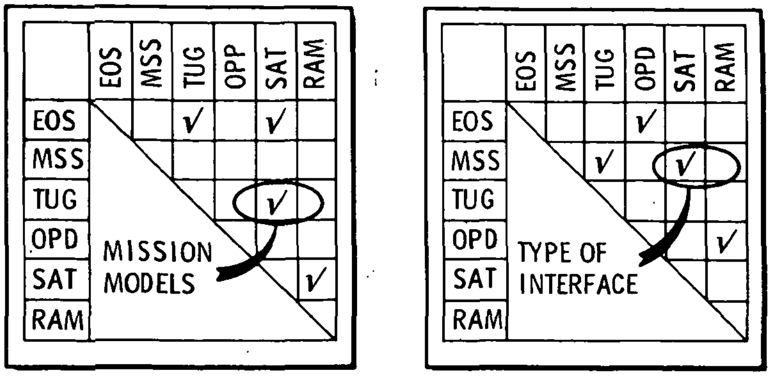
Note (1) Configurations are not defined. Size is critical as to whether the satellite will support a docking port or not.

Note (2) These elements can be modularly assembled. Therefore, an attenuation device is required on one or the other interfaces of the assembly.

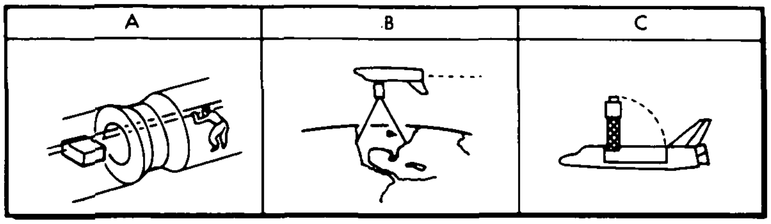
Note (3) The MSS-supported DRAM requires translation capability if it is to free-fly and direct-dock to the MSS.

2.0 ORBITAL ASSEMBLY

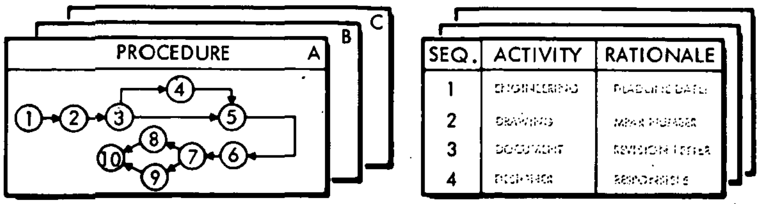
ELEMENT INTERFACES



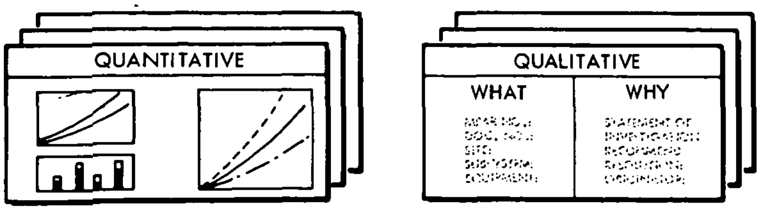
ALTERNATE APPROACHES AND DESIGN CONCEPTS



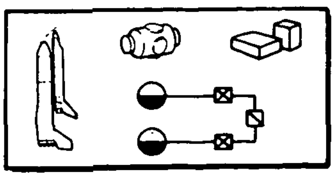
OPERATIONAL PROCEDURES



FUNCTIONAL REQUIREMENTS



DESIGN INFLUENCES AND APPROACH SELECTION



	SAFETY	COST	PERF
A	√	√	
B		√	
C			√

2.0 ORBITAL ASSEMBLY

The orbital assembly interfacing activity includes two distinct classes of operations. One is the assembly of modules of elements for long term orbital operations (e.g., MSS). The other is the temporary assembly of elements or modules of elements on a transport vehicle for subsequent delivery to a higher energy orbit (e.g., OLS modules on a CPS). There are always a minimum of three elements and/or modules involved when orbital assembly occurs. Two elements being joined together is considered a mating activity. Orbital assembly includes the attachment of modules or elements external to an element. It does not include assembly inside an element except for configuring interfaces between elements. Mating and attached element transport activities are closely related to the orbital assembly activity and directly influences orbital assembly concepts.

2.1 SUMMARY

From the total list of elements identified for this study, there are 117 combinations that exist where one or more orbital interfaces can occur. Of these, 71 combinations can involve the orbital assembly activity. Eleven representative mission models were developed to clarify the interrelationships between the various program elements. Of these eleven generic missions, four involve assembly operations. Paragraph 2.2 expands on these interfaces and provides matrices which identify the interfacing pairs and applicable missions.

Three concepts were considered viable options for performing the initial assembly operations. These are direct dock, manipulator berth, and use of a teleoperator. Of those three alternates, the teleoperator approach was rejected relatively early in the study because it introduced a new element into the program, and no required operations could be identified that could not be accomplished by a manipulator. Post rigidization and utilities interconnect could be accomplished using manual techniques (EVA, shirtsleeve or IVA), teleoperator concepts, or automatic methods. The teleoperator was rejected for the same reasons it was rejected for initial assembly operations. EVA was also rejected because it was considered the most hazardous of all the alternates. Paragraph 2.3 provides an overview of each of the above noted alternates.

Paragraph 2.4 identifies a series of conceptual models that were utilized to validate the assembly operations. The models include a mating port design, alignment aids, a manipulator design, rigidization techniques and utilities interconnect methods.

Three procedures were developed for performing assembly operations and are described in paragraph 2.5 with the detail procedures presented in Appendix B. Of the three procedures, two were developed around permanent assemblies and one was developed for a temporary assembly. The three procedures also reflect shirtsleeve and IVA operations where man is involved and automatic operations when the elements are unmanned.

Paragraph 2.6 is a list of the requirements applicable to the orbital assembly activity. Because the teleoperator approach was rejected in favor of the manipulator concept or direct docking, the initial phase of orbital assembly essentially becomes a mating operation and the requirements of the mating activity apply. The requirements developed in this section concentrate on post mating assembly operations, particularly shirtsleeve, IVA, and automatic hookup of utilities. The requirements are presented in two formats. The first format lists the requirements with regard only to the developed procedures. The second form identifies the requirements as they apply to the element pairs.

The design influences and preferred approach selections are presented in Paragraph 2.7. Both permanent (MSS, CPS, RNS, OPD) and temporary assemblies (OLS on CPS/RNS, Resupply Modules on Tug/MSS) are examined for initial mating operations. Either the direct dock or the manipulator concept can be utilized in these assembly operations. But, the manipulator is preferred for MSS assembly and direct dock is preferred for CPS, RNS, and OLS on CPS/RNS assembly. The manipulator approach to MSS assembly was preferred primarily because it allowed for a more versatile MSS design (e.g., a variety of packages could be berthed externally to modules without the handicap of installing docking ports on each end of the packages). Manipulator assembly also allowed for a more compact MSS design. Assembly of a MSS using direct docking is fully feasible, but the manipulator approach provides some additional synergistic benefits. Direct dock was more applicable to the other assembly operations primarily because of the required length of the manipulator (>100 feet) if it were used.

Comparison of approaches for modular interchanges (MSS modules and cargo resupply modules) was inconclusive. In light of the diversification of preferred approaches depending upon the element pairs involved, it was recommended that a combined direct dock-manipulator approach be utilized for modular interchange. Integration of preferred approaches across all activities indicated that, in general, direct dock was preferred but in each activity there were certain operations that were distinctly enhanced and simplified if a manipulator were used (e.g., multi-payload deployment/retraction). The traffic model indicated that the missions that tended to be drivers for manipulators occurred relatively infrequently. Therefore, in general the direct dock concept was preferred. The only element that the manipulator was recommended for was the EOS orbiter; however, the inclusion of the pivotal mechanism, which is applicable to the direct dock concept, was also recommended for the EOS.

Rigidization of multi-module assembly on transport vehicles was evaluated in conjunction with attached element transport considerations. Many cislunar payloads (LSB, resupply modules) must be delivered in a disassembled or stacked configuration. A special multi-docking adapter is required for assembly of the lunar payloads. The design of the adapter must be compatible with delivery to earth orbit by the EOS. This limits considerably the number of viable options for design. The design concept model identified in the attached element transport section is used in the baseline assembly operations described in this section.

Direct dock is the preferred concept for the assembly of payloads on cislunar shuttles. If the manipulator approach is used, the required reach would exceed 100 feet.

Post mating operations are closely related to crew and cargo transfer and attached element operations activities. An integrated preference is for shirtsleeve operations wherever possible. Structural rigidization via the docking system is adequate in all cases. Utility interconnects are required on the MSS, OPD, CPS, RNS, and some Tug payloads. CPS, RNS, Tug interconnects are all recommended to be accomplished automatically. The number of interconnects is quite limited in all cases because the payloads are either dormant or operating in conjunction with a separate control center. MSS interconnects can readily be accomplished in a shirtsleeve manual mode, therefore, the complexity of automated interconnects for this element is not warranted. The non-modular OPD may include the capability for crew to travel to and from fluid interfaces such that interconnects can be made either shirtsleeve or IVA.

The following table reflects the assembly technique selected for each element. The term module infers cargo modules, RAM's, and station modules.

Assembly Operation	Initial Assembly Operations	Post Mating Operations
<u>Permanent</u>		
MSS	Manipulator	Shirtsleeve
CPS	Direct Dock	Automatic
RNS	Direct Dock	Automatic
OPD	Direct Dock	Shirtsleeve--IVA--Automatic (Dependent on Selected Configuration)
<u>Temporary</u>		
Module on Tug from EOS	Manipulator if Reach is Adequate, Combination Direct Dock/Manipulator if Reach is Inadequate	Automatic for Unmanned Tug, Manned Tug can be Shirtsleeve or Automatic
Module on Tug from MSS	Direct Dock	Same as Above
OLS Stacked on CPS or RNS	Direct Dock	Automatic

2.2 ELEMENT INTERFACES AND MISSION MODELS

Of the potential 117 element-to-element interactions, 74 orbital assembly interactions are considered to be viable. These are indicated in Figure 2-1. In 35 of the interactions one of the elements is involved in an assisting capacity. Thirty-nine involve an assembly between modules or elements. Five, involving the space-based tug could be either or both assisting the aseembly or be an integral part of the assembly. The interactions are:

1. The EOS could be used to assist in all orbital assembly operations. The entire inventory of elements/modules is assumed to be delivered to earth orbit by the EOS.

2. The space-based tug could be used to assist in the assembly of elements/modules for cislunar delivery.

3. The space-based tug will be used as the transport vehicle for module to geosynchronous orbits.

4. The ground-based tug could be used for delivery and subsequent assembly of modules to the MSS or cislunar shuttles.

5. The ground based Tug can be assembled to another ground based Tug to extend its capabilities for payload transport. The space based Tug can simiarly be assembled.

6. All other identified interactions are either a part of an operational assemblage of an orbital element or a part of a logistics payload.

Figure 2-2 is a second presentation of the orbital assembly element pair matrix. The missions that include an orbital assembly operation between element pairs are indicated in the appropriate blocks.

Mission 2 is the EOS logistics mission. In this mission the EOS could be involved in all on-orbit assembly operations except those involving a ground-based tug.

Mission 5 is the space tug logistics mission. Its potential function in orbital assembly is essentially the same as the EOS.

Missions 10 and 11 are the geosynchronous/cislunar missions. The orbital assembly operations identified refer to the modular assembly and the attachment of the payload to the transport vehicle.

Mission 8 involves the ground-based tug. It is assumed that if the ground-based tug is involved, its payload was integrated prior to launch. However, upon delivery of the payload to its destination the ground-based tug could be involved in the subsequent assembly of its payload to the on-station element.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	X	X	X	A	A	X	X	A	A	X	X	X	A	A	A		A	A	A	A	A	A	A	A	A
TUG	NON RET											X														
	RETURNABLE											X														
	GRD BASED				M	X			X	X		X	X	X		A		A	A	A		X	X	A		A
	SPACE BASED					M			M	M		X	X	M	M/A	M/A	X	A	A	A	A	A	A	A	A	A
RAM	ATT. EOS																									
	DET. EOS																									
	ATT. MSS														M	M		M		M						
	DET. MSS														M	M		M		M						
SATEL	EOS DELIV																									
	EOS + 3RD ST																									
	RETR, RESUP																									
	EO RESUP MODS													X	M	M		M	X	M		X	X	X		X
MSS	LOW EO														M											
	GEOSYNCH															M		M		M						
CPS	OIS																	X	X	X	X					X
	EO SHTL																	M								X
	CLS																		M		M	M	M	M	M	X
	RNS																			M	M	M	M	M	M	X
LPS	OLS																				M	M	M	M		
	TUG UNMAN																							M	M	X
	TUG MAN																							M	M	X
	RESUP MOD																							M	M	X
	LSB																								M	
	OPD																									M

LEGEND

Potential Interactions	117
Actual Interactions	81
A - Assist Assy	33
M - Assy Interface	48
X - Not Applicable	38

Figure 2-1. Orbital Assembly Interactions

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS				2	2,5, 10,11			2,5, 10,11	2,5, 10,11				2,5, 10,11	2,5, 10,11	2,5, 10,11		2,5 10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11	2,5 10,11	2,5 10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11
TUG	NON RET																									
	RETURNABLE																									
	GRD BASED				2											8		8	8	8				8		8
	SPACE BASED					2,5, 10			2,5, 10,11	2,5, 10,11					2,4,5 10,11	2,4,5 10,11		2,5, 10,11	2,5, 10,11	2,5, 10,11	2,5 10,11	2,5 10,11	2,5 10,11	2,5 10,11	2,5 10,11	2,5 10,11
RAM	ATT. EOS																									
	DET. EOS																									
	ATT. MSS														2,5	2,5, 10,11		2,5, 10,11		2,5, 10,11						
	DET. MSS														2,4,5	2,4,5 10,11		2,5, 10,11		2,5, 10,11						
SATEL	EOS DELIV																									
	EOS + 3RD ST																									
	RETR, RESUP																									
	EO. RESUP MODS														2,5	2,5, 10,11		2,5, 10,11		2,5, 10,11						
MSS	LOW EO														2,5,8											
	GEOSYNCH															2,5,8 10,11		2,5, 10,11		2,5 10,11						
CPS	OIS																									
	EO SHTL																	2,5,8, 9,10								
	CLS																		2,5,8, 9,10		2,5, 10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11	
	RNS																			2,5,8, 9,11	2,5, 10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11	
LPS	OLS																				2,5,8, 9,10,11	2,5, 10,11	2,5, 10,11	2,5, 10,11		
	TUG UNMAN																							2,5,8, 10,11	2,5,8, 10,11	
	TUG MAN																							2,5,8, 10,11	2,5,8, 10,11	
	RESUP MOD																							2,5,8, 10,11	2,5,8, 10,11	
	LSB																								2,5,8, 9,10,11	
	OPD																									2,5,8,9

Figure 2-2. Applicable Mission Models for Assembly

2.3 ALTERNATE APPROACHES

Two major phases of orbital assembly were considered:

"Initial Mating Activities" which involve operation up to and including mate of the elements/modules to be assembled and "Post Mating Activities" which include supplemental rigidization and utility interconnect operations.

The first phase is essentially a mating operation. The approaches, design concepts, procedures, and functional requirements for this phase of orbital assembly are the same as for mating. The second phase of orbital assembly is dependent upon the extent of the interfaces involved and the type of assembly (permanent or temporary). If the assembly is to be relatively permanent and is associated with a manned element such as the MSS, then orbital assembly post capture operations can expect that crew and cargo transfer capability will be reflected at the interface. This means that more than likely, the interface will be designed for shirtsleeve access and extensive utility interfaces can be involved. On the other hand, if the assembly is temporary, such as the temporary attachment of a module to a Tug for subsequent transfer to another element, minimal interfacing can be expected. Between these two extremes are the modularly designed vehicles (OPD, CPS, RNS) that may not provide capability for crew access to the assembly area but could still have relatively complex utility interfaces.

The alternate approaches for the first phase of orbital assembly include those of mating-direct dock, and manipulator, plus the use of a teleoperator. Figure 2-3 illustrates these concepts. The mating activity for this study involved only two elements at a time. Orbital assembly always involves at least three elements. The third element is essentially passive in nature such that it is under full control of the element or elements to which it is attached.

The teleoperator approach was initially considered because it is a safe viable concept. However, no assembly operation of elements and/or modules could be identified that could not be accomplished by one of the mating approaches. The additional complexity, cost, checkout, maintenance, etc., with the introduction of a new element into the space inventory for assembly operations was not warranted. This conclusion is not intended to preclude either the desireability or requirement for a teleoperator for other orbital operations such as on-orbit maintenance, "mini tug" operations, or element repair activities.

Approaches for post capture rigidization operations included manual-EVA, IVA and shirtsleeve-automatic, and teleoperator. Figure 2-4 illustrates these approaches. Here again no post capture operations were identified that would require a teleoperator and thus this option was given no further consideration. The automatic concepts could be integral or supplemental to the docking mechanism. Although EVA provisions may be required for other operations, for the elements/modules involved in orbital assembly no further consideration was given to this option. Three approaches--shirtsleeve, IVA, and automatic--are available and involve less risk than an EVA operation. Preliminary analysis indicated that provisions for the remaining approaches would be required by

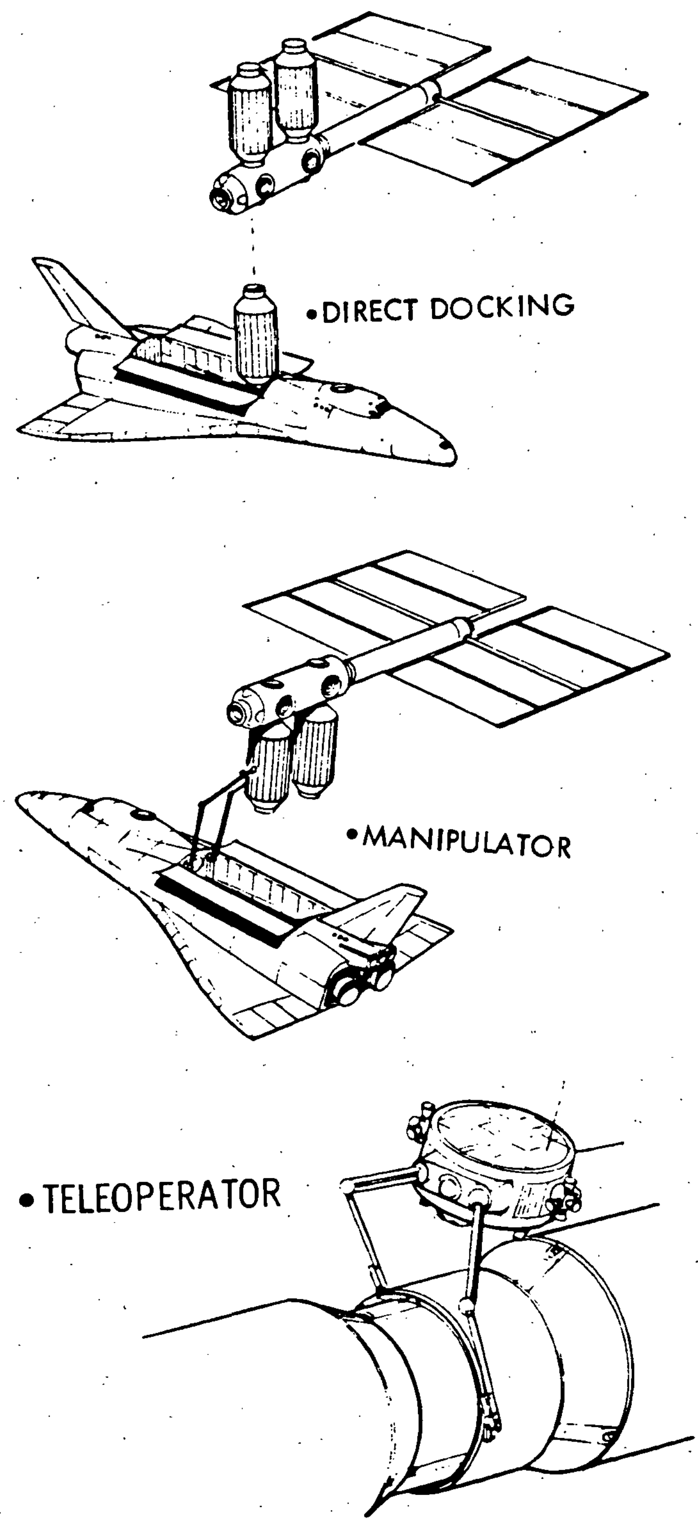


Figure 2-3. Orbital Assembly Alternate Approaches through Hard Dock

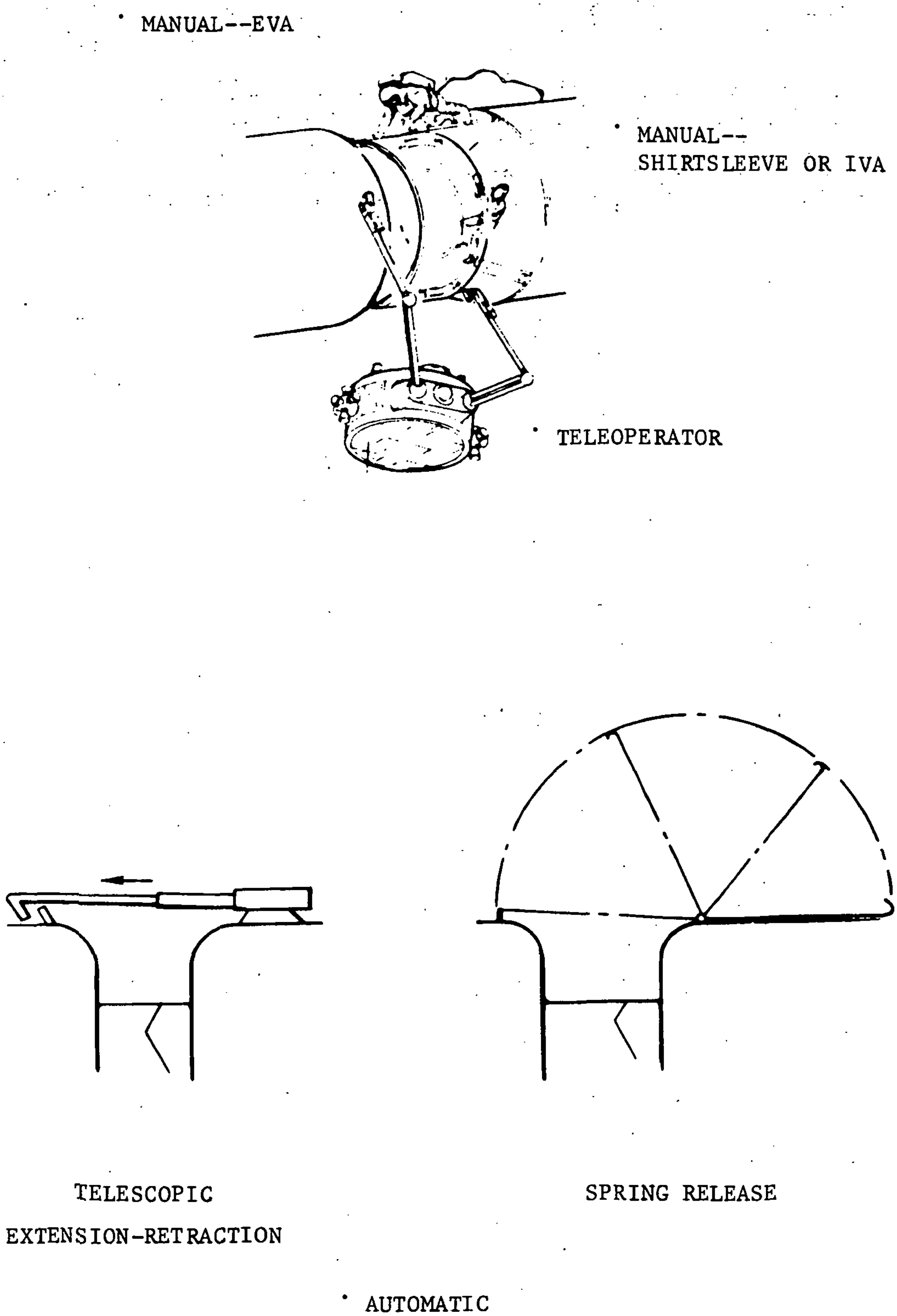


Figure 2-4. Post Capture Rigidization Options

other activities (crew, cargo and propellant transfer, mating, attached element transport). The design impact on the elements involved would be minimized (commonality maximized) if one of these approaches were applicable.

Alternate concepts for utility interconnects are illustrated in Figure 2-5. The two manual approaches are applicable if access is available to the mated interface. It is not considered a viable option (severe design impact) to provide manual access to the interface solely for this function (e.g., assembly of modular RNS). Therefore, the automatic concept must be considered in more detail.

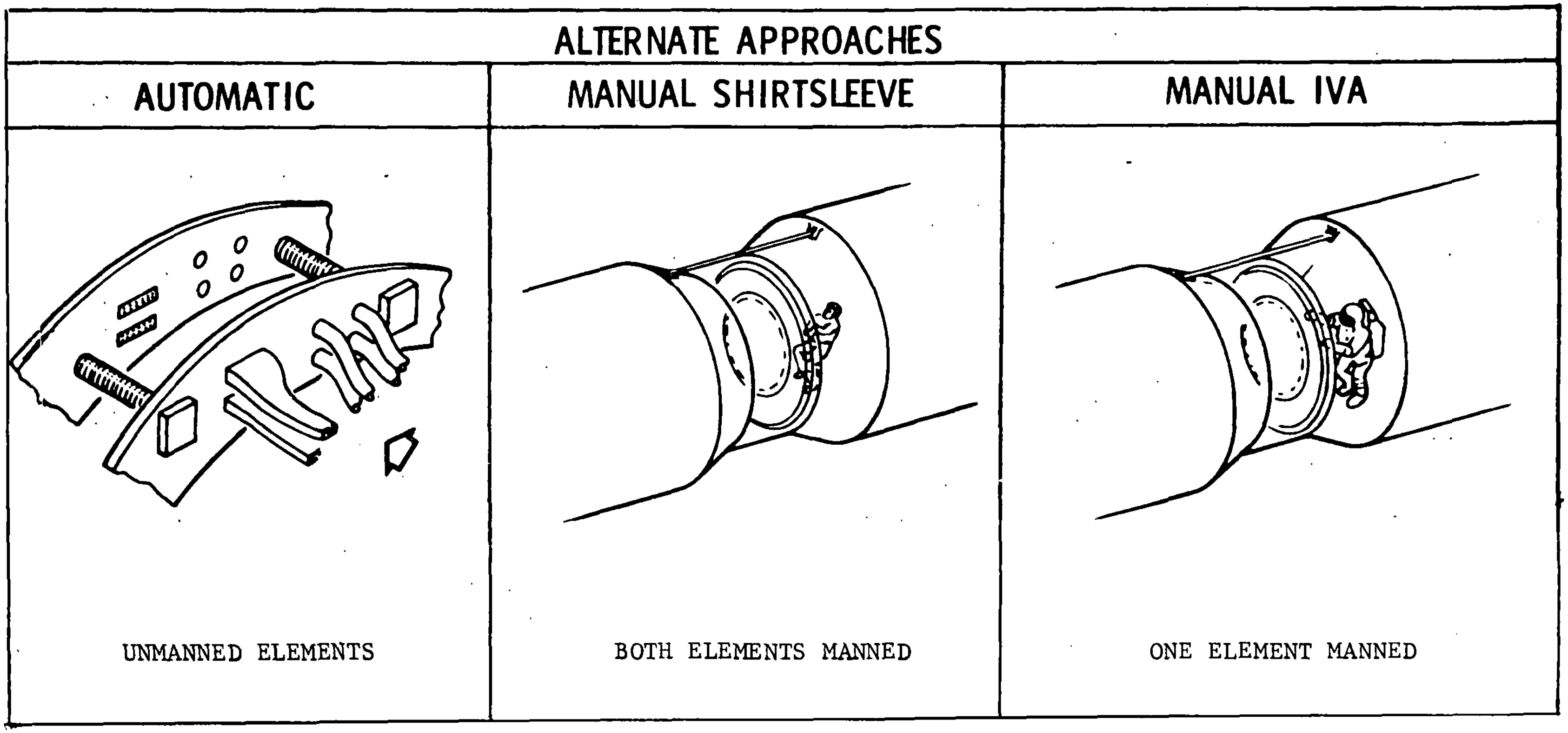


Figure 2-5. Utility Interconnect Alternate Approaches

2.4 DESIGN CONCEPT MODELS

As stated previously the first phase of orbital assembly operations through capture are the same as mating operations. The functional requirements and constraints are discussed in detail in Section 1.0. The results of the mating analyses, as they apply to the orbital assembly activity are summarized below.

MATING ANALYSES SUMMARY

The mating activity analyses resulted in selecting an automatic direct docking concept as opposed to the manipulator berth approach. The manipulator approach was rejected primarily because of the higher cost and difficult task of maintaining it. However, if a manipulator is selected for other programmatic reasons, the mating activity preferred that it be allocated only to the EOS orbiter and that the EOS orbiter also be redundantly equipped for direct docking. The mating activity indicated that installing a manipulator on any other element would not provide enough benefits to warrant the additional costs.

The automatic direct dock concept provides for the mating of all identified study element pairs associated with orbital assembly using common hardware and is not perturbated if the elements are manned or unmanned. The concept will effectively attach two elements together, structurally align the elements, and where applicable, provide a shirtsleeve passage between the elements. The following paragraphs describe the general characteristics of the models developed for the mating activity.

Mating Port

The mating port model would be a neuter (or androgynous) docking system that allows space vehicles with similar or identical docking hardware to be docked together. In addition to the androgynous design, several other criteria that were considered primary design requirements on the mating port are listed as follows:

1. Provide an unobstructed clearance within the confines of the mating port for routine crew and cargo transfer. This clearance shall be available without the removal of mating mechanisms.

2. Be applicable to a wide variety of spacecraft configurations and mass properties. In this sense the mating port should be capable of attenuating large ranges of impact energy and be capable of positioning the spacecraft to allow structural interconnection between vehicles.

3. Provide a structural and dynamic attachment between elements capable of withstanding maneuvering or attitude control loads applied by logistics vehicles.

4. Provide area for utilities interconnections of both permanent and temporary type.

5. Provide a sealed interface after mating to afford a shirtsleeve environment for crew transfer.

6. Have inherent or built-in redundancy.

7. Provide the capability of being maintained in a shirtsleeve environment.

The mating activity selected the ring and cone mating port for its model, see Figure 2- 6, because it provided the smallest outer diameter ring and still provided a relatively large internal passage and because it was most applicable to rotational oriented dockings. The advantages of small outer diameter docking ports are reflected when an element requires side docking ports. For this type element, when the docking port outer diameter is increased, the overall effective internal diameter of the element is reduced. For elements with multiple mating ports located in a common Y-Z plane, a large diameter port will reduce the clearance between modules mated to these ports. Rotational oriented mating allows approach corridors to be selected by vehicle configuration, see Figure 2- 7, rather than docking port indexing. For manipulator assembly, this is particularly beneficial in that it reduces manipulator reach and complexity of operations as shown in the figure. For direct docking, it allows the logistics vehicle to attach to an element in a manner that will provide maximum clearance during the mating operation. The selected mating port will provide a shirtsleeve passage between elements and does not dictate a particular hatch design or size.

Direct Docking Alignment

For direct docking, the mating activity selected the laser radar concept as the primary alignment aid. Figure 2- 8 shows the interfaces required for the assembly of a module onto an MSS using the EOS orbiter as the transporting element. It can be seen that the radar transceiver and corner reflectors are located at the interfacing ports. This is the recommended configuration; however, other locations on elements are acceptable, but they will be less common and require special computation to determine the actual alignment of the mating ports.

Manipulator Alignment

For manipulator operations, if the manipulator is automated (computerized), the alignment is associated only with the capature of a target vehicle. With a TV camera located at the terminal end of the manipulator transmitting pictures to the control center, alignment becomes a visual judgment task. The vehicle rates are nulled until a low limit cycle deadband is achieved between vehicles. The controller then needs only to direct the end effector into the capture receptacle making small corrections as the manipulator tip approaches the receptacle. The more difficult task may be to manipulate the associated joints such that manipulator arms do not come in contact with appendages of the target vehicle. With a second manipulator, this hazard can be reduced by strategically locating the second manipulator so that its TV camera can view the working manipulator arms as illustrated in Figure 2- 9. The use of a TV integrated manipulator operation should considerably enhance orbital assembly operations, particularly where intricate operations are involved.

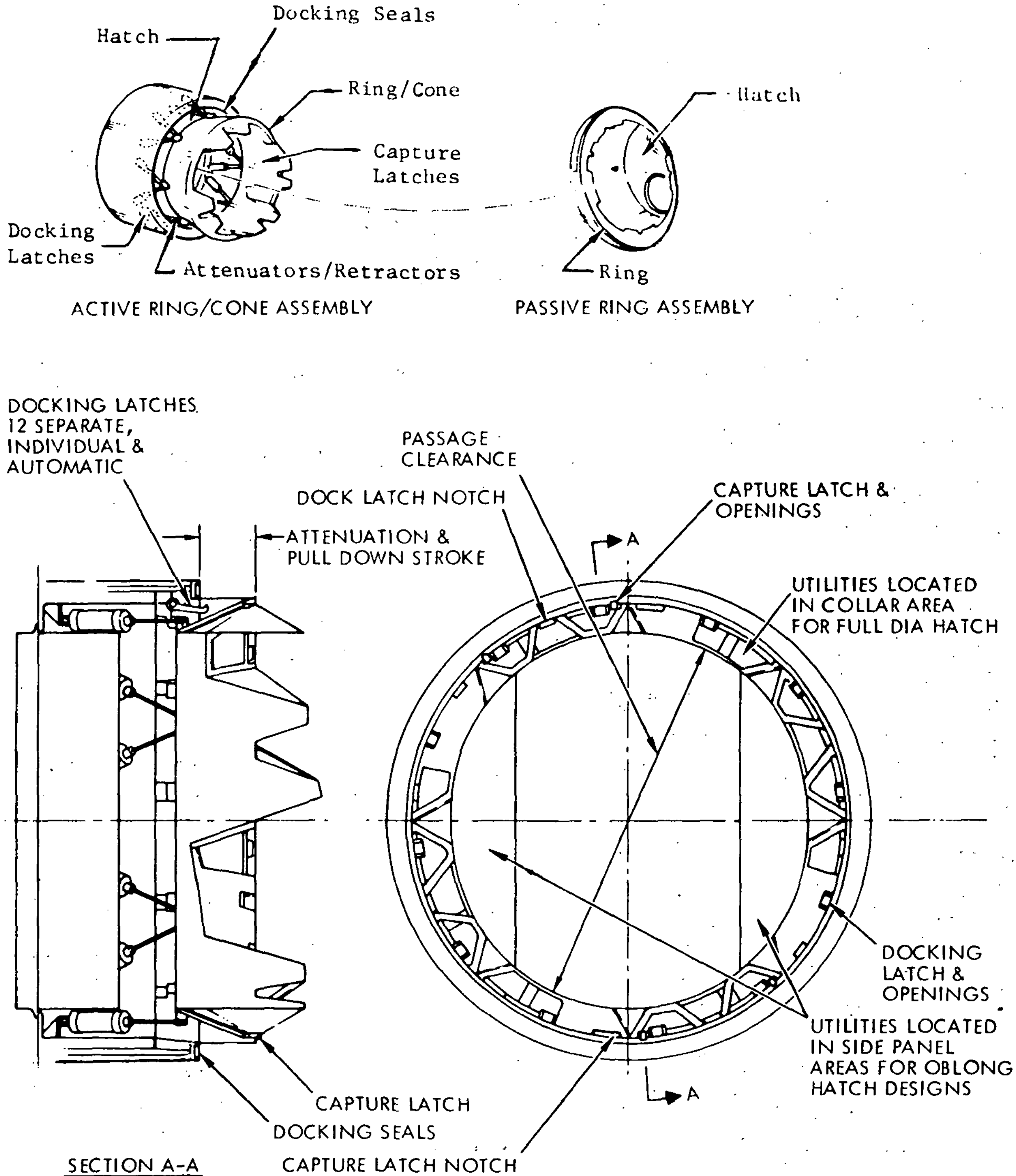


Figure 2-6. Mating Port Model

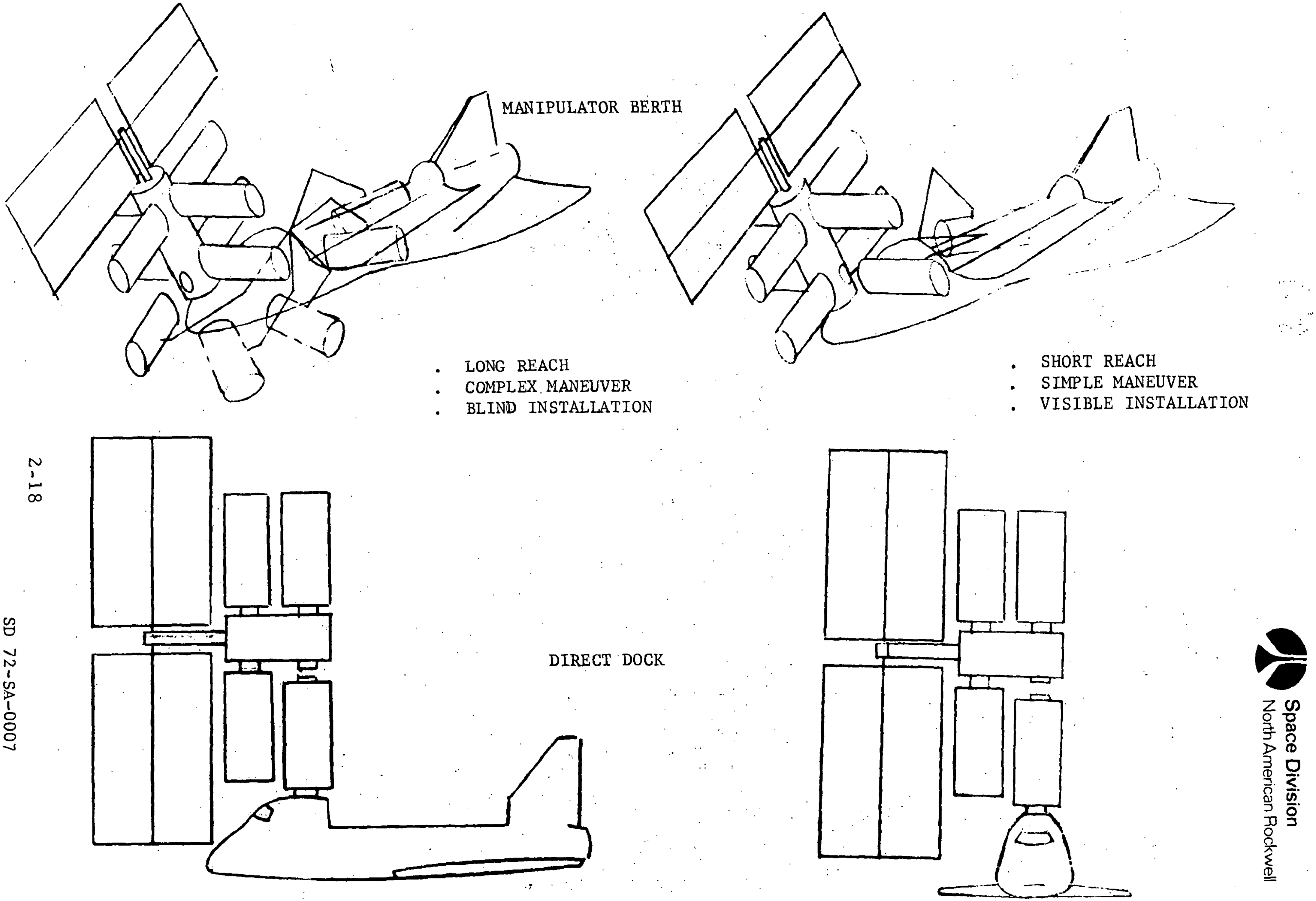


Figure 2-7. Rotational Orientation Mating Advantages

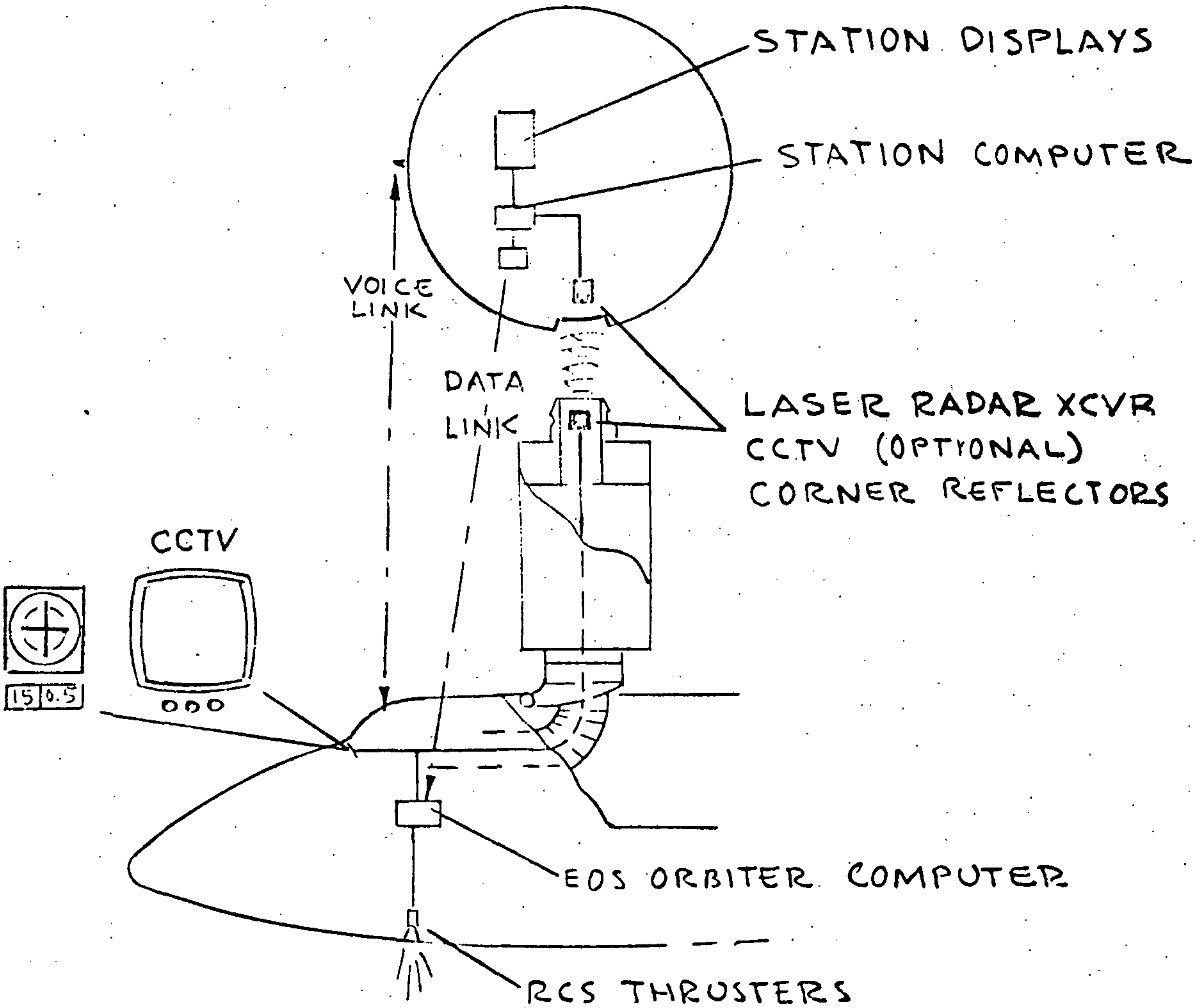


Figure 2-8. Automatic Docking Either Vehicle with Laser Radar

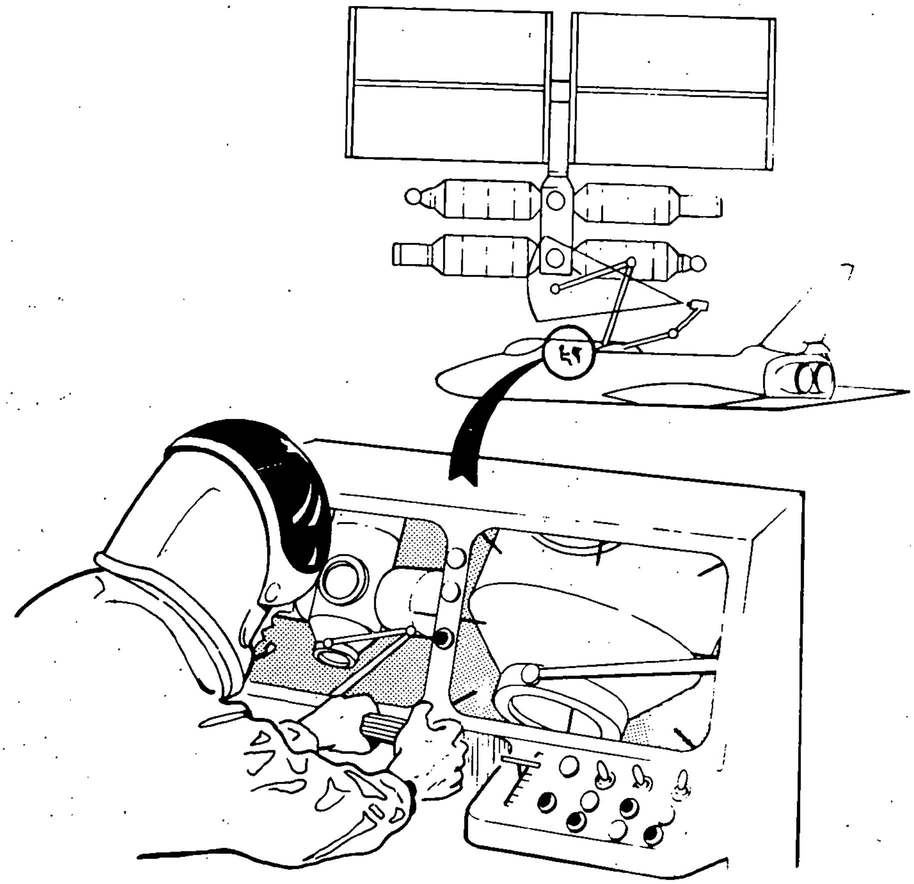


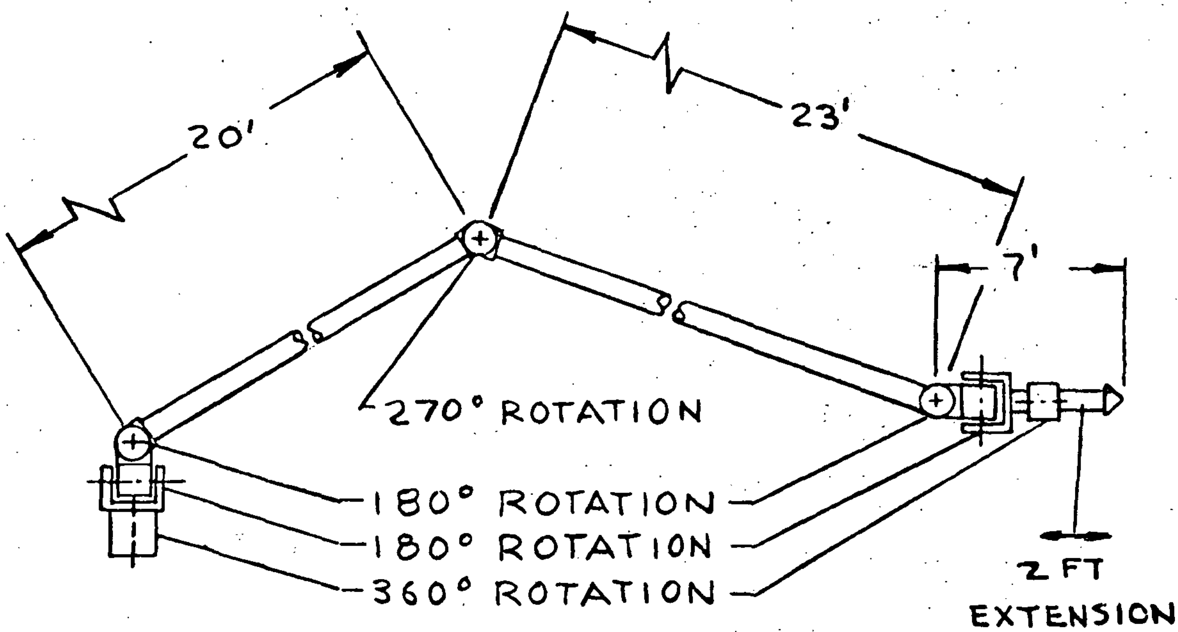
Figure 2-9. TV Manipulator Integration

Manipulator Design Concept

Figure 2-10 depicts the manipulator design utilized for the mating study model. The design incorporates a seven axes arrangement which allows the upper arm and forearm links to be positioned and operated in essentially any desired plane. During docking the seven axes system can control all degrees of relative motion between the vehicles.

The manipulator can be directly controlled manually, it can be computer controlled, or it can be remotely controlled. The assembly consists of upper and lower structural elements, pivot joint actuators, and the wrist mechanism. The arm carries a remote control TV camera and spotlight mounted near the terminal end of the arm. Dual torque motors are provided and designed such that the failure of one motor does not prevent drive by the other.

Two generic types of end effectors have been identified: (1) claw concept and (2) probe concept. Figure 2-11 illustrates one claw concept which is designed to envelop a square bar attached to a payload . . . and clamp onto it. The bar is itself enclosed in a conical recess which serves both as a guide to assist the claw in capturing the bar and as a guard and scuff plate for element protection. Figure 2-12 illustrates the probe concept which is modeled after the Apollo probe and drogue docking latch principle. The probe is guided into the receptacle by a pyramidal shaped cone and makes an initial capture to prevent disengagement. Final expansion of the probe secures the engagement.



TORQUES AND FORCES

- Shoulder--Up/Down and Rotate: 500 ft-lb
- Elbow--Up/Down: 300 ft-lb
- Wrist--Up/Down and Right/Left: 200 ft-lb
- Wrist--Rotate: 200 ft-lb
- Wrist--Extend: 100 ft-lb

Figure 2-10. Manipulator Model

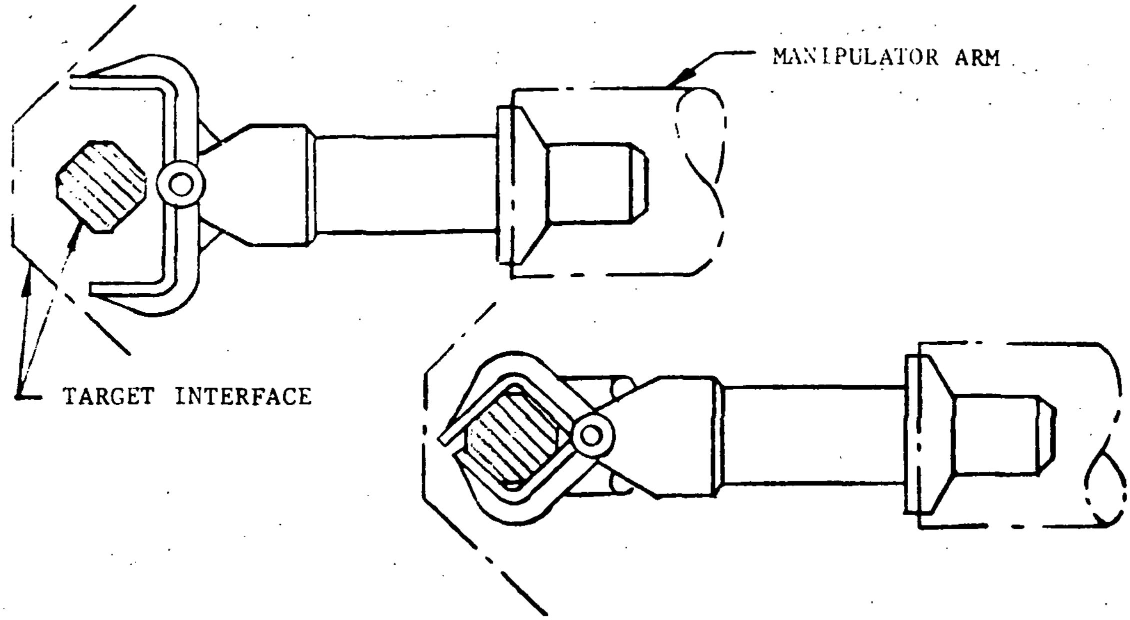


Figure 2-11. Claw End Effector

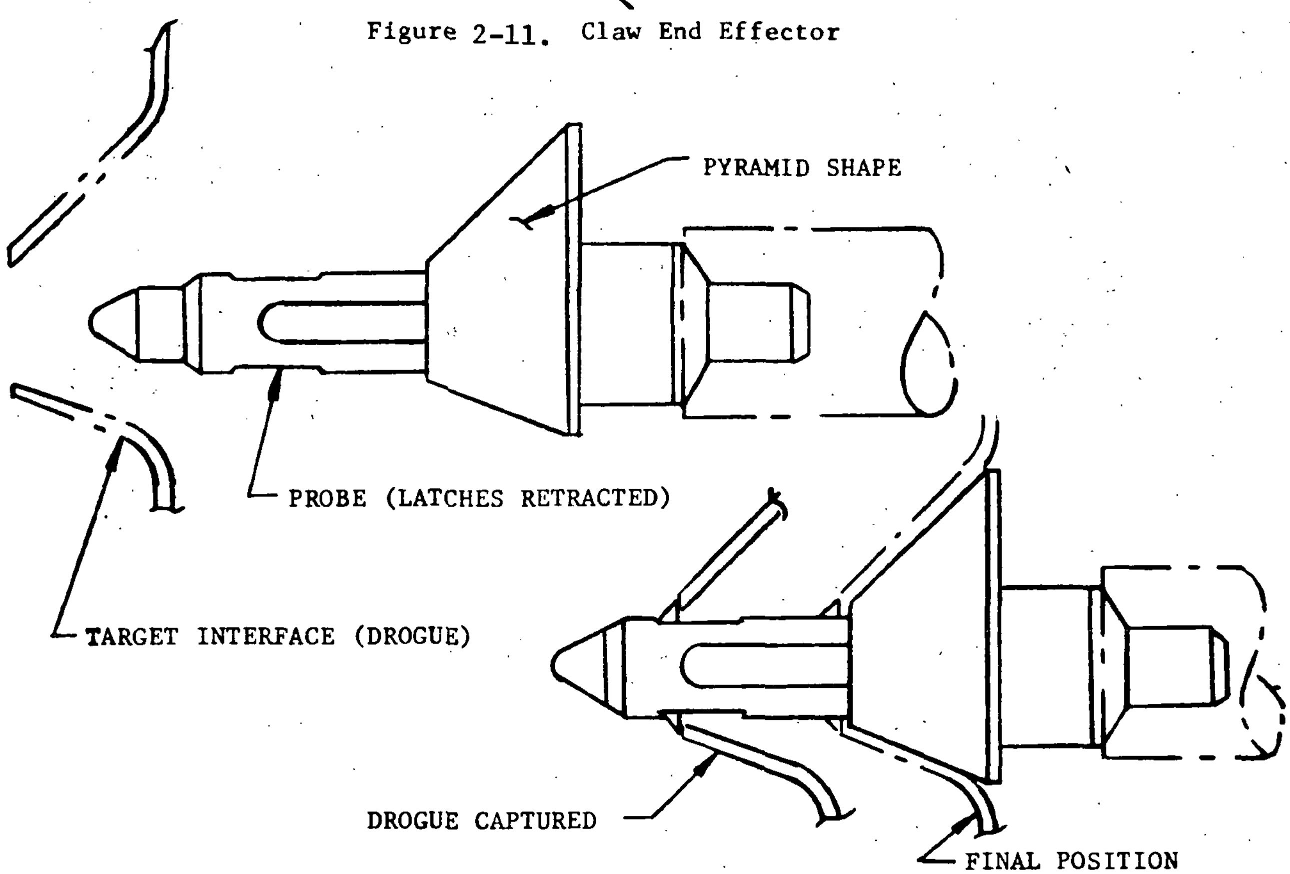


Figure 2-12. Probe End Effector

POST CONTACT OPERATIONS

The second phase of orbital assembly is concerned with post capture operations and the subsequent operations that the assembled elements/modules will independently perform. There are two aspects of the post capture operations relating to the interface: structural rigidization and utility interconnect.

Structural Rigidization

The three alternates for post capture rigidization are manual shirtsleeve, manual EVA, and automatic. Automatic could be an inherent part of the docking hardware or supplemental hardware could be used. Figure 2-13 illustrates several common rigidization concepts.

The augmentation concept utilizes supplemental rigid or flexible tension ties connecting the shells of the elements/modules together. It could be mechanized by any of the three approaches. The shell-to-shell concept is a minor variation of the augmentation scheme. It is comparable to connecting two electrical connectors together, only on a very large scale. Again, all three approaches are applicable. Manual jack screws or clamps could be employed or motor driven jack screws with alignment guides could be designed.

Side by side assembly of elements/modules include two mating concepts and a large Marman clamp concept. The transit concept uses a flat pack multiple docking adapter on the two ends of the modules to be assembled. The major problem with this concept is the alignment tolerances required during the mating process, particularly when the modules are relatively long. This can be alleviated by designing a pivoting transit device such that the modules initially mate their major axis perpendicular to each other and then rotate one element to align the major axes. Figure 2-14 illustrates the operation.

The strap concept would be extremely complex and hazardous to incorporate. Stationkeeping at the close proximity required would be undesirable. The concept is limited to an automated design. Standoff or pads are required between modules. The tension or pressure applied by the clamp will be critical in certain assemblies (e.g., propellant tanks).

The permanent connection concept is equivalent to a "field splice" or on orbit welding of elements together. Obviously this concept is not acceptable for transport or temporary assembly cases. Operational assembles such as the MSS, OPS or RNS could use this concept. It could be accomplished by either a manual approach or by an automatic concept (see Figure 2-4). The primary undesirable operational characteristic is that it all but precludes modular disassembly, repair and/or replacement.

Reliance upon the mating port design concept to provide post capture rigidization would be the preferred technique. One set of equipment for both mating and orbital assembly functions would provide maximum commonality. Programmatic costs could also be minimized provided the requirements of both activities can be met without undue complexity in the equipment. To determine

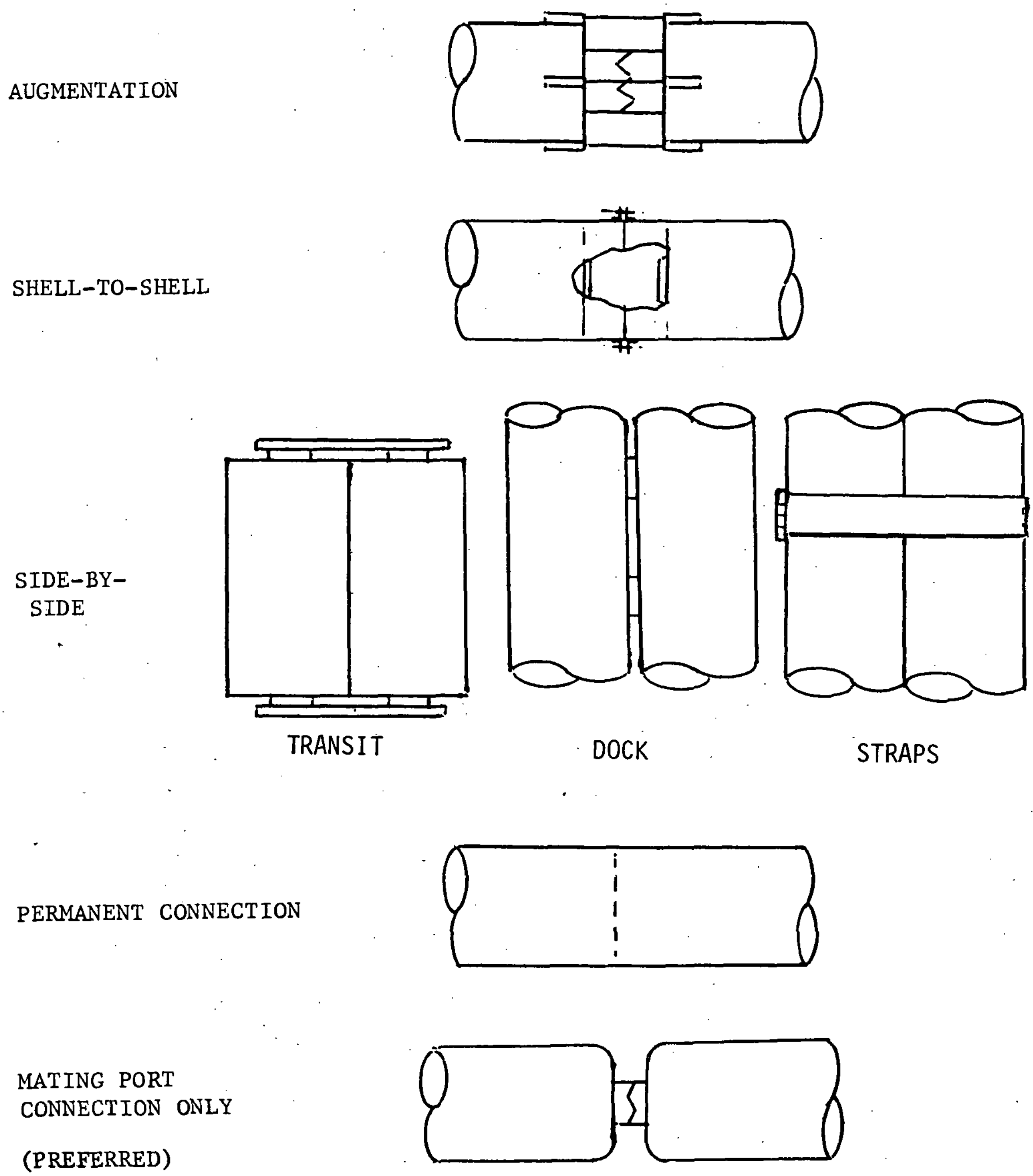


Figure 2-13. Modular Assembly Concepts

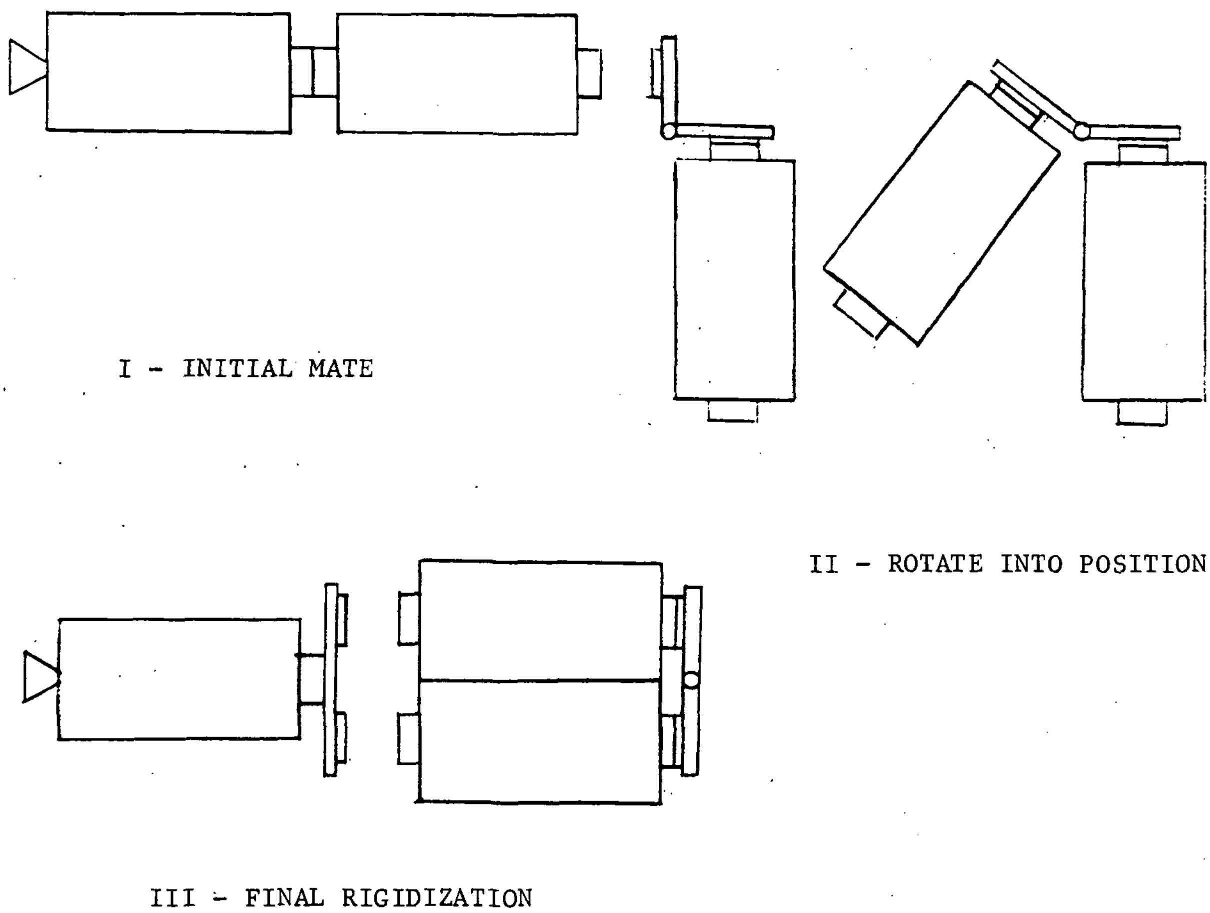


Figure 2-14. Parallel Module Assembly

the applicability of the various mating ports to support the rigidization requirements, it was necessary to identify the potential loads that can occur at the assembly interfaces and then determine if the mating port designs are or can readily be made compatible with these loads.

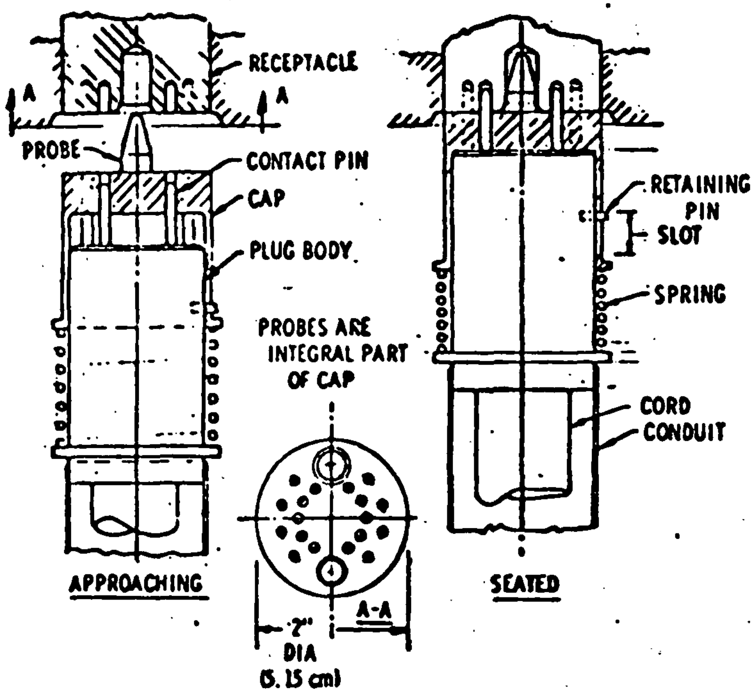
A docking and structural interface assessment was conducted. The results of the analyses are contained in Appendix A8. Four docking concepts were evaluated; square frame, probe and drogue, ring cone, and the international docking mechanism. Based upon the alignment attenuation, and pull down requirements for mating, it was determined that the axial loads associated with transport thrusts of the tug, CPS and RNS were within the capability of all four docking concepts. It was assumed that the thrust was through the combined center of mass of the vehicles. Supplemental rigidization provisions were not required.

Utility Interconnect

Electrical interconnect options were briefly described in Section 1.0, Mating. For maximum flexibility and minimum complexity, manual interconnects are preferred. However, some electrical interconnects are required where manual access to the operation is impractical (e.g., CPS stage to CPS stage). Figure 2-15 illustrates one design concept for automatic electrical interconnect of an individual connector that can be accommodated in any of the candidate docking mechanisms. Figure 2-16 illustrates an example of a controlled multiple connector engagement.

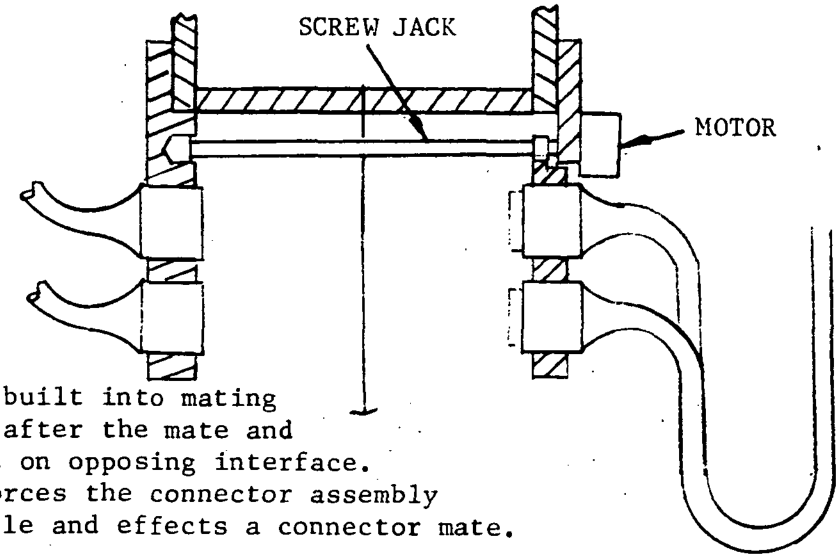
Fluid interconnects are discussed in detail in Cargo Transfer (Volume II, Part 4, Section 2) and Propellant Transfer (Volume II, Part 4, Section 3). The analyses performed by these activities concluded that automatic plumbed interfacing, though feasible, is complex and costly, limit flexibility, and require more complex maintenance than manual connected plumbed interfaces. Therefore, whenever the interface is accessible, a manual plumbed concept is preferred with shirtsleeve operations recommended over IVA techniques.

If access is not practical (e.g., propellant tank interchange), an automatic concept such as illustrated in Figure 2-17 can be implemented. This concept is essentially the same as currently used on the Apollo S-II. It is adaptable to any of the concepts evaluated.



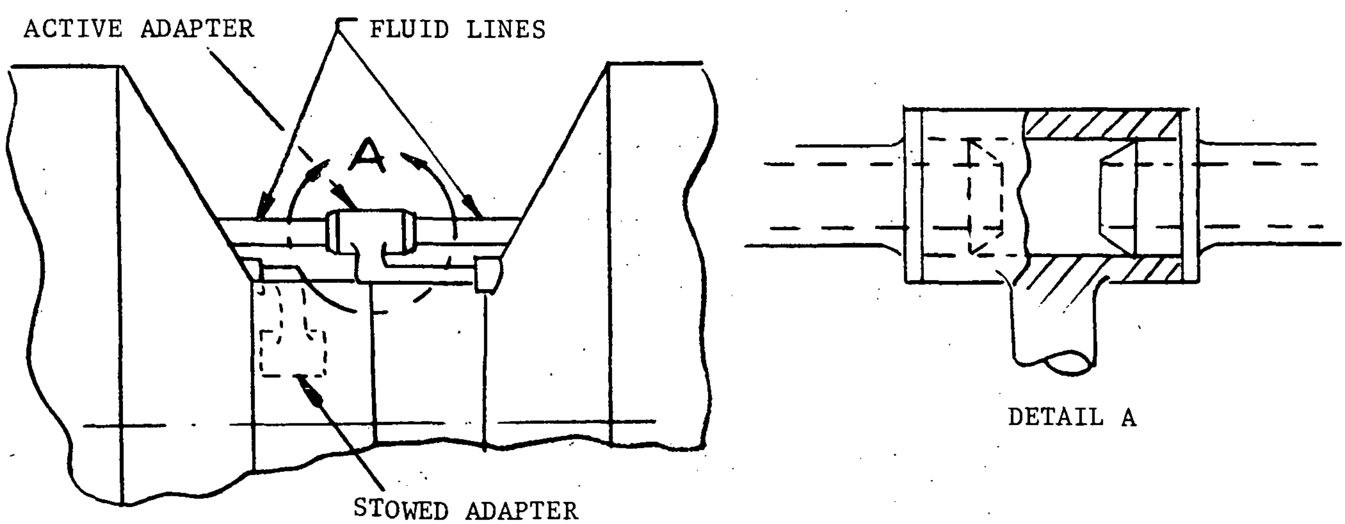
- OPERATION:
  - THICK BASE OF CAP PROTECTS PINS BEFORE ENGAGEMENT
  - CAP HELD IN EXTENDED POSITION BY SPRING
  - PROBES ON CAP PRODUCE RADIAL & ANGULAR ALIGNMENT OF PINS
  - PROBES ON CARRIER PRODUCE PRIMARY ALIGNMENT
  - PINS FORCED THRU HOLES IN CAP AND ENGAGE RECEPTACLE
  - CARRIER CONTAINS LOCK
- PROJECTED TOLERANCE CAPABILITIES
  - MISALIGNMENT - 1/8 INCH
  - ANGULARITY:
    ROLL - 5°
    PITCH - 5°

Figure 2-15. Automatic Electrical Interfacing Concept



OPERATIONS:
Screw jack probe built into mating assembly extends after the mate and feeds into guide on opposing interface. The screw then forces the connector assembly across the vestible and effects a connector mate.

Figure 2-16. Automatic Multiple Connector Concept



OPERATIONS:
Adapter on passive vehicle remains in stowed position. Adapter on active vehicle rotates and extends to operational position. Fluid lines containing probes extend and engage drogues in adapter. An applicable drogue and probe fluid line connector containing locking and sealing device and self-alignment features is in use on the S-II.

Figure 2-17. Probe/Drogue Fluid Line Connection

2.5 OPERATIONAL PROCEDURES

Two types of orbital assembly activities must be procedurally evaluated. One is the physical attachment of modules to an element for extended operations. The other is a temporary attachment of modules on an orbiting booster element (CPS, RNS) for subsequent transport to a higher energy orbit.

The primary operations required to achieve the assembly of a module are (1) mate, (2) rigidize the interface, and (3) connect the utilities across the interface. Extended mated operations involve all three operations, but the temporary assembly involves only the first two operations. The mating activity is performed utilizing one of the procedures developed in Section 1.0 of this document. The rigidization operation applies to rigidization that is in addition to the rigidizing that occurs through the normal mating function. Rigidization for the orbital assembly activity involves such concepts as installing cable tension ties, rigid stiffening members, interconnect clamps, etc. The operation can be performed IVA, shirtsleeve, or can be an automatic technique as in the case of using a multiple docking adapter to provide rigidization across a number of parallel stacked modules. The development of operations for IVA and shirtsleeve rigidization requires that the rigidization techniques to be employed must be known. That is, the methods used to install cable tension ties would probably be different from those used to install a rigid member. Therefore, the procedures developed herein go only to the depth of preparing for the rigidizing operation and in one step identifies the rigidization operation. Utilities interconnect involves the mating of electrical connectors and fluid couplings and verification of the interface.

As noted, the rigidization operation could be performed IVA, shirtsleeve, or automatically. For the permanent operation, all three concepts are viable; however, for the temporary operation the automatic technique appeared to be the only method that would be universally acceptable. Therefore, the procedure for the temporary assembly operation was developed around an automatic rigidizing technique and the other two techniques were covered under the permanent assembly procedures.

The mating techniques to be utilized could be either the direct dock or the manipulator berth. It was arbitrarily decided that the direct dock concept would be utilized for the temporary assembly and the manipulator berth for the permanent assembly. Since two procedures had to be developed for the permanent assembly in order to cover shirtsleeve and IVA rigidization techniques, the manipulator for one procedure was placed on the element delivering the module for assembly and in the other procedure, the manipulator was placed on the element being assembled.

In order that the full array of assembly operations would be provided for, it was necessary to have a manned element support assembly of a manned element and a manned element assemblying an unmanned element.

Finally, it was necessary to identify the supporting elements to model the procedure around. For the permanent assemblies, the EOS orbiter was selected and for the temporary assembly, the space tug would be the assembler.

Table 2-1 shows the three procedures that were developed and the variables selected to develop each procedure.

Table 2-1. Procedure/Criteria Matrix

Procedure Type	Type of Mate	Model		Manning		Rigidizing Technique
		Assy. Elem.	Support Elem.	Assy. Elem.	Support Elem.	
Permanent	Manipulator on Transport Element	MSS	EOS Orbiter	Unmanned	Manned	Shirtsleeve
Permanent	Manipulator on Assembly Element	MSS	EOS Orbiter	Manned	Manned	IVA
Temporary	Direct Dock	OLS on CPS	Space Tug	Unmanned	Manned	Automatic

These three procedures are shown in detail in Appendix B.

PROCEDURAL COMPARISON

As noted, the orbital assembly procedures have been developed around two different types of assembly operations. One type is the assembly of elements that are of a permanent nature where man is directly involved in the assembly of the interface. Figure 2-18 outlines the operations for this type of procedure and shows the deltas if the interface is configured using IVA techniques as opposed to shirtsleeve operations. The single "mate" balloon can be performed using any of the mating concepts. The only real differences between IVA and shirtsleeve operations are the airlock and module depressurization operations.

The second type of assembly is the temporary assembly of an element or portion of an element on an orbiting booster that is used to place an element into a higher energy orbit. This procedure effectively configures interfaces utilizing automatic techniques. As shown by the figure, the automatic technique requires only three operational steps: (1) mate, (2) rigidization, and (3) interface connection/verify.

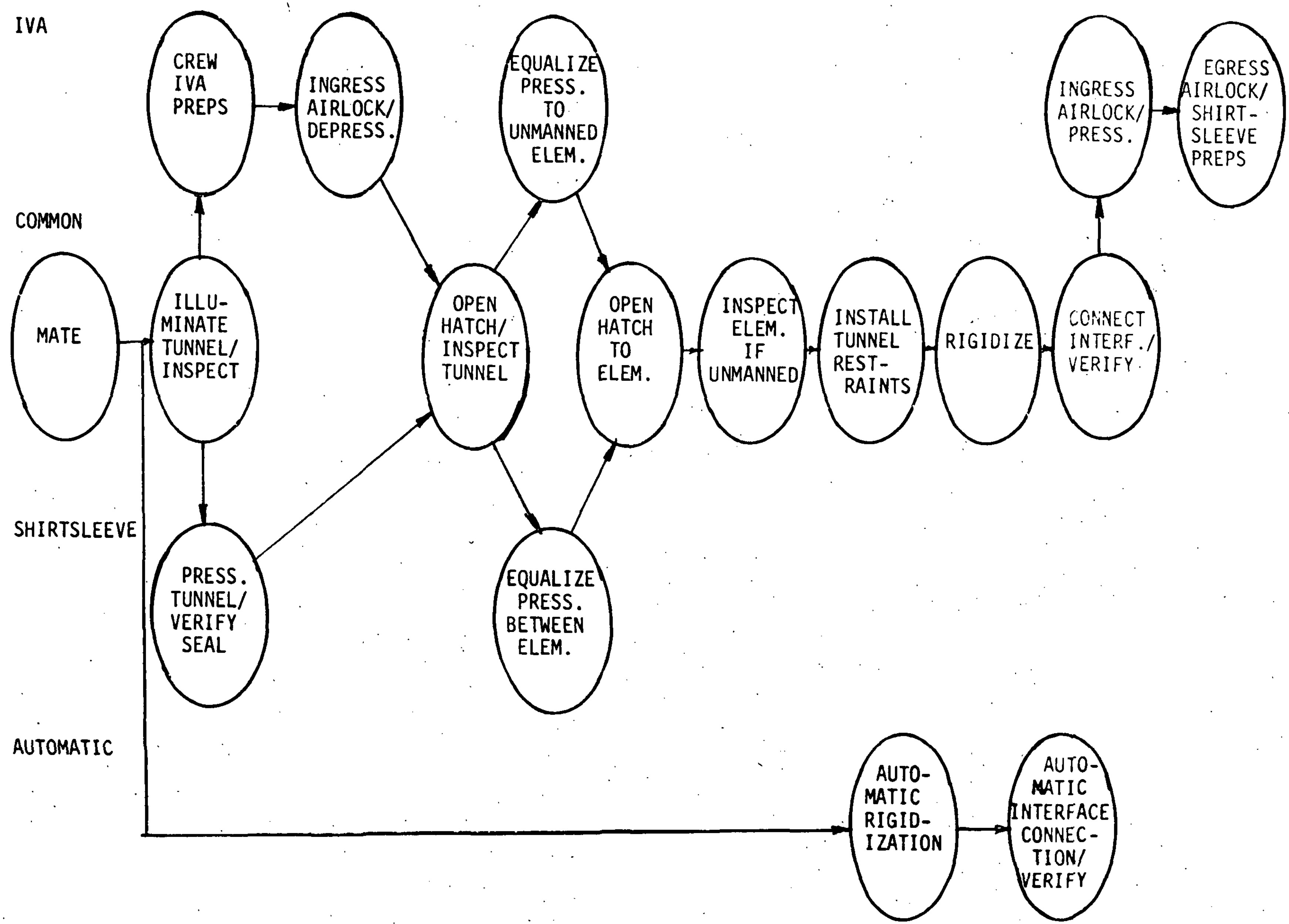


Figure 2-18. Procedure Comparison

PROCEDURES APPLICABILITY

Each procedure that was developed was reviewed for its applicability to support the feasible assembly operations. The review indicated that those elements utilizing automatic assembly techniques are the vehicles that will be assembled in a temporary configuration aboard a booster element rather than in their final configuration. Also, the modular RNS, modular CPS, and OPD vehicles would be automatically assembled because their design does not permit crew travel to the assembly interface other than by EVA. Other elements that are assembled in low earth orbit can be assembled using either shirtsleeve or IVA techniques. The space-based tug will use both concepts dependent on whether it is manned or not. Appendix B shows the results of this analysis in matrix form.

2.6 FUNCTIONAL REQUIREMENTS

The functional requirements presented in this section are provided such that the various conceptual approaches to orbital assembly can be further evaluated against the criteria that will be imposed on or by the concept.

The columns on the right-hand side of the requirement identify the operational procedure to which the requirement is applicable. The 2-1 and 2-2 procedures are the permanent assembly type procedures. The 2-3 procedure is the temporary assembly of modules on an orbiting booster element. As can be seen, almost all of the requirements are applicable to the first two procedures. The temporary assembly procedure involves primarily mating and separation activities; therefore, requirements applicable to those activities would also apply to this procedure.

Item	Procedure No.: Manip SS 2-1	Manip IVA 2-2	Dock Auto 2-3
1. All equipment installations in the assembly areas shall be capable of use for push-off and shall be capable of reacting to crew impact loads. Equipment that is susceptible to damage shall be color coded, placarded, and/or protected. During assembly operations in a zero-g environment, it will be difficult to predict where or what a crewman will use to apply leverage or grasp for stability.	X	X	
2. Free-floating work modes are not to be utilized for assembly operations. This mode is not suitable for any task requiring sustained forces. Momentary forces can be achieved; however, reactive forces also would be generated which would frequently be undesirable. This mode is also not applicable for intricate tasks requiring the use of two hands simultaneously.	X	X	
3. Waist tethers alone, unless they are of the rigidized type, are not acceptable for assembly operations. If waist tethers are utilized, hand and/or foot holds must also be provided such that workers can restrain their body when applying forces.	X	X	
4. Restraint aids shall be selected on their capability to be utilized for the required assembly operations. Table 2-2 (DS-529) provides a general guide on the capabilities of particular restraint techniques:	X	X	

Table 2-2. Restraint Technique Characteristics

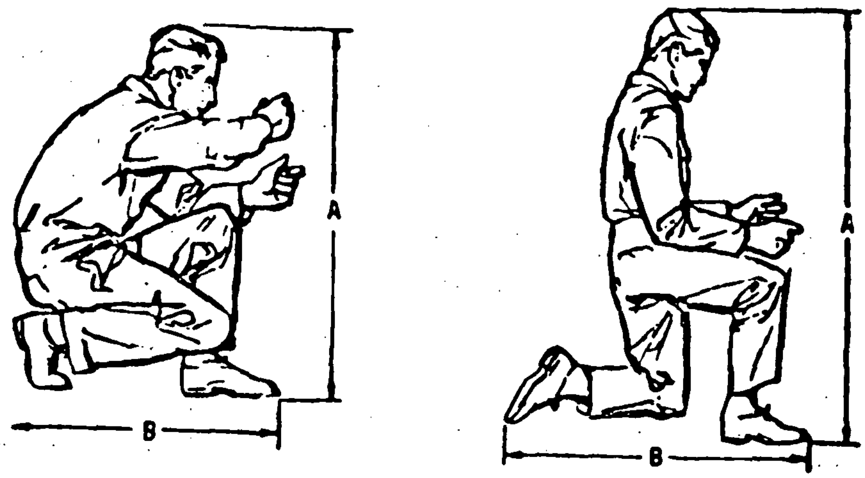
SUSTAINED FORCE (MEANS) (POUNDS)						
Restraint	Push	Pull	Up	Down	Right	Left
None	0	0	0	2	0	0
Handhold	1	2	5	0	10	17
Waist	15	22	10	10	12	12
Shoes	4	4	17	21	9	8
Hand and waist	29	31	14	16	15	17
Hand and shoes	30	35	18	26	16	21
Waist and shoes	35	37	17	19	14	15
Hand, waist and shoes	43	38	17	21	16	19
MOMENTARY FORCE (MEANS) (POUNDS)						
None	35	43	19	23	18	18
Handhold	41	43	21	26	22	29
Waist	43	46	23	23	22	22
Shoes	46	48	28	33	22	23
Hand and waist	57	51	23	26	25	28
Hand and shoes	62	61	31	37	28	34
Waist and shoes	58	57	28	30	23	25
Hand, waist and shoes	69	61	29	32	27	30
Note: Circled items indicate the highest force values.						

In summary, it is apparent that sustained force cannot be achieved when no restraints are used. Momentary forces can be achieved; however, reactive forces also would be generated, which would frequently be undesirable.

	Procedure No.		
	Manip SS 2-1	Manip IVA 2-2	Dock Auto 2-3
5. Restraint aids shall conform to the following design criteria:	X	X	
a. Shall be in place and ready for use or readily deployable by the work crew			
b. Shall be located within the reach envelope of 5th to 95th percentile crewman wearing a pressurized EVA suit			
c. The cross section of the aids shall allow for use of a pressurized glove. The preferred cross section of handle-type grips is an elliptical shape with the minor axis greater than one inch (DS-513)			
d. Shall be capable of sustaining any load capable of being imposed by crewmen wearing an IVA suit			
e. Shall have provisions for attachment of tethers			
f. Surface materials shall be selected to ensure that high and low temperatures and conductivity are not limiting factors in using the aids (DS-509)			
6. Interface assembly operations should be designed such that a minimum number of tools is required for the operation. Where possible, designs should be such that common tools can be utilized.	X	X	
7. Assembly areas shall be large enough such that a worker is not constrained in his movements, thereby increasing the difficulty of his task.			
Where personnel are required to work in limited spaces, the task shall be analyzed to determine the body position that will be assumed and the appropriate dimensions selected. Additional factors that will affect the necessary dimensions are:	X	X	

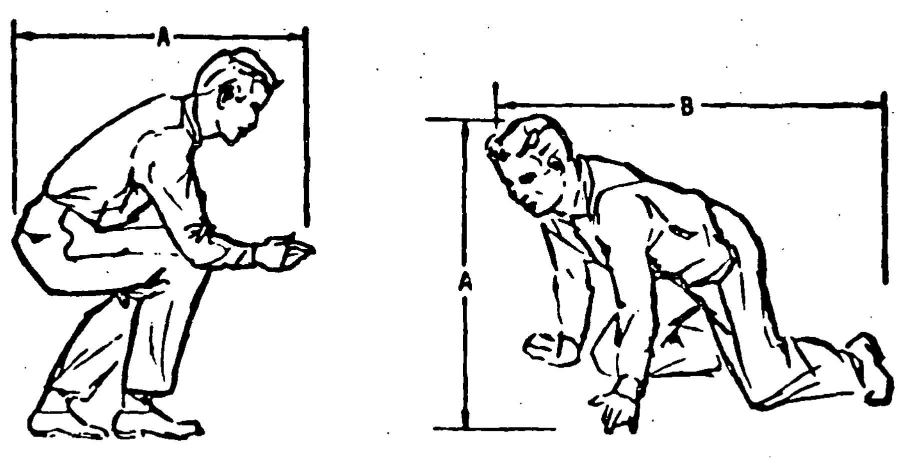
	Procedure No.		
	Manip SS 2-1	Manip IVA 2-2	Dock Auto 2-3
a. Duration of the task and comfortableness of the position			
b. Dimensions of the tools, equipment, and aids required to execute the task			
c. Dimensions of units that will be installed			
d. Protective garments or devices worn by the personnel			
e. Doors, access covers, or other equipment projecting into the workspace			
Figure 2-19 shows the minimum dimensions required by a worker for various positions, while working in a planetary environment.			
8. Illumination shall be provided to permit easy visual detection of the location and orientation of handgrips, rails, tether points, and restraint devices along transfer paths and at the work site. Fixtures shall be designed and located to provide even lighting on surfaces to be illuminated, generate minimum stray light, minimum glare, and minimum reflections. IVA operations in direct sunlight may require that the spacecraft be oriented such that glare, direct and specular, does not hinder visual acuity. Minimum lighting should range as follows: Direct diffused lighting, 30-50 foot candles Supplementary local, 50-70 foot candles Portable lights shall be capable of providing floodlight-type direct illumination of 100 foot candles at a distance of 10 feet. Portable lights shall be equipped with a carrying handle, clamping device for mounting it to surrounding structure, and shall have an actuation device that is compatible with a gloved hand (suited/pressurized operations) (DS-208).	X	X	

SQUATTING WORK SPACE KNEELING WORK SPACE



		BULKY PROTECTIVE CLOTHING	LIGHT CLOTHING
SQUATTING WORK SPACE	"A"	51 MIN	48 MIN
	"B"	40 MAX	36 MIN
KNEELING WORK SPACE	"A"	59 MIN	56 MIN
	"B"	50 MIN	42 MIN
STOOPING WORK SPACE	"A"	44 MIN	36 MIN
KNEELING CRAWL SPACE	"A"	38 MIN	31 MIN
	"B"	62 MIN	59 MIN

NOTE: ALL DIMENSIONS IN INCHES.



STOOPING WORK SPACE KNEELING CRAWL SPACE

Figure 2-19. Work Space Requirements (Limited Spaces)

	Procedure No.		
	Manip SS 2-1	Manip IVA 2-2	Dock Auto 2-3
9. IVA assembly shall always be performed using the "buddy" system.	X	X	
10. Duplex voice communications shall be provided between IVA work crews and with the element command center.	X	X	
11. Assembly operations in blind spots shall be avoided. No deviation shall be permitted where high voltage sources, hot or cold components, or other dangerous equipment are present.	X	X	
12. Access openings shall be deburred and rounded. Where sharp edges or protrusions could injure personnel or equipment (IVA suits) protection shall be available for installation around these areas.	X	X	
13. If parts cannot be designed to be installed in only one position, they shall be labeled so that fore and aft parts are distinguishable.	X	X	
14. All electrical interfaces shall be deadfaced on both sides of the interface prior to being connected. The possibility of connecting "hot" connectors is likely if deadfacing is not part of the interface design. Shorting a hot pin to the wall of a connector or to a ground pin in the mating receptacle could cause a spark which may in turn create a fire if the atmosphere happened to contain a combustile contaminant. Shorting the pin to a wrong pin may also damage hardware in one or both of the elements.	X	X	X
15. Prior to activating electrical interface circuits or closing deadface switches, proper mate of the interface connectors shall be verified.	X	X	X
16. Prior to activation of fluid interfaces, seal integrity should be verified. Deviation is not permitted where liquids or hazardous gases are involved. For non-hazardous cases, the lines shall be activated individually with the interface integrity verified prior to activation of the next line.	X	X	

		Procedure No.		
		Manip SS 2-1	Manip IVA 2-2	Dock Auto 2-3
17.	Extension and connection of automatic utility interface connectors and couplings shall be delayed until after the mating rigidizing mechanism has engaged and locked up. Early extension may fail to mate the connectors if the interface is not properly aligned. If engagement does occur, torquing of the interface by rigidizing latches may damage the receptacles.	X	X	X
18.	Shirtsleeve interface connections shall be located, designed and mounted such that a worker can mate the connectors in a pressurized IVA suit.	X	X	
19.	All manual interconnects shall be located to permit visual inspection of the connection. Automatic interconnects shall be located to permit visual inspection where practical.	X	X	
20.	Interfacing assemblies that contain plugs, receptacles, and couplings shall be equipped with compatible guides and indexing such that alignment will be achieved prior to engagement of the connectors. Individual connectors and fluid couplings shall be provided with mechanical guides such that alignment is achieved prior to engagement of connector pins or fluid coupling interface seals.			
21.	Electrical cables and fluid lines that traverse crew and cargo passages shall be suitably enclosed or otherwise protected to minimize hazards to the crew and provide protection for the hardware.	X	X	
22.	Direct insertion or quick-disconnect connectors shall be used unless high pressures demand threaded connections.	X	X	
23.	If it is necessary to route cables and wires through holes in metal partitions, the cables shall be protected from mechanical damage by installation of gromments or other acceptable means. Routing electrical cables along fluid lines or near high temperature sources shall be avoided (DS-509)	X	X	

Requirement	Procedure No. Manip SS 2-1	Procedure No. Manip IVA 2-2	Procedure No. Dock Auto 2-3
24. A credible accident to, or a credible failure of an interface function or adjacent function shall not cause the loss of redundantly provided functions or compound the accident or failure by creating additional hazards (explosion, fire). In this sense, the following criteria apply: a. Hazardous fluid lines shall be barriered or physically separated from power wires and each other (O_2 lines shall be considered hazardous in interface areas). (DS-208) b. Redundant fluid lines shall be separated a minimum of 45 degrees (DS-208). c. Redundant connectors shall be separated a minimum of 45 degrees (DS-208).	X	X	X
25. When electrical or fluid interfaces are to be mated between elements, a ground connection between the element structures shall be established to provide a consistent measured low impedance bond between the elements rather than rely on the mating interface for structural ground.	X	X	X
26. Interface connectors and couplings shall be routed, sized and/or adequately coded (color mating) such that the wrong connection cannot be made.	X	X	
27. Rigidizing techniques shall be designed such that during the application of the rigidization, the module structural fabrication cannot be overstressed. Cylindrical modules of relatively long size may be bowed to some extent due to tolerance buildup. This bowing is rigid and can be over-torqued to the breaking point if the base of the module is retained and the extreme end forced into an in-line position.			X

FUNCTIONAL REQUIREMENTS BY ELEMENT PAIR

All but one of the functional requirements are concerned with post-mating activities. The exception is requirement 27, which refers to the assembly of modules on a transport element. This requirement is pertinent to the OLS, geosynchronous MSS, and the LSB. Post-mating activity requirements are developed around shirtsleeve, IVA, and automatic techniques for assembling element pair interfaces. Automatic concepts are required where interfaces are inaccessible or the element pair is unmanned. IVA is considered only for elements where there is no interface seal around the mating port or where pressurization of the interface is considered impractical. Applicability of the requirements to the three modes are shown in Table 2-3. The requirement numbers follow a one-to-one relationship with the requirements of the previous paragraphs.

Table 2-3. Requirement/Mode Applicability

Reqmt. No.	Mode			Reqmt. No.	Mode		
	SS	IVA	Auto		SS	IVA	Auto
1	√	√		15	√	√	√
2	√	√		16	√	√	
3	√	√		17			√
4	√	√		18	√		
5	√	√		19	√	√	√
6	√	√		20	√	√	√
7	√	√		21	√	√	
8	√	√		22	√	√	
9		√		23	√	√	
10		√		24	√	√	√
11	√	√		25	√	√	√
12	√	√		26	√	√	
13	√	√		27	√	√	
14	√	√	√				

Table 2-4 lists the element pairs between which post-mating activities may occur. Also shown in the table are pairs applicability for shirtsleeve, IVA, and/or automatic interface configuring.

Requirements applicability for a particular element pair can be determined by first locating the element pair from Table 2-4 and identifying the "mode" of interfacing operation (shirtsleeve, IVA, automatic), then refering to Table 2-3 to determine which requirements are applicable for the particular mode.

Table 2-4. Element/Mode Applicability

Element Pair	Mode Shirtsleeve	Mode IVA	Mode Automatic
Space-Based Tug			
Space-Based Tug	✓		✓
MSS DRAM	✓		
Resupply Module	✓		
MSS-			
MSS ARAM	✓		
MSS DRAM	✓		
Resupply Module	✓		
MSS Module	✓		
MSS ARAM-			
MSS	✓		
MSS DRAM-			
Space-Based Tug	✓		
MSS	✓		
CPS			✓
RNS			✓
Resupply Module			
Space-Based Tug	✓		
MSS	✓		
CPS	✓		
RNS	✓		
CPS or RNS-			
OLS			✓
CPS or RNS Module			✓
Resupply Module	✓		
LSB			✓
OLS-			
CPS			✓
RNS			✓
OLS Module	✓		
OPD-			
OPD Module		✓	✓

Rationale for Mode Applicability

The space-based tug can be manned or unmanned. The MSS DRAM is designed for manual interface mating to be compatible with the MSS. The resupply module will not require interfaces with the space-based tug unless it is directly resupplying space-based tug.

All MSS and OLS interfaces are designed for shirtsleeve hookup. Therefore, all elements that are assembled to the MSS or OLS must be designed to be compatible.

The CPS and RNS can be manned or unmanned. Elements that mate for assembly, if they are mated in an assembled configuration, can be interfaced manually if the CPS or RNS is manned. However, if the elements are stacked on the CPS or RNS in a disassembled manner, than if a utility interface exists (which is highly unlikely), interface configuring will be automatic. The modular CPS and RNS require automatic techniques for mating their utility interfaces. The modular OPD utility interfaces will be automatic with the possibility of some interfaces being accessible by IVA methods if a crew module is included in the assemblage.

2.7 DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

Both phases of orbital assembly are closely related to other interfacing activities. The first phase--initial mating--is directly related to the mating and separation activities. The post-mating phase of orbital assembly involves operations very similar to those of crew and cargo transfer and attached element operations interfacing activities. Therefore, the preferred approaches for this activity are strongly influenced by the analyses of the related interfacing activities.

INITIAL MATING

Two classes of assemblies are considered (1) permanent assemblies—modular assembly for operational purposes; and (2) temporary assemblies--module and/ or element assemblages for purposes of transport. The considerations are significantly different for each class and are analyzed individually.

Permanent Assemblies

Elements that are in this category are the MSS, CPS, RNS, and OPD. The modular CPS and RNS are similar with respect to assembly operations. The OPD, dending on the selected design, falls somewhere between the logistics vehicles (CPS, RNS) and the MSS. For analyses purposes, the RNS and MSS have been selected for the subsequent analysis.

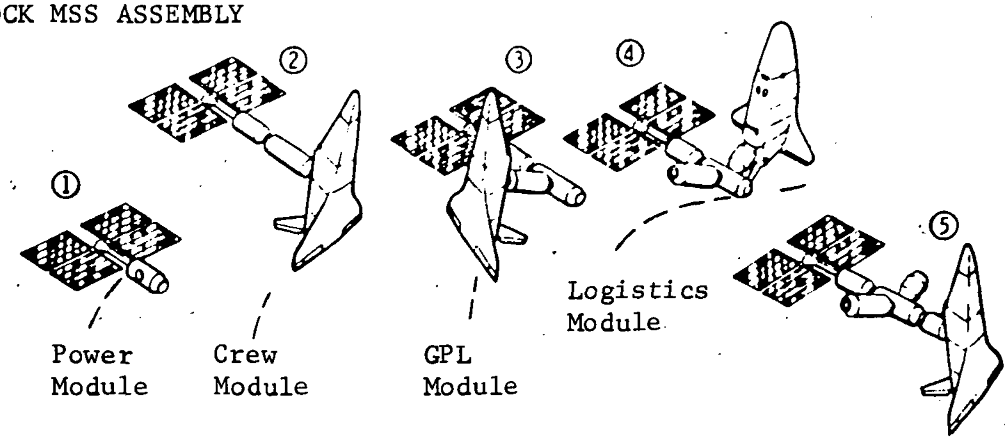
MSS Assembly

Figure 2-20 illustrates the MSS being assembled using the direct dock approach and the manipulator berthing technique. It can be seen that either approach results in a fully configured MSS. The same number of EOS missions are required for either approach. Some of the advantages and disadvantages are discussed below.

Required Docking Ports. All modules direct docked require a docking port on each end of the module, whereas for manipulator berth, the modules attached to the core require only one mating port. By eliminating the one mating port on a module, the module length can be extended by as much as three feet and a reduction in weight of about 200 pounds (assumes no passage at the eliminated docking port). However, the weight of the manipulator is significantly greater than the "extra" docking ports and the deleted ports preclude subsequent docking to the MSS appendages.

Figure 2-21 (DS-243) is a plot of the weight for various length modules of 14- and 15-foot diameter. The graph also provides data on the maximum average density to be expected for particular sized modules (based on 25,000 pounds maximum allowable weight). Previously studied MSS configurations are indicated on the graph. It can be seen that if modules were designed around 50-foot lengths, the density would be somewhere around one pound per cubic foot which is a relatively low density module when compared to densities of modules

DIRECT DOCK MSS ASSEMBLY



MANIPULATOR BERTH MSS ASSEMBLY

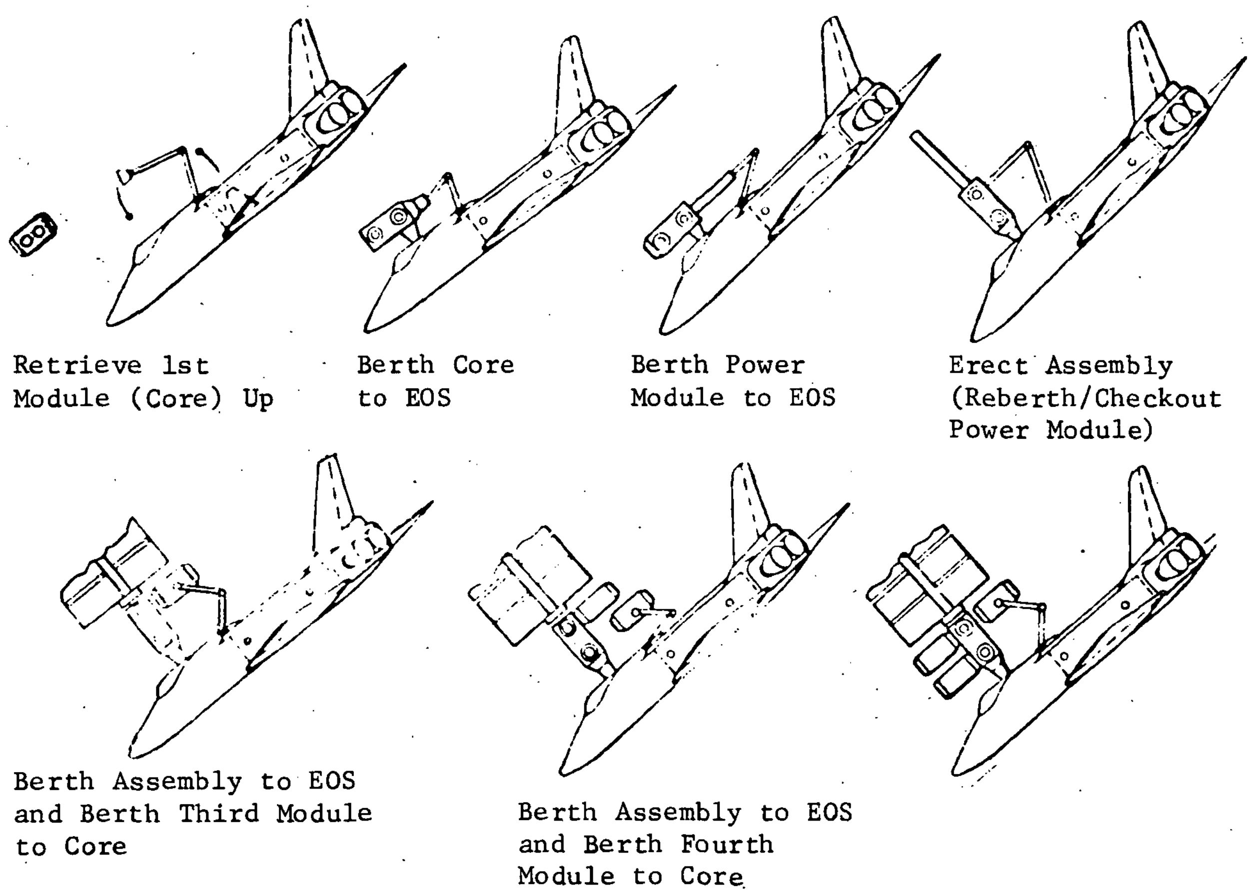


Figure 2-20. MSS Assembly Concepts

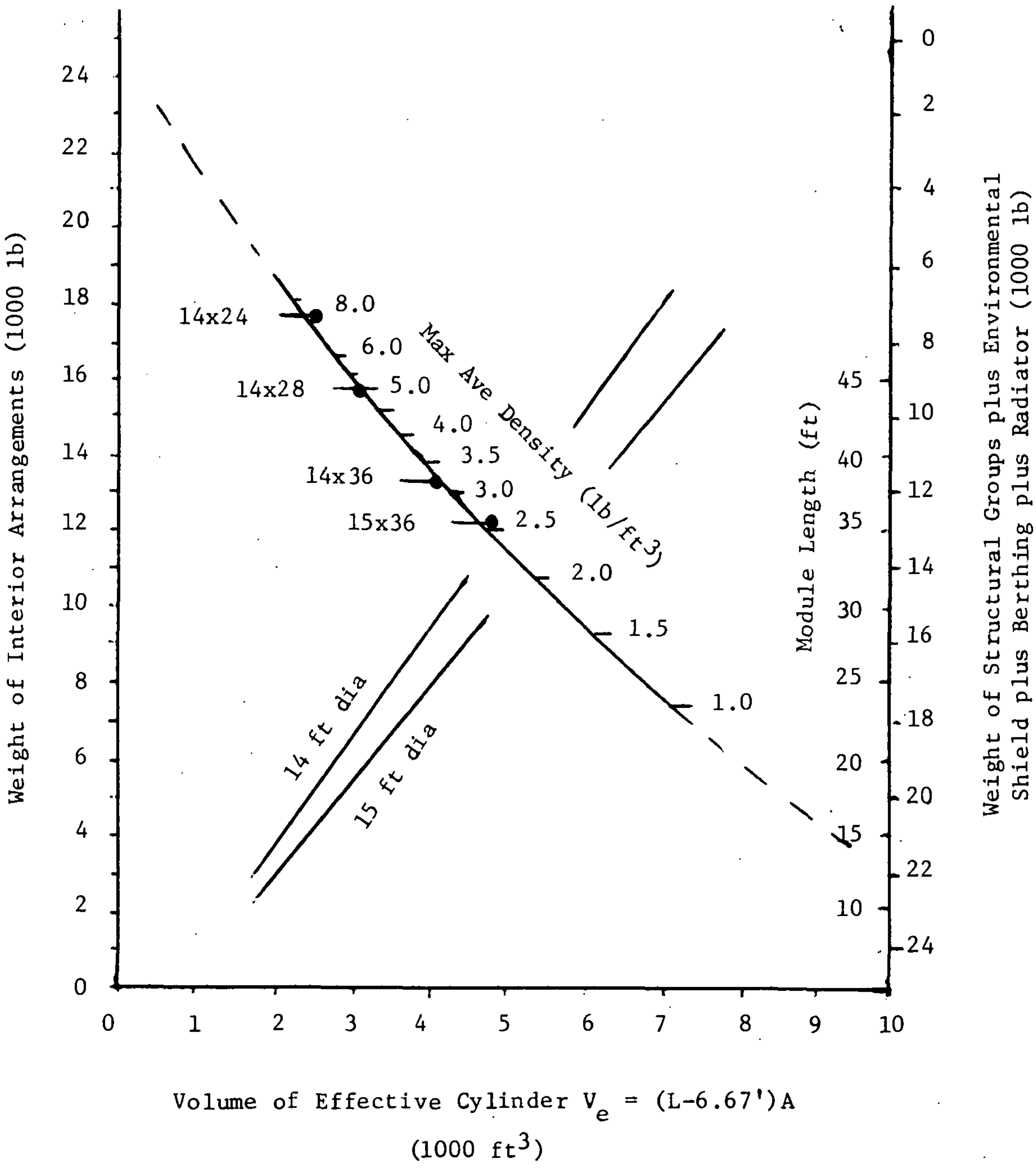


Figure 2-21. Weight-Length-Density Correlation for Modular Space Station

derived during Phase B studies. It is, therefore, concluded that the additional three-foot length to be gained with a manipulator available would probably not affect the optimum MSS module design unless EOS payload bay sizing is reduced to some length less than 50 feet.

Docking Operations. Assembling a module using direct dock is a simple operation, whereas for manipulator berth, the MSS assembly must first be berthed to the EOS and then the new module is manipulated from the cargo bay and berthed to the MSS. However, both of these operations are considered safe and feasible by the mating activity. Although an additional operation is required with the manipulator, the second operation can be made relatively easy to execute because it can be fully automated.

Crew Transfer. If crewmen must transfer between the EOS and MSS during each module assembly operation, the direct docking concept requires that each module provide crew transfer between the module and the EOS. The EOS must separate and dock to another port if crew transfer is required by means other than through the new module. With the manipulator berth concept crew transfer is always through the EOS holding port. In all buildup operations of modular space stations, the study contractors consider that crew will transfer and perform checkout operations. For all designs, whether direct dock or manipulator berthing was employed, a hatch was provided at both ends of the appendage modules. The hatch was for transfer of crew from an EOS or other element or for transfer into an additional module that may be added at a later date (i.e., airlock. The significant difference is that with a manipulator, the EOS-MSS crew transfer interface can be primarily developed around a single mating port rather than be incorporated at all mating ports.

Appendage Avoidance. Direct docking at some points in the assembly is somewhat more critical when appendages must be avoided. Manipulator berth is always at the same port after the initial assembly.

Solar array orientation during direct docking must be such that the resultant impact loads do not create high torques on the arrays such that they will experience large deflections. Therefore, arrays must be oriented in a manner that will provide the least resistance to the acceleration loads. With the modules closest to the solar array, this means a rather critical clearance problem.

The manipulator approach drastically reduces the mating loads. Clearance problems are somewhat alleviated in that the EOS orbiter appendages will be well clear of interference when using a manipulator.

Module Spacing. Any differences in the module spacing requirements for the different operational modes considered will have an impact on the core module design in terms of the required spacing between berthing and docking ports. The module spacing is dictated primarily by considerations of the errors associated with berthing or docking. The error sources considered for the two basic alternatives are identified in Figure 2-22. For the berthing mode, the position (translation), angular alignment, module manufacturing tolerances, manipulator stability deadband, and errors in orientation of adjacent modules (docked module alignment) must be considered. For the docking alternative, station attitude stability, EOS attitude stability, EOS position accuracy, module manufacturing tolerances, and docked module alignment must be considered. The magnitude of the alignment errors considered representative for the berthing concepts are also summarized in the figure. As can be seen, a minimum module spacing of approximately 20 inches is required for module lengths of 40 feet. Applying a 50 percent margin, the required displacement must be 30 inches.

The magnitude of the alignment errors for the direct docking mode are summarized in the figure. An examination of the error sources has shown that the module manufacturing tolerances and the docked module alignment errors are insignificant relative to the station attitude stability, shuttle attitude stability, and shuttle position accuracy error sources. In considering these three error sources, the required module separation for a 40-foot length module is approximately five feet. As a result of the increased errors, the direct docking mode requires approximately twice the module separation required by the berthing mode.

Spacing modules close together can assist with element control; however, any additional control gained by reducing the 80-foot long MSS by 5 or 10 feet, which is possible with manipulator berthing, does not appear to be a driver. More than likely, wide spacing will assist with radiator heat dissipation.

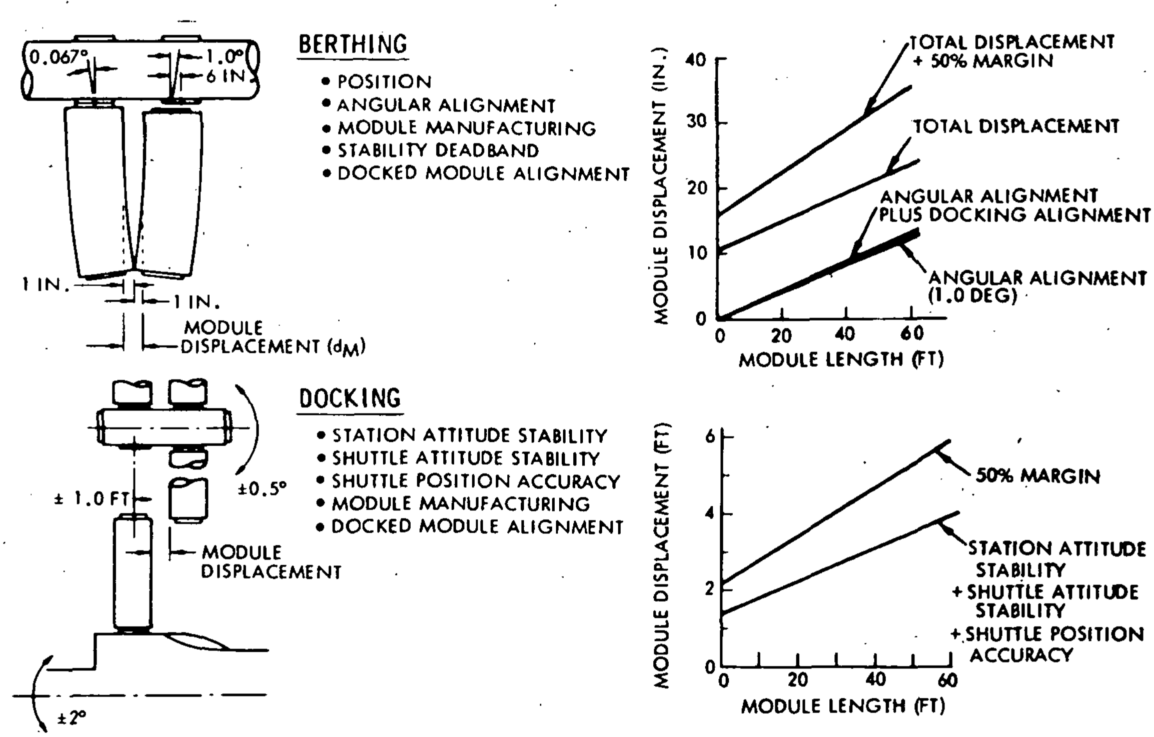


Figure 2-22. Alignment Errors

Supplemental Equipment. Attaching supplemental hardware, such as high gain dish antennas requires a complex antenna assembly for direct docking or the assembly must be an inherent part of the modules and erected after the module is docked. With manipulators the provision for assembly can be relatively simple. One study contractor has equipped the MSS with two high gain dish antennas and two experiment airlocks that dock on the outside of modules. If this is the final design, than manipulators will provide a synergistic benefit for installation of these items.

Summary. Assemblying the basic modules of the MSS can be achieved by either the direct dock or the manipulator approach. However, the manipulator provides increased flexibility in almost all phases of the operation. Supplemental hardware additions to the MSS are accomplished much more readily with the manipulator. The potential automation of the majority of the assembly operations with the manipulator provides a margin of safety over the direct dock approach. The manipulator is the preferred approach for assembly of the MSS.

RNS Assembly

Figures 2-23 and 2-24 illustrate a modular cislunar shuttle being assembled using the direct dock approach and the manipulator berth technique.

Direct Dock Concept. The initial phases of the direct docking concept do not impose any difficulty except for possible alignment during the docking operation. The mating activity recommends that a laser radar transceiver be located at the mating end of a module extended from the EOS orbiter. It would be impractical to incorporate laser equipment on each module for a one-time assembly operation. Besides the expense for the equipment and system checkout, the required hardline interface between the logistics vehicle and the module would very possibly be the only necessary electrical interface between the two vehicles, thus adding complexity that could be avoided. A design that would be acceptable is to locate the laser radar in the nose of the shuttle with viewing reflectors on the side of each module to be assembled. By triangulation, the alignment could be determined. Another method would be to locate the laser radar behind the crew compartment viewing directly up the side of the module and illuminating an extended target. Figure 2-25 illustrates both of these options.

The cluster assembly, Phase III (Figure 2-23), uses a pivotal mechanism which permits sequential addition of propellant tanks in close proximity to the centerline of the vehicle without requiring extremely stringent tolerances during the docking operation. The final assembly has all of the modules major axes aligned parallel. The pivotal mechanism will result in a reduction of the effective diameter of the tank it is mounted on in order to stay within the 15-foot diameter limit of the EOS cargo bay. An option would be to build a multiple docking adapter assembly which would be located at the docking ports of the clustered modules and the in-line module. Figure 2-26 illustrates this concept.

The final problem is the assembly of the engine. The method illustrated requires a special adapter that encompasses the engine bell or core and attaches to the support structure above the core. This adapter operates in a manner similar to the SLA panels of the Apollo. After mating is accomplished between the cislunar shuttle assemblage and the engine module, the adapter panels are "folded back" and separation occurs.

FOLDOUT FRAME 1 FOLDOUT FRAME 2 FOLDOUT FRAME 3 FOLDOUT FRAME 4

Figure 2-23

PP. 2-53/2-54

DIRECT DOCK MODULAR CISLUNAR SHUTTLE ASSEMBLY

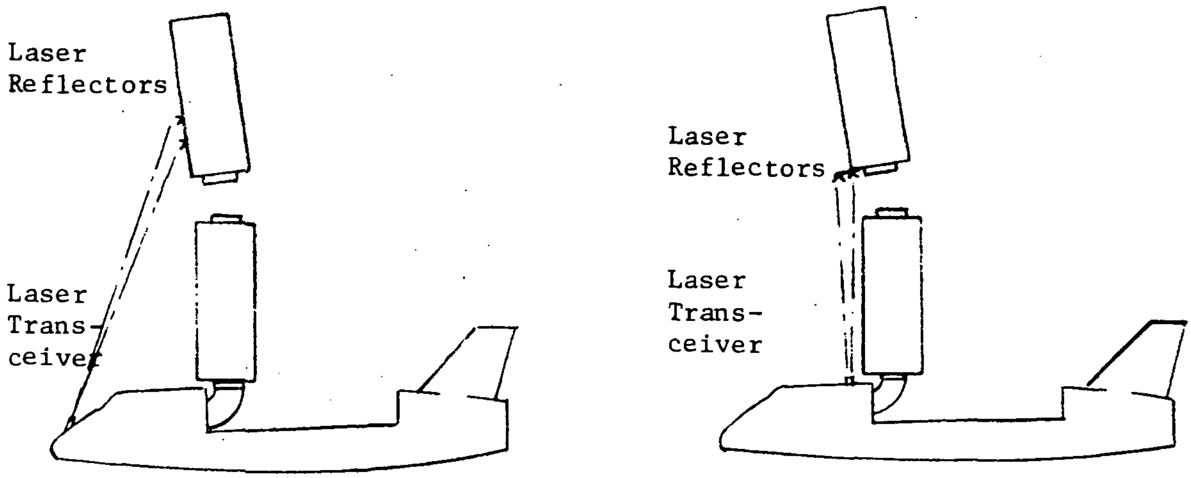
SD 72-SA-0007

Figure 2-24

PP. 2-55/2-56

MANIPULATOR
MODULAR CISLUNAR
SHUTTLE ASSEMBLY

SD 72-SA-0007



Triangulation Alignment

Direct Alignment

Figure 2-25. Optional Laser Radar Locations

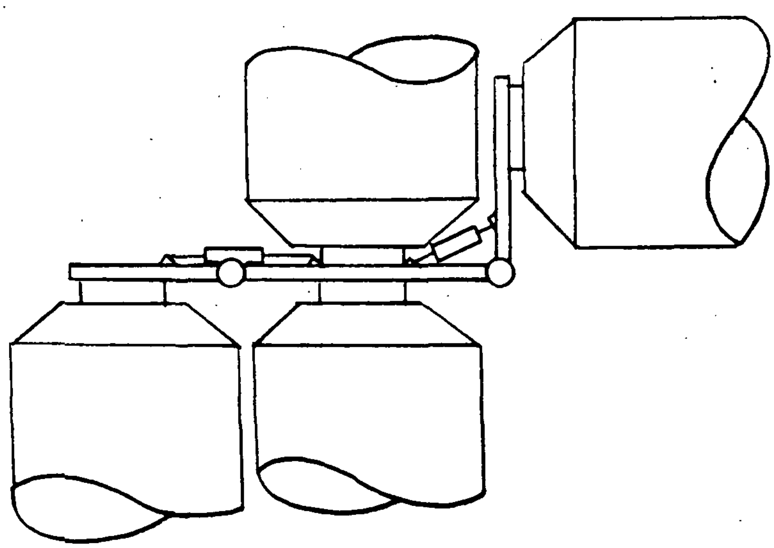


Figure 2-26. Mating Port Mounted Multiple Docking Adapter

Manipulator Berthing Concept. This assembly concept uses the recommended mating technique for manipulator berthing; that is, a single working manipulator, no stationkeeping berthing, and a single berthing port on the EOS orbiter. The critical part of the operational concept is the manipulator reach requirements. It can be seen that the reach must be long enough to capture an element in a stationkeeping position and maneuver it onto the new module which is berthed to the EOS orbiter nose port. The arm for this operation must be in the range of 100 feet.

In Phase III (Figure 2-24), the same rotating mechanism is required as was used for direct docking. An option would be to use side-mounted berthing ports. With a manipulator available, closer tolerances are acceptable. Side docking can be safely accomplished with a manipulator.

Phase IV installs the engine and like the direct docking option uses an adapter to hold the engine. Figure 2-27 illustrates a design concept devised by one contractor for engine installation. It essentially consists of an extension boom with a rotating attachment mechanism. The boom is remotely actuated and performs the capture function in a manner similar to a conventional manipulator. Because this pseudo berthing operation involves much lower loads, and provides added protection for the engine cone, and is adaptible for direct docking ports. Figure 2-28 is an alternate option whereby the EOS berths to one of the side-mounted modules and manipulates the engine into place.

Summary. In the case of the modular cislunar shuttle both approaches are feasible. The direct dock concept is preferred primarily because of the length of the manipulator required. Not only are the dynamics of a manipulator on the order of 100 feet long severe, but stowage in the EOS cargo bay will require a unique "fold back" design. If dual manipulator options can be employed or stationkeeping manipulator berthing operations developed, than manipulator assembly becomes a more attractive alternate.

Permanent Assembly Summary

The assembly of the MSS should impose no insurmountable design problems using either the direct dock or manipulator berth concept. Manipulators will provide some additional benefits if supplemental hardware must be installed.

The assembly of the cislunar shuttle is complex no matter which concept is selected. Direct docking will probably require non-common alignment techniques whereas the manipulator approach will require a very long reach. The most critical operation is the installation of the engine. The direct dock approach requires a special adapter. The manipulator approach (neglecting the length) is more straightforward and requires no unique hardware. All factors considered the direct dock is the preferred approach. It is believed that the special adapter is a much simpler design problem than a 100-foot plus manipulator.

Temporary Assembly

Two types of temporary assemblies are considered. The first type is the transfer of a single module to another element that will remain with the other element for a specific period and then be demated. The other type assembly is that of stacking a group of modules on a transport element for subsequent boost to a higher energy orbit.

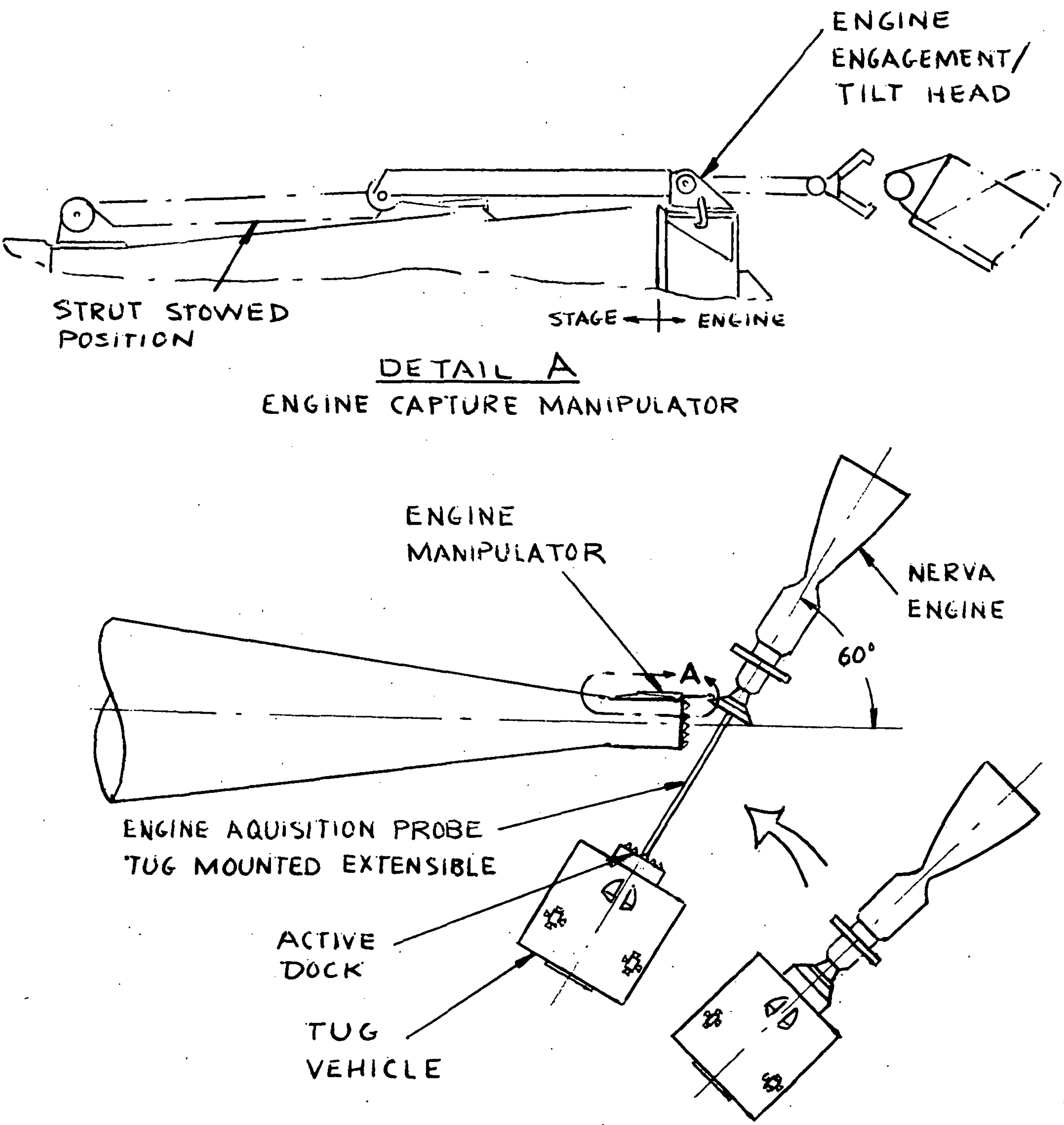


Figure 2-27. Engine Assembly Using Direct Dock/Capture Manipulator

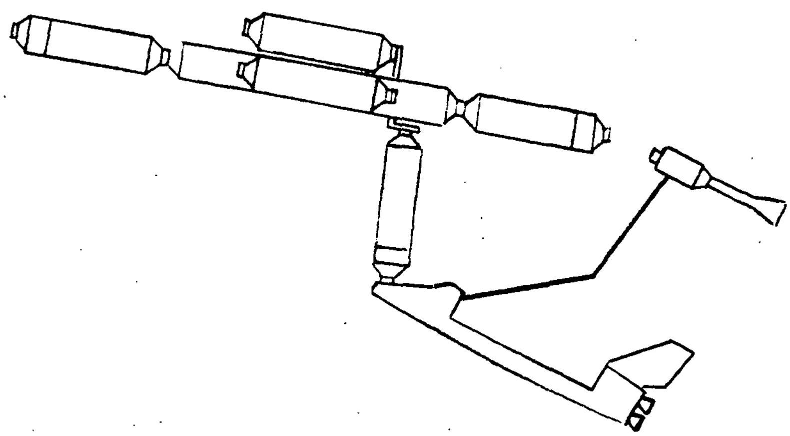


Figure 2-28. Engine Assembly with Manipulator on EOS

Single Module Transfer/Transport

The transfer of a single module can occur between two logistics vehicles and between a logistics vehicle and an assembly complex (i.e., MSS). The interchange of a module between two elements on the same port using direct dock requires that a holding port be available. The operation involves four dockings as shown in Figure 2-29.

A module exchange between an EOS and a tug can be operationally easier; however, it requires a second docking and pivotal device on the EOS. Figure 2-30 shows this operation.

Figures 2-31 and 2-32 illustrates these two previous operations using a manipulator.

MSS Modular Interchange. The interchange of modules on the MSS using direct docking requires about 1000 pounds of propellant above that of using the manipulator concept. However the payload weight of a manipulator will be greater than this propellant usage.

If module separation, manipulation, and berthing can be automated using the manipulator--and this is a viable concept, than manipulator interchange of modules should be a less hazardous task than the four dockings required to perform the same operation using the direct docking method.

One of the primary considerations in the evaluation of modular interchange is the potential frequency of this type of operation. In the case of all the orbital facilities the basic design goal is a minimum of ten years of operation before modular replacement is required. Elements such as the CPS or RNS do not

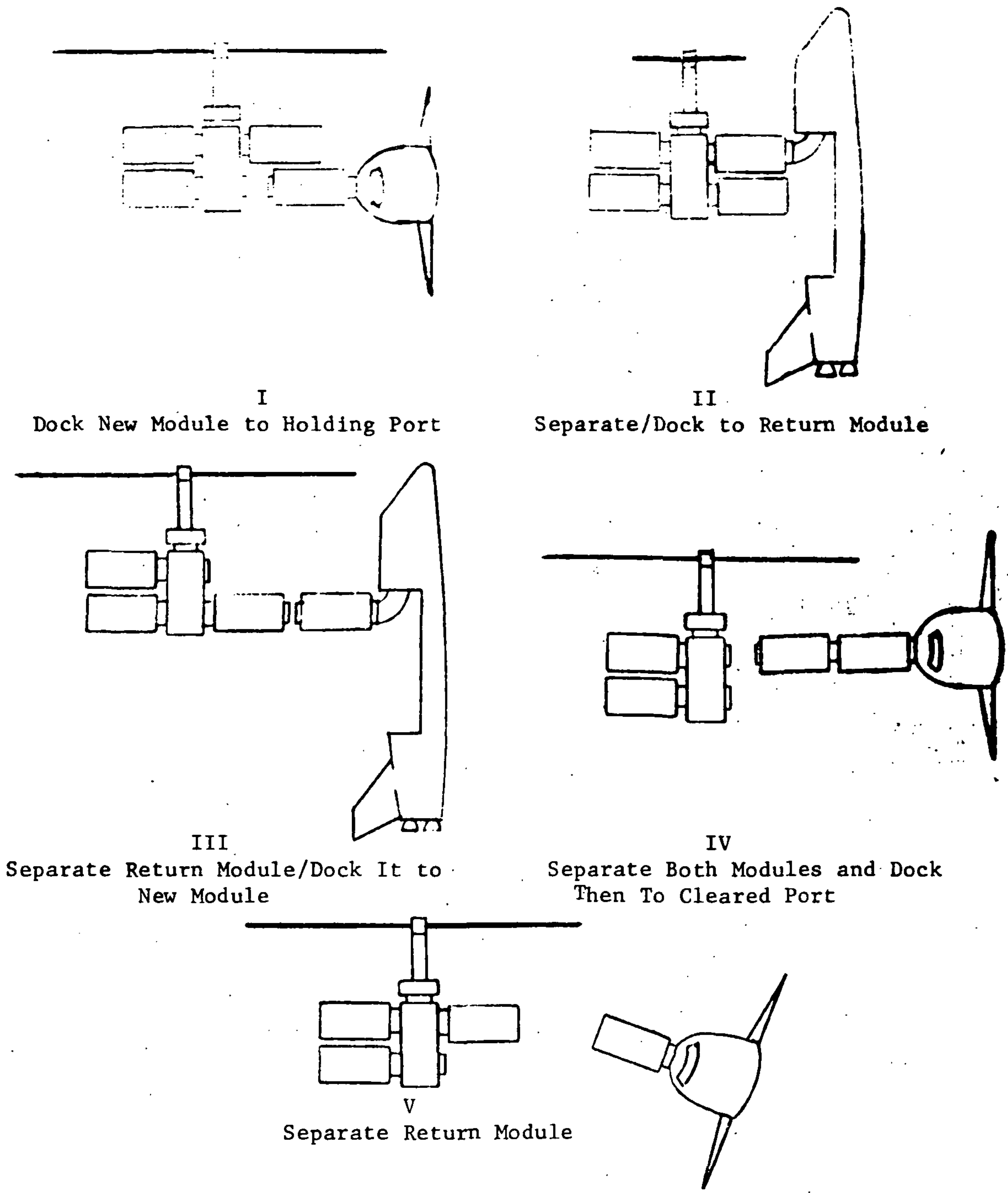
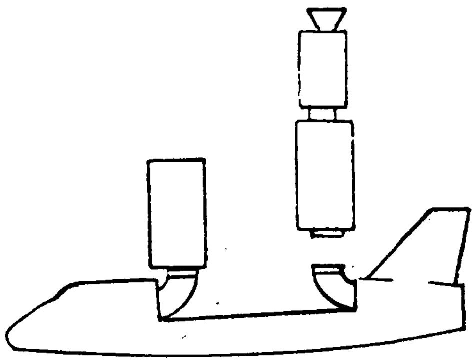
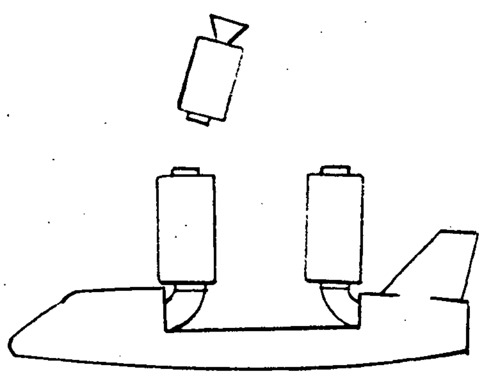


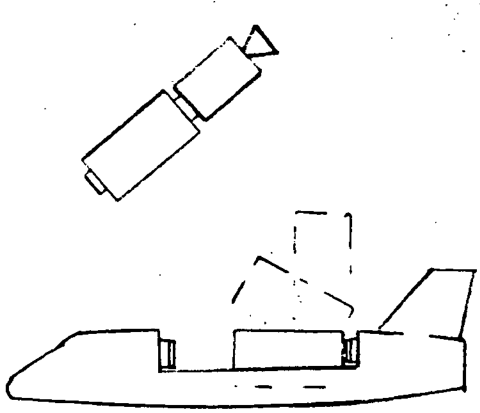
Figure 2-29. MSS-EOS Module Interchange at the Same Port Using Direct Dock



EOS erects new module and supplemental docking port. Tug docks return module to open port.

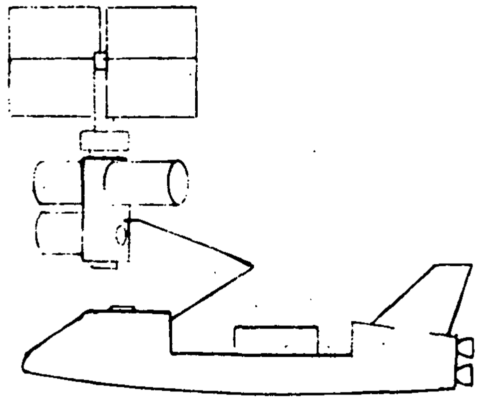


Tug separates and docks to new module.

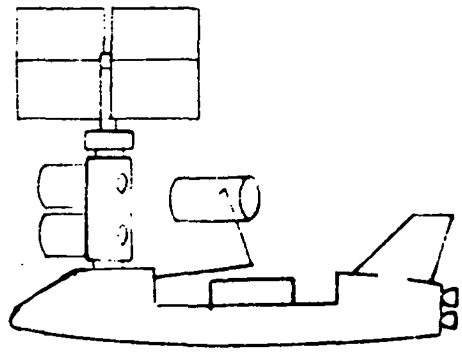


Tug separates with new module and EOS retracts module and cleared port.

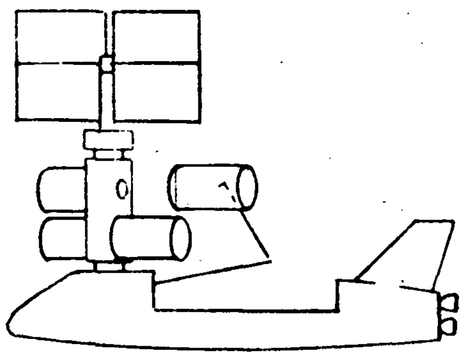
Figure 2-30. EOS-Tug Module Interchange Using Direct Docking



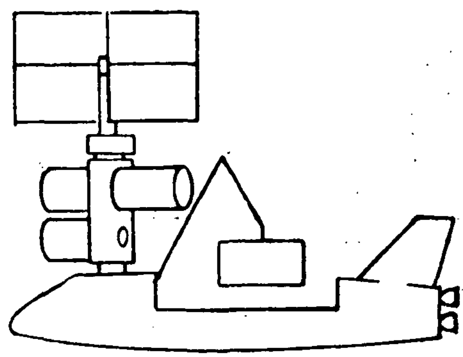
I
Berth EOS to MSS



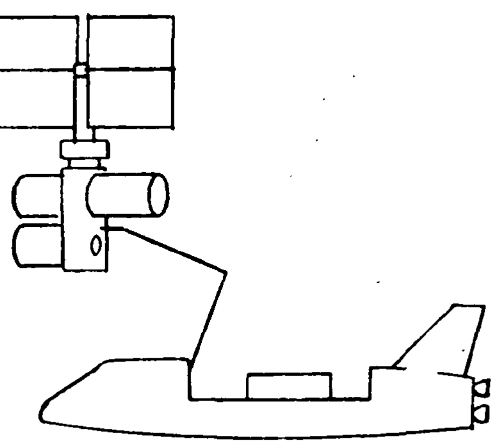
II
Separate Return Module/Berth it to Holding Port



III
Remove New Module from Cargo Bay/ Berth It to Cleared Port



IV
Remove Return Module/Stow in Cargo Bay



V
Separate EOS from MSS

Figure 2-31. MSS-EOS Module Interchange at the Same Port Using a Manipulator

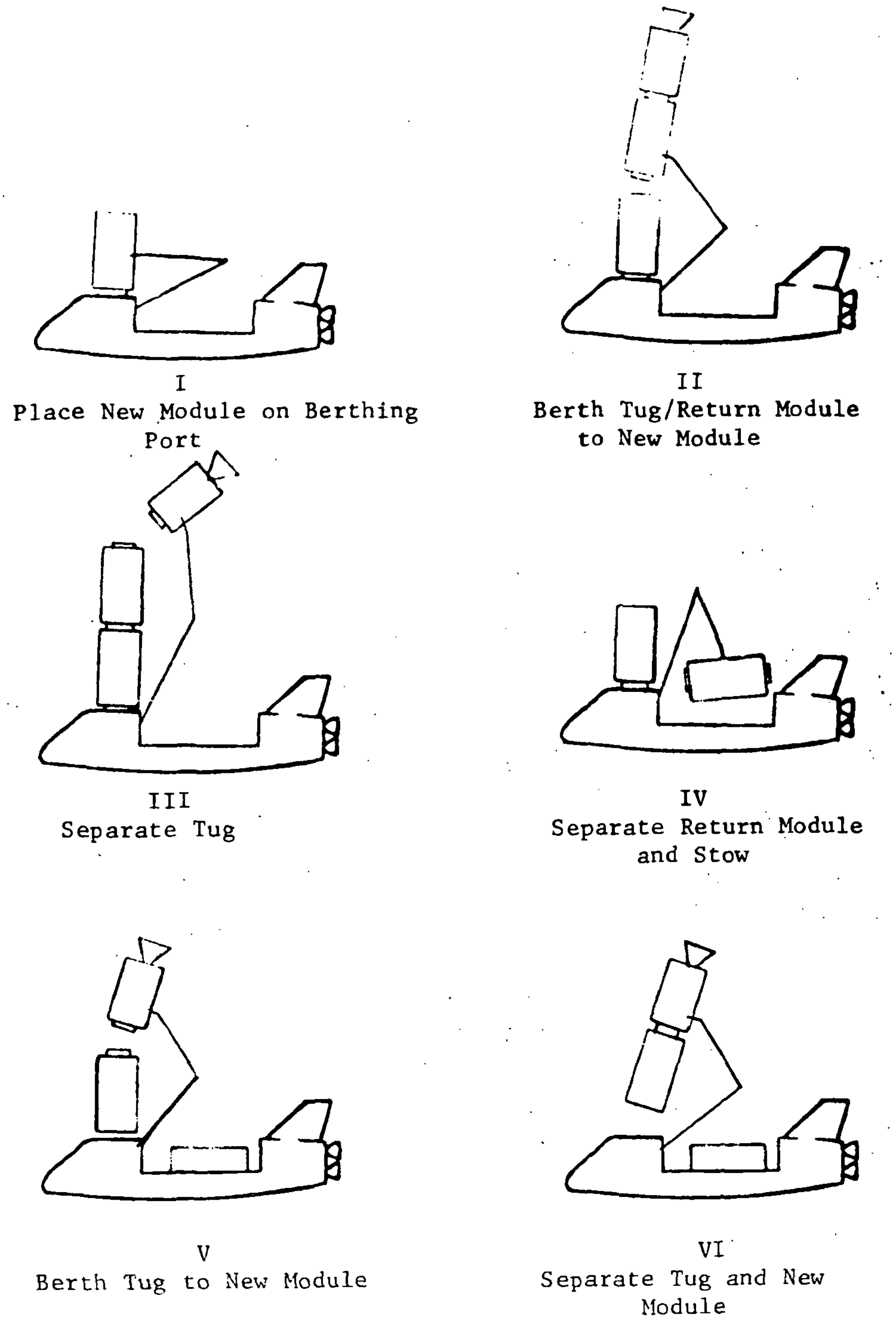


Figure 2-32. EOS--Tug Module Interchange Using a Manipulator

envision replacement of modules during the useful life of some five years. Thus, advantages/disadvantages of the two approaches to modular replacement do not significantly influence the preferred approach selection.

A second class of modular interchange is a relatively frequent occurrence. This is the normal logistics resupply operation to orbital elements by means of a resupply module. Two potential operations of this type are propellant tank exchange and cargo module exchange. The propellant tank exchange concept is analyzed in the propellant transfer activity. The operation is an alternate mode of resupplying an element (CPS or RNS) with propellant. The concept consists of the EOS orbiter delivering a full propellant tank to the CPS or RNS, removing the empty tanks from the CPS or RNS and installing the full tank. With direct docking, this concept requires a holding port and several dockings or the tank must be attached to another parallel feed point. Though this concept is viable, the propellant transfer activity did not select it from its alternates. Rather it selected fluid transfer from a logistics tank to the user element. Manipulator versus direct dock was not a major factor in the preferred approach selection. Cargo module transfer is a regular function that occurs between the MSS and the logistic elements. If the cargo module is interchanged at the same port, then the problem becomes one of four direct dockings or a manipulator with multiple berthing. The designs of the MSS's that have been investigated use dual cargo modules in the program that mate to different ports. That is, when a new module is delivered it is mated to an open port and remains there. The return cargo module is then picked up and returned. The open port is now available for the next routine resupply module. Because of this design, there is no preference for either the direct dock or manipulator concept.

Comparing a module interchange between the logistics elements using direct docking or manipulator results in determining whether or not the addition of the second pivotal and docking port is less costly than developing a manipulator with a reach capable of capturing a tug and stacking it on an extended module. This reach will be in the range of 100 feet.

Tug-EOS Modular Interchange. Figures 2-30 and 2-32 illustrated the direct dock and manipulator concepts for interchange of modules between the tug and the EOS. The direct dock concept requires two docking ports. The manipulator concept requires a berthing port and a manipulator length of approximately 100 feet. The advantages and disadvantages of each tug-EOS interchange concept are essentially the same as the corresponding concepts for MSS modular interchange. The frequency of the operation is relatively low especially as a result of the conclusion reached in the analysis of propellant transfer. If the EOS replenishes cislunar shuttle and the MSS directly, the tug-EOS interchanges are drastically reduced.

Figure 2-33 illustrates a combined direct dock-manipulator concept. The "berthing" port on the EOS is strengthened sufficiently to accept the transmitted direct docking loads of the tug through the replacement module. The manipulator length is appreciably reduced thus making it more realizable.

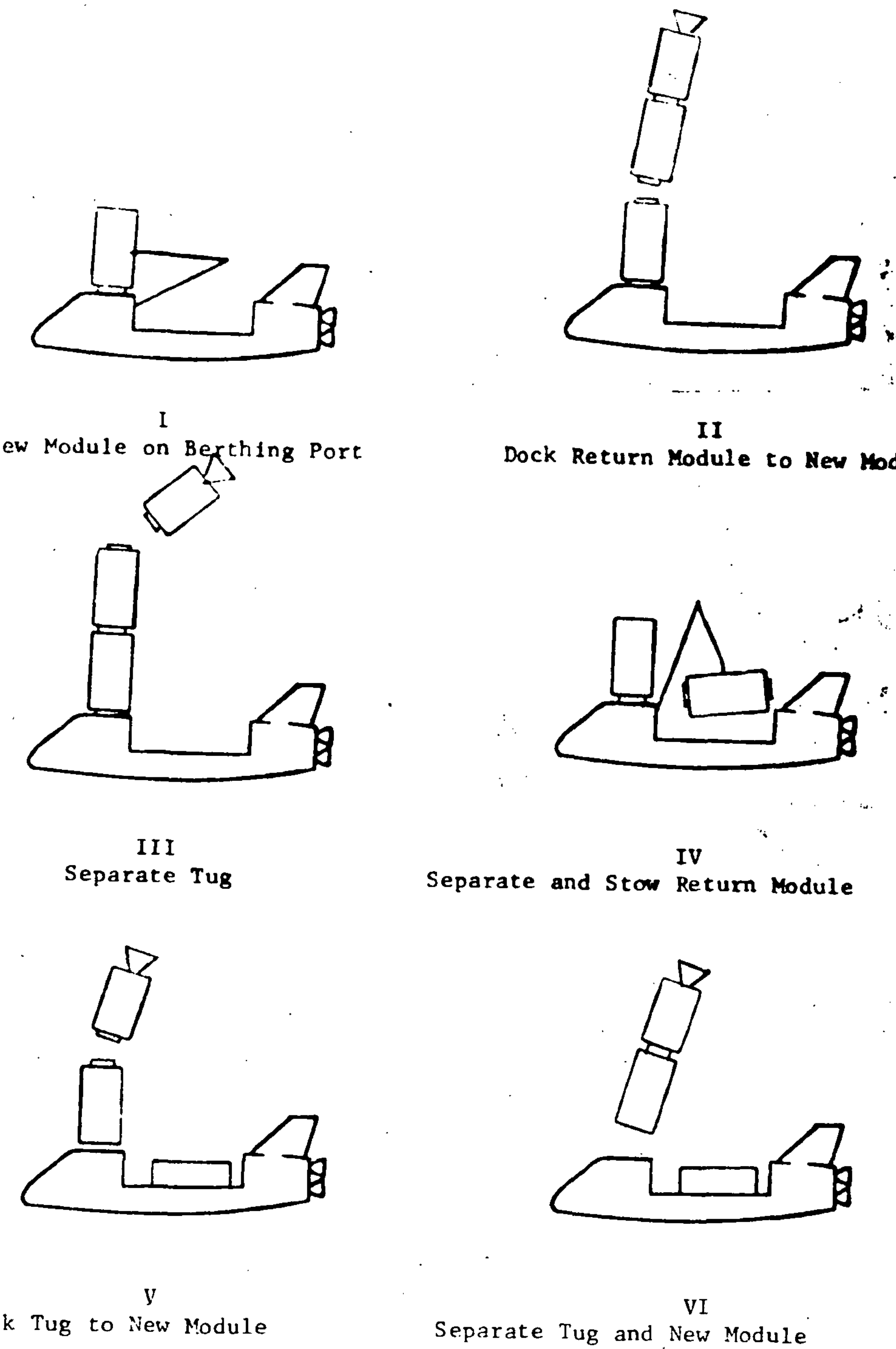


Figure 2-33. Direct Dock/Manipulator Utilization for Module Interchange

This combined concept is introduced to achieve a degree of commonality across interfacing activities. Mating preferred direct docking but also noted a recommendation for both direct docking capability and a manipulator on the EOS. Similarly, EOS payload deployment and retraction recommended the direct dock pivotal mechanism with the manipulator identified as a required kit installation. The selection of direct docking or manipulator berthing is inconclusive for tug-EOS payload interchanges. If a combination manipulator-direct dock capability is available, it would be recommended.

Multiple Module Transfer/Transport

The assembling of an element on an orbiting logistics element (cislunar shuttle) for transport to a higher energy orbit is concerned with the loads the assembly will be exposed to during thrusting maneuvers. The RNS and CPS elements are the prime cislunar shuttles identified. The RNS is of less concern because it does not impose very high acceleration loads on attached elements. The CPS on the other hand will generate acceleration loads on the order of 2.5 g's. The worst case elements for transport to the higher energy orbits are geosynchronous MSS and the OLS. Both of these elements are all similar in design; therefore, only one--the OLS will be considered.

Assembled Attachment. Two options for stacking the OLS on the booster element are available. The OLS can be placed on the boost element in the fully configured assembly with some sensitive exceptions (i.e., solar arrays retracted) or the OLS can be stacked on the booster in a disassembled state. The decision is one of compatibility with the acceleration loads. If the fully configured element is placed on the booster element, the stack will appear somewhat like that shown in Figure 2-34

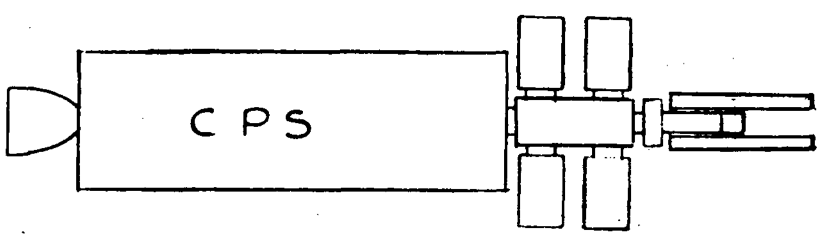


Figure 2-34. MSS Assembly Stacked on CPS

The problem with this design are the loads applied on the OLS appendages and at appendage mating ports. If the modules are not designed to withstand the bending load or the mating port is subject to separation due the applied load, then supplemental structure or rigidizing techniques must be employed that will support these loads. Attached element transport analyses indicated that in the case of the CPS and assembled OLS, bending moments as high as 12M inch-pounds would be experienced.

Supplemental structural design could be built into the attachment points of the module, but practical limitations will require additional external rigidization.

Figure 2-35 illustrates two design concepts that could be employed. Each of these concepts can be installed with a manipulator but only "B" is applicable to the direct dock approach. It requires five additional dockings and an automated tension strap mechanism or EVA operations.

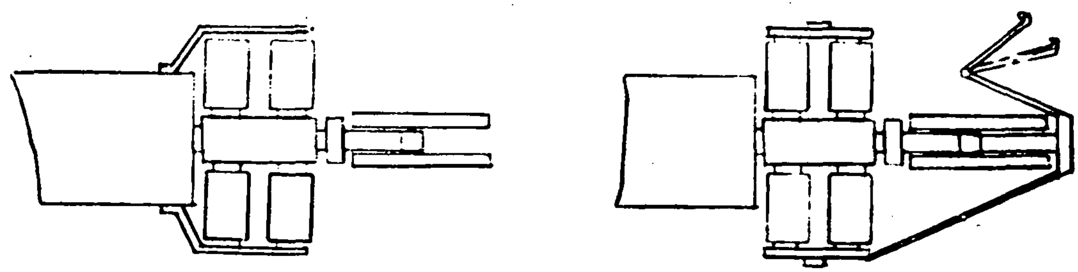


Figure 2-35. Add-on Rigidization

Disassembled Attachment. By stacking the modules in an unassembled manner, only direct dock is applicable. If the manipulator were used, additional berthing ports would be required and the length of the manipulator again would exceed 100 feet.

A special docking adapter is required for stacking of modules. The details of the adapter are discussed in the attached element transport section. It consists essentially of three "beams" docked one on top of the other at successive 60 degrees offsets. Each beam has three in-line docking ports. The two outboard ports are pivotal to facilitate attachment of modules. The "underside" of the beams that form the base of the second tier also have docking ports in order to "cap" and rigidize this module in the first tier. The entire sequence is illustrated in Figure 2-36.

As discussed in attached element transport, several multi-port adapters were evaluated. Designing an adapter that multi 15-foot diameter modules will be docked to and yet can be delivered to orbit in the 15-foot diameter EOS cargo bay severely restricts the viable concepts.

Preferred Multi-Module Transport Assembly. Although the CPS was used in the example because of the high acceleration levels of this element, similar problems arise when the LSB is considered regardless of the transport element used. The LSB cannot be assembled in earth orbit. It must be "stacked" on the cislunar shuttle. Therefore, it would not be practical to develop external rigidizing design concepts to accommodate an assembled OLS or a geosynchronous MSS that could not apply to the LSB. The stacking concept is preferred. This presents a singular development of a rigidizing concept such as the multi-beam design identified above.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

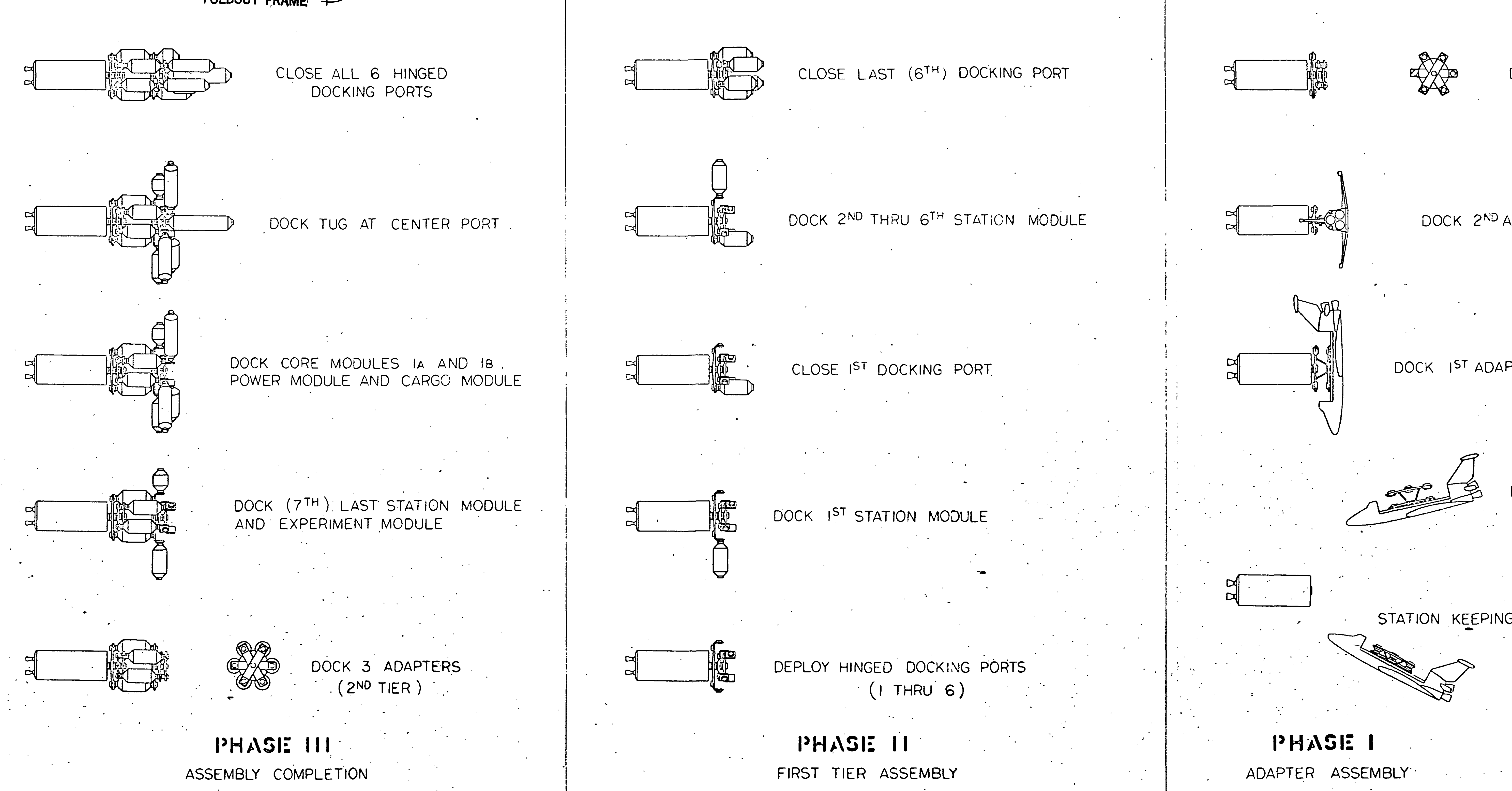


Figure 2-36

PP. 2-69/2-70

CISLUNAR SHUTTLE PAYLOAD ASSEMBLY

Summary of Temporary Assembly Operations

Single module exchange or interchange did not show a strong preference for either of the two concepts. The final recommendation was a combination of the direct dock and the manipulator approach. Multi-module temporary assembly did illustrate a preference for the direct dock concept. This activity as in other activities such as mating, separation, EOS payload deployment, and EOS payload retraction favored the direct dock concept for almost all on-orbit operations. However, the manipulator was either required or highly desirable for various unique operations. It was pointed out that either concept could be adapted to the tasks required but in certain cases the penalties would be large and the designs extremely complex and costly. Therefore, the integrated preferred approach is a combination pivotal direct dock and manipulator. Based solely upon frequency of applicable operations, the direct dock is preferred as the baseline.

POST-MATING ACTIVITIES

The alternates for post capture rigidization and utilities interconnect are automatic, manual shirtsleeve, and manual IVA. As noted previously, post capture rigidization is not required because mating port designs are such that they provide the necessary rigidization without supplemental hardware. Therefore, this section shall limit the discussion to connection of interfacing electrical and fluid lines. Table 2-5 is a list of various factors by which each of the alternates can be compared in an attempt to identify if any alternate is superior or generally inferior.

Technology

Shirtsleeve and IVA connection of interfaces is present state of the art. Standard connectors and couplings are available and can be considered as off-the-shelf hardware. Automatic interfacing configuring will require some development for space activities; however, the concepts are available. Automatic interconnecting of connectors and couplings is an everyday routine (electronic units are continuously removed and replaced with the connectors automatically engaging). Mechanisms for forcing the engagement of two assemblies should impose no problem and alignment can be achieved using various standard techniques.

Checkout and Maintenance

Manual shirtsleeve interfaces will impose no problem for checkout. Connectors and couplings can be inspected visually for proper mate. The connectors and couplings can easily be opened, continuity checked, or leak checks performed on fluid couplings as necessary. Test equipment can also easily be installed such that in-depth analysis of the problems can be ascertained. Maintenance on connectors and couplings will be somewhat more difficult than ground operations because of the environment. However, if the interfaces are relatively non-complex, than connector replacement, seal replacement, and simple assembly should not impose any problem. IVA checkout should be no more difficult than shirtsleeve checkout except that clearance to the interfaces and visual capabilities will be hampered by the IVA suit. Maintenance in an

Table 2-5 . Alternate Comparison

Comparison Factor	Alternatives: Shirtsleeve	IVA	Automatic
Technology	Preferred state of the art	Acceptable--some development required	Acceptable--some development required
Checkout/maintenance	Preferred	Acceptable--for checkout, less acceptable for maintenance	Acceptable--for checkout, not acceptable for maintenance
Relative cost	Low	Low-medium	High
Commonality	Least preferred	Preferred--common with shirtsleeve	Least preferred
Safety	Acceptable	Least preferred	Acceptable
Frequency of activity	Preferred	Acceptable--if other IVA activities are required	Acceptable
Reliability	Preferred	Acceptable	Acceptable
Near term bias	Preferred	Acceptable	Least preferred
Far term bias	Preferred	Acceptable	Acceptable

IVA environment will be difficult and much more limited than shirtsleeve maintenance. Automatic concepts will have to be verified remotely which will require extensive measurement techniques. Maintenance will require IVA at the very least and will be much more entailed than IVA-shirtsleeve interfaces. This study recognizes checkout as being feasible for automatic systems, but maintenance is not acceptable. Automatic systems will have to be made more reliable by using long-life parts or providing sufficient redundancy.

Relative Cost

The shirtsleeve interfaces will be the least cost to configure. Common hardware and common techniques can be employed. IVA hardware will be somewhat more costly because placement must be more selective and parts must be manufactured that can be used with a gloved hand. The cost of automated systems will not be competitive with the shirtsleeve or IVA option. Development of the hardware, installation, testing, and providing reliability will all exceed the costs of the manual systems.

Commonality

IVA concepts will provide the most commonality because IVA hardware can be utilized for shirtsleeve operations. Automatic techniques will be designed dependent upon the type of interfaces to be connected, the number of connections involved, clearance available, and number of times the connection must be made. Therefore, even automatic systems between elements will not provide common design. Common techniques in most cases could be implemented, but the actual hardware will be tailored to the particular element interfaces. Interfaces for a singular element will vary (i.e., the interface between a space-based tug and a detached RAM will not be the same as the interface between the space-based tug and an earth orbital cargo module) such that a single identical design can be derived. Typical designs that utilize common hardware, however, could be developed. For instance, a single connector on the space-based tug could use particular pins in the connector for interfacing with the detached RAM and other pins for interfacing with the cargo module. A goal should be to develop and locate hardware that will result in the most common interface design between elements. Such a design may appear as shown in Figure 2-37.

If interfaces are controlled only to this extent, elements will at least be capable of plumbing and routing lines such that the interface between various elements can be made with a minimum of intertwinning cables. With manual mating techniques, common interfaces can be much more readily designed.

Safety

The most unsafe activity has to be the IVA operations. The possibility of suit failure or damage to the suit during the assembly operation can result in loss of a crewman; therefore, this mode of operation is considered least preferred. Because both of the other concepts, manual shirtsleeve and automatic connection can be designed for safe operations, they are preferred and considered equivalent.

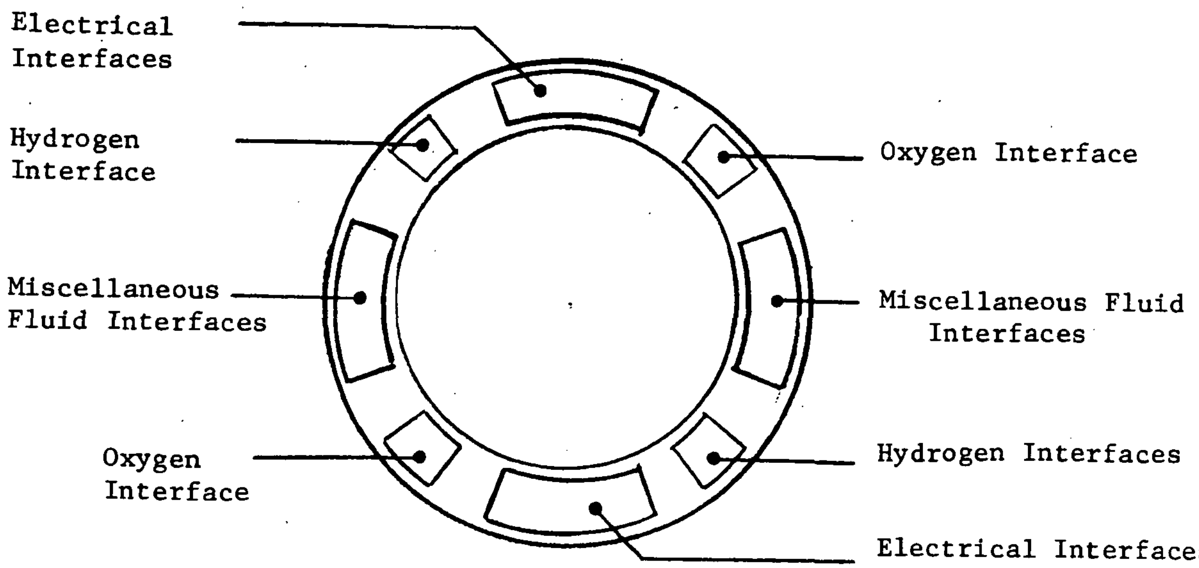


Figure 2-37. Example of Controlled Interface Arrangement

Frequency of Activity

Frequency of activity has to be related to the number of interconnects to be made. Except for the module interfaces within the MSS and OLS complexes, the interfaces between other elements will not be extensive. At the most, four electrical connectors and perhaps four to six plumbed lines would be the total complement.

Usually automatic systems are considered the best technique for operations that are performed on a routine basis. But, because of the uniqueness of the various interfaces and because of the few connections to be made, where shirt-sleeve access is available, it is the preferred approach. Where IVA would have to be employed for some other operation, it would be selected over automatic.

Reliability

Between shirtsleeve and IVA, reliability should be equivalent in that the connectors and couplings will essentially be identical. Shirtsleeve operations should be somewhat more reliable in that better feel and visual clarity is enhanced. Automatic systems provide reliability in the connector mating; however, the automating mechanism to effect the mate is less reliable than a manual operation. For this study shirtsleeve is considered preferred with IVA and automatic acceptable.

Near Term Bias

The various comparative factors indicate that the shirtsleeve operation is the preferred option or equivalent in all cases except commonality. The reason the shirtsleeve fails in this category is that IVA operations will at times be required and shirtsleeve hardware is not compatible with IVA. The functional requirements sections identifies a contingency requirement which states that shirtsleeve interconnects shall be IVA compatible. Because of of this requirement, the uncommonality between shirtsleeve and IVA is considered academic and the comparison should pertain only to the operational aspects not the hardware. For unmanned assembly neither shirtsleeve or IVA will be used and automatic is required. Automatic designs would not be acceptable for interfaces such as the assembly of modules on the MSS where a multitide of connectors and couplings must be mated in very restrictive areas. For most matings of element pairs, if a manned element is one of the elements, the mating port design is such that upon mate an inherent seal is formed protecting the interface from the space environment. The design also provides access for a crewman to the connectors. Because of this characteristic it is preferred that the interface be made by shirtsleeve. If the interface is exposed to the space environment, but an airlock at the interface will allow a crewman to enter this environment within the confines of the mating port, then IVA is preferred over automatic.

Far Term Bias

There is no reason to expect shirtsleeve preferences to change, however, with the development of common hardware designs and increased missions, automatic interconnect techniques could become more common such that on-orbit interfacing assembly time can be used more efficiently for other operations. Therefore, the far term bias selects the shirtsleeve approach where available and considers IVA and automatic acceptable and equivalent.

SUMMARY OF SELECTED CONCEPTS

Initial Mating Activities

Neither the permanent assembly operations nor the temporary assembly operations could identify a driving requirement which eliminated either the direct dock approach or the manipulator berth approach as a method for performing the assembly tasks. Both operations did identify some synergistic benefits that would result if a manipulator were available. However, the reach requirements that would be imposed on a manipulator could tend to drive the state of the art. Because all assembly operations can be performed using direct dock, and because there is some doubt that a manipulator can support all operations, on a commonality basis alone, the direct docking approach is preferred. If the manipulator reach criteria does not impose the problems that it appears it will, then the manipulator would probably be favored.

Post Mating Activities

The preferred approach is shirtsleeve hookup of utilities for all manned elements if the interface is accessible. Automatic concepts should be used only on unmanned to unmanned assembly pairs.

DESIGN INFLUENCES

Initial Mating Activities

If the manipulator concept is selected, then the various candidate assembly elements will be designed with berthing ports and will be equipped with manipulator end effector receptacles. The MSS designs can select berthing parts on both ends of modules or on a singular end as it benefits the configuration and not the mating operation. The EOS orbiter and the manned space-based tug are the only elements that are recommended for inclusion of a manipulator.

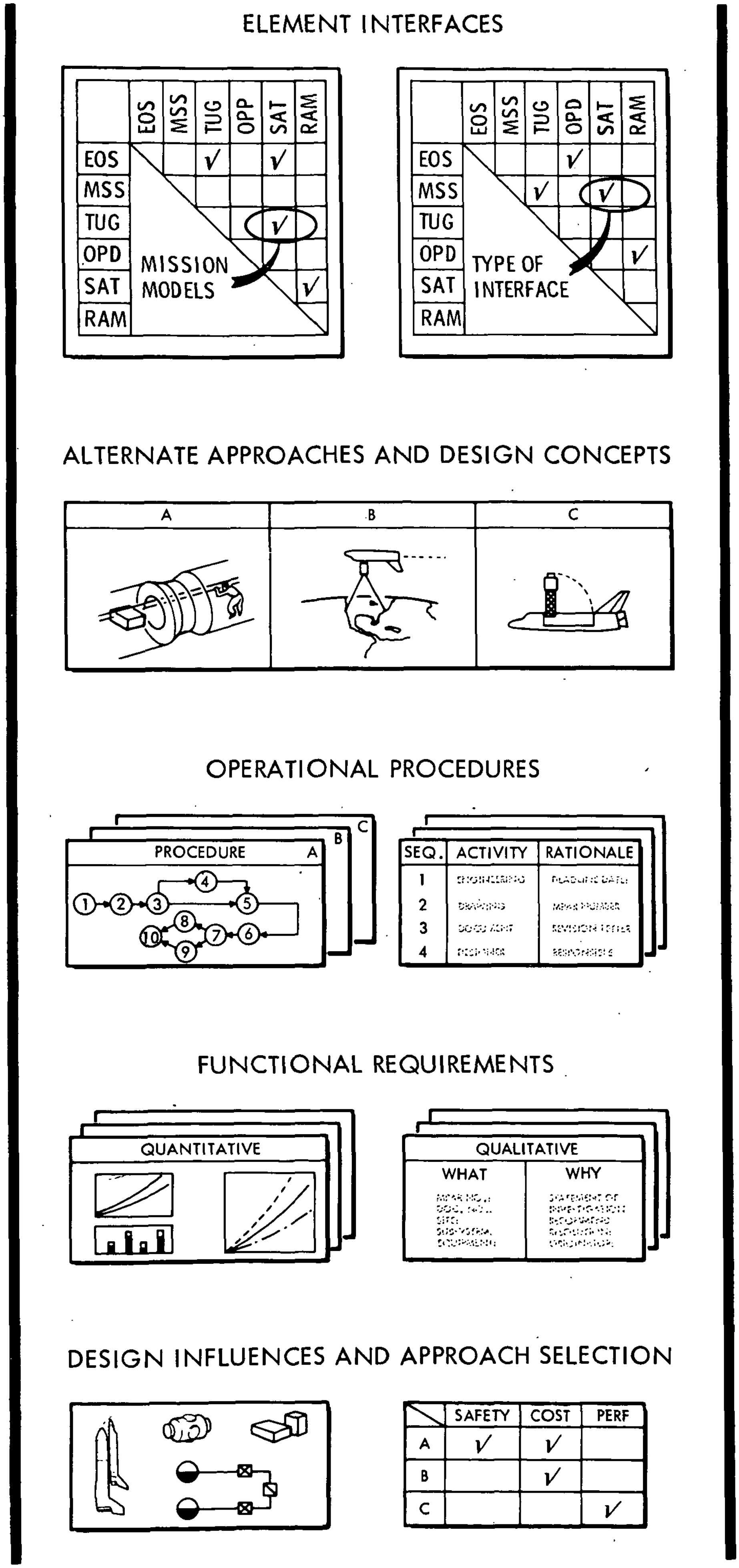
If the direct dock concept is selected, the various candidate elements will be equipped with direct docking ports. Laser radar transceiver will be required at the module assembly interface and passive radar reflectors on the other element. An option is to locate the laser radar transceiver in the EOS orbiter and space-based tug such that viewing will be up the side of the modules. Passive reflectors would then be located on the mating element such that the radar transceiver could detect them and, using triangulation methods, determine alignment at the docking ports.

Multiple docking adapters or rigidizing hardware will be required to support temporary matings of assembly complexes on cislunar shuttles.

Post Mating Activities

Shirtsleeve connection designs should be implemented for all permanent element assemblies except the CPS, RNS, and OPD. The CPS, RNS, and OPD elements require automatic techniques for interconnecting the modules. The OPD may be such that intermodule travel can be performed. If this is so, than IVA or shirtsleeve interconnects are acceptable.

Temporary assemblies which will have shirtsleeve interconnects are those involving the MSS DRAM and earth orbital resupply modules. Geosynchronous MSS and OLS which interface with the CPS and RNS for boost to higher energy orbits could have utility hookup requirements, although they will be small (one or two connectors). This interface can be made automatic. The only interface that is definitely an automatic interface is that which involves an unmanned space-based tug and a temporarily attached payload. The necessity for providing a utility interface between the unmanned space-based tug and the payload has not been defined at this time (appears questionable). The one exception is during the propellant transfer operation involving the refueling of the tug. This interconnection must be automated for both electrical and fluid interchanges.



3.0 SEPARATION

3.0 SEPARATION

The separation activity for this study is applicable only to elements that interface at a mating port. The activity includes prerelease events (disconnect of electrical and fluid interfaces, checkout of separation systems, hatch sealing, etc.), release (physical uncoupling of the elements from the mating port), and separation maneuvers required to provide clearance between the vehicles such that the elements can perform independent operations.

3.1 SUMMARY

From the total list of elements identified for this study, there are 117 combinations that exist where one or more element-to-element interfaces occur. Of these, all but two can involve a separation activity. For this study 11 representative mission models were developed to clarify the interrelationships between the various program elements. Of these, only one mission did not involve a separation activity. Paragraph 3.2 expands on these interfaces and provides matrices which identify the interfacing pairs and applicable missions.

Four alternate approaches were visualized for separation: (1) jet translation which utilizes jet thrusting to separate the mated elements, (2) mechanically imparted thrust which utilizes some mechanism that can store energy in a mechanical form and release it upon command to impart a separation thrust between the elements, (3) combination (mechanically imparted thrust and jet translation, and (4) mechanical extension (manipulator) which physically separates the elements utilizing some type of extension arm.

Two of these alternatives were eliminated from the analyses. The mechanically imparted thrust and the combination methods were considered to be less viable for universal usage than the other two concepts. Paragraph 3.3 expands on the selected and rejected alternate approaches.

Paragraph 3.4 identifies design concept models for a manipulator, jet translation alignment aids, and the communication interfaces between representative separating elements. These models are essentially the fallout of the conceptual approaches for performing the separation activity. For a model to be valid it must conform to the requirements and procedures.

Three procedures were developed for performing separation and are presented in Paragraph 3.5 and Appendix B. These three procedures are applicable to five different separation concepts: (1) manned element jet translation separation from a manned element, (2) manned element jet translation separation from an unmanned element, (3) unmanned element jet translation separation from an unmanned element, (4) manned element manipulator separation from a manned element, and (5) manned element manipulator separation from an unmanned element. At least one of the five separation concepts is applicable to any of the element-to-element separation interfaces identified.

Paragraph 3.6 identifies the functional requirements applicable to the separation activity. The requirements are presented in two formats. The first format lists the requirements with their applicable parameters and the rationale justifying the requirement. The second format lists the requirements in an abbreviated form and cross references them to the applicable element pair. In most cases, the requirements are generic in that they apply equally to any orbital separation operation. However, some are directly related to either the jet translation alternative or the manipulator separation approach.

The requirements are essentially developed around four categories: (1) active operations which includes alignment criteria, separation distances, and mating port and manipulator dynamics, (2) monitoring and sensing activities which includes requirements for systems verification, separation sensing, alignment knowledge, and communications, (3) pre-separation activities such as tunnel depressurization, interface disconnecting, and alignment of inertial measurement systems, and (4) general criteria such as jet plume impingement control, backup criteria, and illumination. Where applicable, the requirements have been quantified.

The preferred approach for separation is selected in paragraph 3.7. The approach selection is essentially made by first analyzing the alternatives, jet translation and manipulation, as they apply solely to the separation activity. The results of this analysis were then evaluated for synergism by comparing the selected concept against the selected concepts of other activities. These two evaluations resulted in the selection of the jet translation approach for separating the various element pairs. The manipulation approach was rejected because its high cost outweighed the separation benefits gained. If the manipulator were selected for other programmatic reasons it would be fully suitable for the separation activity.

The final paragraphs list the design influences as they apply to the various elements to support the jet translation separation approach.

3.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

Figure 3-1 lists all the study elements and identifies in matrix form the potential separation interactions. The matrix identifies 117 potential interactions of which 115 involve the separation activity. The two that do not are the RAM attached to the EOS orbiter and the nonreusable, but returnable, tug-satellite interface. Both of these interfaces, by definition, are non-separable interfaces.

Because the EOS orbiter and the tug vehicles are primarily logistics vehicles that are involved in mating activities with almost all of the identified elements, it follows that separation activities would be involved in the same missions; the matrix concurs with this assumption but also adds one additional separation; the EOS orbiter and nonreusable tug interface includes a separation interaction but does not include a mating activity because this type tug is never recovered.

Except for the RAM attached to the EOS orbiter, which by definition is not separated, RAM's are periodically separated from their supporting elements. RAM's may separate independently (utilizing internal controls), be assisted (utilizing a third logistics element), or the element to which the RAM is attached can perform the separation activity.

Satellites are almost always separated from their delivery elements. The single exception is the returnable tug used as a third stage for the EOS + third stage satellite (returnable, nonreusable tugs, by definition never separate from their payload).

Earth orbital resupply modules are designed to be shuttled between earth and orbiting elements. The transporting element will always be one or more of the logistics vehicles. Because resupply modules are not limited to low earth orbital missions, separation activities will occur between the high-energy orbit delivery elements (CPS or RNS) and the resupply module. This operation has the resupply module separating from the logistics vehicle after it is transported to the CPS or RNS. Separations between the resupply module and the CPS or RNS occur both on return from the higher orbit and when the resupply module is delivered to its intended destination in the higher orbit (i.e., geosynchronous MSS).

Low earth orbital MSS separation activities include modular disassembly, cargo module logistics support, RAM support, and EOS orbiter support activities. The geosynchronous MSS involves all of the low earth orbital separation activities and adds the separation interaction with the EO shuttle and the RNS. This latter activity normally occurs after delivery of the complex to the geosynchronous orbit but also can occur in low earth orbit, if for some reason after mating the delivery vehicle does not check out for the boost operation.

The CPS orbital insertion stage (OIS) is utilized to deliver heavy payloads to low earth orbit that cannot be transported by an EOS orbiter. The RNS and other CPS elements (EO shuttle and CLS) are used to transport heavy payloads from low earth orbit to higher energy orbits. The single separation interface between the OIS and the space-based tug occurs if the OIS requires

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	S	S	S	S	S	X	S	S	S	S	S	S	S	S	S		S	S	S	S	S	S	S	S	S
TUG	NON RET											S														
	RETURNABLE											X														
	GRD BASED				S	S			S	S		S	S	S		S		S	S	S		S	S	S		S
	SPACE BASED					S			S	S		S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
RAM	ATT. EOS																									
	DET. EOS																									
	ATT. MSS														S	S		S		S						
	DET. MSS														S	S		S		S						
SATEL	EOS DELIV																									
	EOS + 3RD ST																									
	RETR, RESUP																									
	EO RESUP MODS													S	S	S		S	S	S		S	S	S		S
MSS	LOW EO														S											
	GEOSYNCH															S		S		S						
CPS	OIS																	S	S	S	S					S
	EO SHTL																	S								S
	CLS																		S		S	S	S	S	S	S
	RNS																			S	S	S	S	S	S	S
LPS	OLS																				S	S	S	S		
	TUG UNMAN																							S	S	S
	TUG MAN																							S	S	S
	RESUP MOD																							S	S	S
	LSB																								S	
	OPD																									S

LEGEND

Potential Interactions	117
Actual Interactions	115
S - Separation	115
X - Not Applicable	2

Figure 3-1. Separation Interactions

support for delivery to a particular parking orbit or for disposal assistance. The RNS, EO shuttle, and the CLS vehicles would separate from any element they deliver to a higher energy orbit. In addition, these elements can be multi-stage elements that can be mated and separated in low earth orbit.

Lunar program systems are delivered either directly to the low earth orbital assembly station by the EOS orbiter, or the delivery can be assisted using the space-based tug.

The ground-based tug utilized as a tanker would deliver propellant to the lunar tugs and resupply modules. Each of these operations involve separation activities as indicated by the matrix.

The OPD is involved in separation activities whenever a refueling operation has been accomplished. The matrix identifies those elements that support the facility or can utilize its refuel capability. The OPD itself can be modularly disassembled.

Figure 3-2 utilizes the same matrix format that was used to identify the separation interfaces and identifies the applicable missions from the 11 generic missions developed in Volume I of this document where the separation activity can occur. It is apparent that all missions except Mission 3 can utilize the separation activity. Mission 3 is an EOS orbiter sortie mission where a shuttle orbiter delivers an experiments payload to earth orbit, the orbiter remains attached to the payload throughout the experiment operations and then returns the payload to earth.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	2	1	1	1,2,7,8	1,2,4,5	X	1,2	2	1,2	1,2	1	1,2	2	1,2	1,2		1,2	1,2	1.2	1,2	1,2	1,2	1,2	1,2	
TUG	NON RET											1														
	RETURNABLE											X														
	GRD BASED				8	8			7,8	7,8		7	7,8	8		7,8		7,8	7,8	7,8		7,8	7,8	7,8		7,8
	SPACE BASED					4,5			5	4,5		4	4,5	5	5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
RAM	ATT. EOS																									
	DET. EOS																									
	ATT. MSS														2,4,5	2,4,5		2,4,5		2,4,5						
	DET. MSS														2,4,5	2,4,5		2,4,5		2,4,5						
SATEL	EOS DELIV																									
	EOS + 3RD ST																									
	RETR, RESUP																									
	EO. RESUP MODS													2,4,5,8	2,4,5,8	2,4,5,8		2,4,5,8	2,4,5,8	2,4,5,8		2,4,5,8	2,4,5,8	2,4,5,8		2,4,5,8
MSS	LOW EO														1,2,4,5,8											
	GEOSYNCH															1,2,4 5,8		9,2,4,5		2,4,5						
CPS	OIS																	9	9	9	9					9
	EO SHTL																	2,4,5, 6,9,10								10
	CLS																		2,4,5, 6,9,10		2,4,5,	2,4,5	2,4,5	2,4,5	2,4,5	10
	RNS																			2,4,5,6	2,4,5	2,4,5	2,4,5	2,4,5	2,4,5	11
LPS	OLS																				2,4,5	2,4,5	2,4,5	2,4,5		
	TUG UNMAN																							2,4,5	2,4,5	2,4,5
	TUG MAN																							2,4,5	2,4,5	2,4,5
	RESUP MOD																							2,4,5	2,4,5	2,4,5
	LSB																								2,4,5	
	OPD																									2,4,5

Figure 3-2. Applicable Mission Models for Separation

3.3 ALTERNATE APPROACHES

Four alternate approaches are visualized for separation: (1) jet translation, (2) mechanically imparted thrust, (3) combination (mechanically imparted thrust and jet translation), and (4) mechanical extension. Figure 3-3 generically illustrates these concepts.

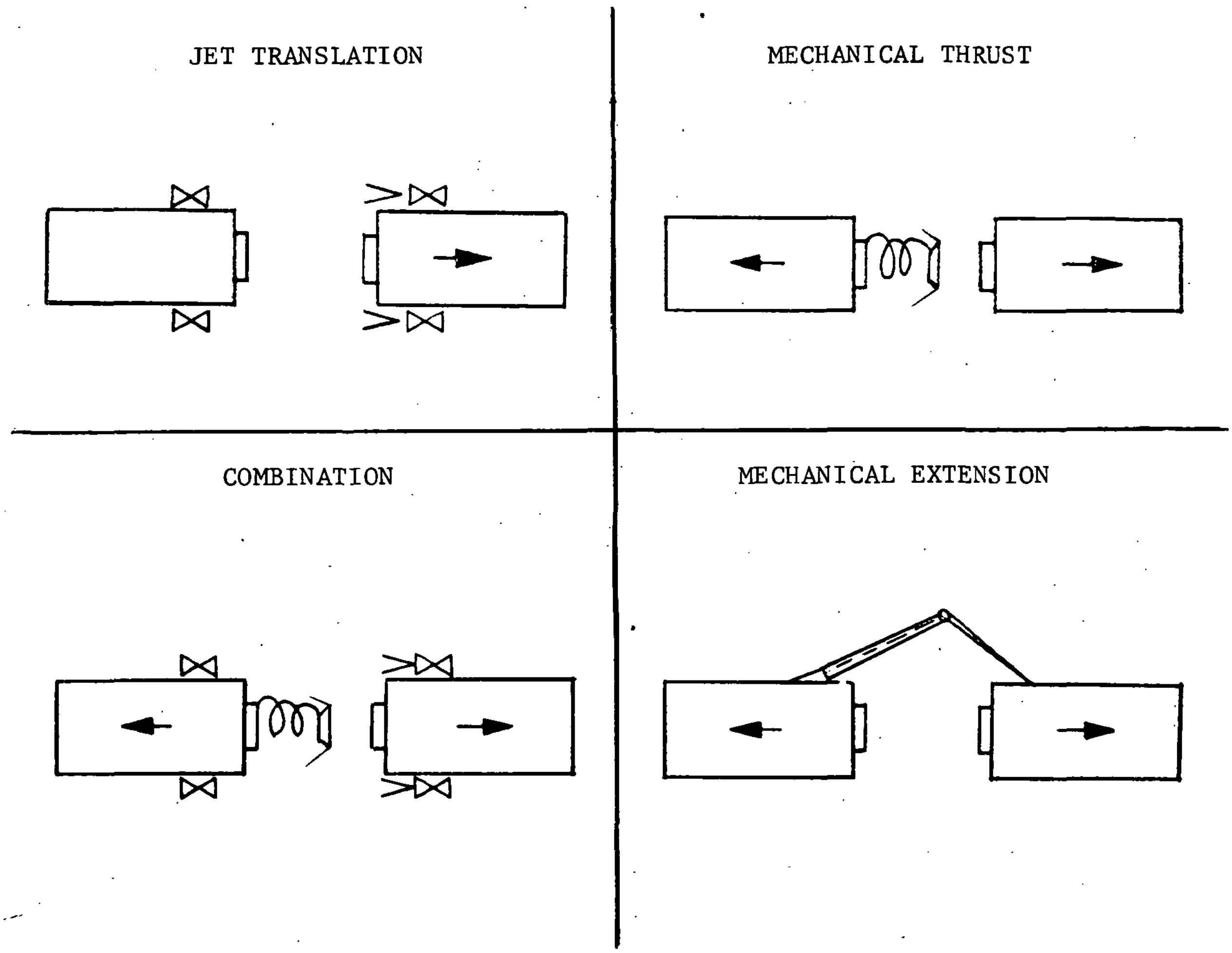


Figure 3-3. Alternate Approaches for Separation

JET TRANSLATION

The jet translation approach can employ two methods. It can be performed utilizing jets on one of the two elements to achieve separation, or both elements can simultaneously utilize their jets to achieve separation. The criteria for the selection of the latter is the need to separate rapidly without imparting excessive g-levels on either element.

This jet translation separation method is dependent upon the propellant being available for the separation task and that vehicle propulsion jets be so located that they are capable of providing a linear translation along the mating port centerline. Because it is highly unlikely that all satellite configurations will be known in the near future, it is necessary for the delivery elements to be designed to provide the translation thrust to accomplish separation. Another problem with jet translation is that jet exhaust plumes may impinge the separating elements and damage or contaminate them such that their operational capability is affected. Therefore, it is not only necessary to provide correct jet location, but plume shape and types of propellants may also have to be controlled.

MECHANICALLY IMPARTED THRUST

This approach employs the use of a mechanism (e.g., spring, pneumatic or hydraulic piston, tension ties, etc.) that can impart translational motion between the mated elements to achieve separation. The array of elements that a single element can mate with requires that the thrust applied by the mechanism be controllable (i.e., forces applied to separate two 100,000-pound masses would not be the same as that required to separate a 100,000-pound mass from a 100-pound mass). Also, this method does not allow one element to remain in a fixed position without resorting to the use of reaction jets to counteract applied forces. If the thrusting element does not apply the force directly through the center-of-mass of the element, a torque will be applied that must be counteracted in order to maintain a fixed attitude and direction of flight.

COMBINATION (MECHANICALLY IMPARTED THRUST/JET TRANSLATION)

This approach utilizes both of the preceding options to achieve separation. It first applies a mechanical thrust to achieve initial separation, then one or both of the elements use jet translation to complete the separation activity. The advantage of this method is that the initial thrust can be low level. Also, if the initial separation is great enough, jet plume impingement can possibly be reduced to an acceptable level.

MECHANICAL EXTENSION

The mechanical extension approach uses a device that physically separates attached elements to a relatively safe distance prior to any individual control. Figure 3-3 depicts a manipulator concept, however, several other techniques are equally as functional, particularly if the device is utilized solely for separation operations. The extension-retraction probe, Figure 3-4, is one such device that appears to have some validity and is one of the mating alternates.

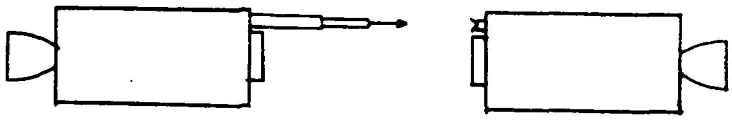


Figure 3-4 Extension-Retraction Probe

With the manipulator separation method, if a manipulator is not attached to one of the separating elements, a third element containing a manipulator must be available for use. Manipulator operations do provide the capability to achieve controlled separation and can strategically place a separated element in a stabilized attitude.

The extension-retraction probe is essentially a manipulator with a single degree of freedom. The probe(s) must be located such that it will apply translational forces along the mating port longitudinal axis. The probe(s) must maintain alignment and attitude stabilization of the element being separated relative to the element the probe(s) is permanently affixed to. The handicap associated with the use of such probes is that if they must provide wide separation between elements, it would be difficult to maintain the required strength and stiffness and still be able to stow the probes when they are retracted and not interfere with mating port passages.

Two of the alternatives were eliminated from the study. The "mechanically imparted thrust" was eliminated because it would not be universally acceptable. The numerous element pairs that must be separated are of such vastly different characteristics (configuration/mass) that multiple independent designs would be required. The "combination" concept utilizes a mechanical thruster which imparts less thrust than the foregoing concept and could possibly be made universal. However, it still could not apply a translational force through the c.g. of many of the element pairs. Without this capability, the separating elements would be rotated at time of separation requiring that an ACS be available immediately to counteract this rotation. This eliminates one of the major benefits of the mechanical thruster; reduction in plume impingement. With the elimination of these two concepts, requirements and procedures were developed for both jet translation separations and manipulator separations.

3.4 DESIGN CONCEPT MODELS

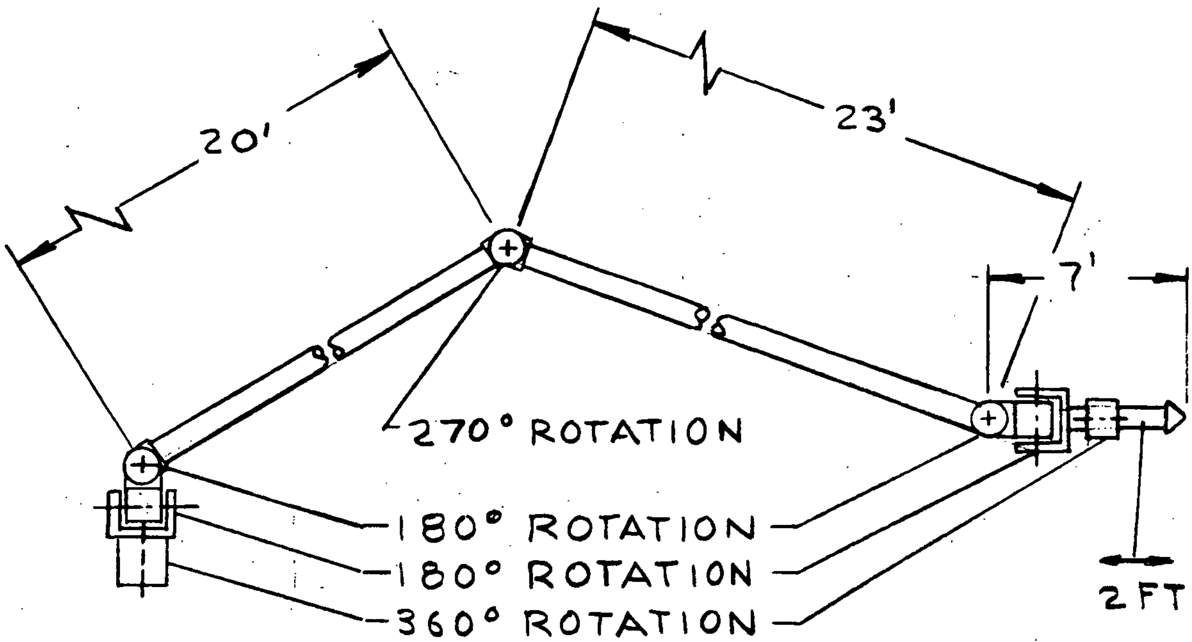
Applicability of the separation concepts to the array of study elements required that a series of hardware design models be selected or developed for each separation function. The model was considered valid when it was compatible with the procedures, requirements, and study element designs. Where a model would not suffice for any one of the three filters it was revised, or discarded and another model generated. If no model could be developed, the concept was considered invalid.

MANIPULATOR MODEL

Figure 3-5 depicts the manipulator design to be used for the study model where the manipulator separation concept is applicable. The manipulator can be directly controlled manually, it can be computer controlled, or it can be remotely controlled. The assembly consists of upper and lower structural elements, pivot joint actuators, and the wrist mechanism. The arm carries a remote control TV camera and spotlight mounted near the terminal end of the arm. Dual torque motors are provided and designed such that failure of one motor does not prevent drive by the other. The wrist assembly provides a collet which can lock onto various terminal devices, or tools and actuates them as required.

Two generic types of end effectors have been identified: (1) claw concept and (2) probe concept. Figure 3-6 illustrates one claw concept which is designed to envelop a square bar attached to a payload . . . and clamp onto it. The bar is itself enclosed in a conical recess which serves both as a guide to assist the claw in capturing the bar and as a guard and scuff plate for element protection. Figure 3-7 illustrates the probe concept which is modeled after the Apollo probe and drogue docking latch principle. The probe is guided into the receptacle by a pyramidal shaped cone and makes an initial capture to prevent disengagement. Final expansion of the probe secures the engagement.

A manipulator can separate an element either by directly translating it from the mating port or by translating and rotating the element. Figure 3-8 illustrates these two options. The direct translation results in the minimum separation distance because of the manipulator geometry and end effecter location. The direct translation, however, will be required where appendages interfere with an element when rotation is applied. The direct translation of a modular space station with the end effector receptacle located at the midpoint of the station (similar to Figure 3-8) allows a maximum separation of about 10 to 13 feet with a berthing port forward of an EOS Orbiter crew compartment and a maximum separation distance of about 15 feet with the berthing port behind the crew compartment. If the end effector receptacle location can be placed at a point on the modular space station closest to the manipulator base when berthed, the maximum separation distance can be increased to near the maximum length of the arm, however, this could be the worst location for manipulator control of the element.



TORQUES AND FORCES

- Shoulder--Up/Down and Rotate: 500 ft-lb
- Elbow--Up/Down: 300 ft-lb
- Wrist--Up/Down and Right/Left: 200 ft-lb
- Wrist--Rotate: 200 ft-lb
- Wrist--Extend: 100 ft-lb

Figure 3-5. Manipulator Configuration

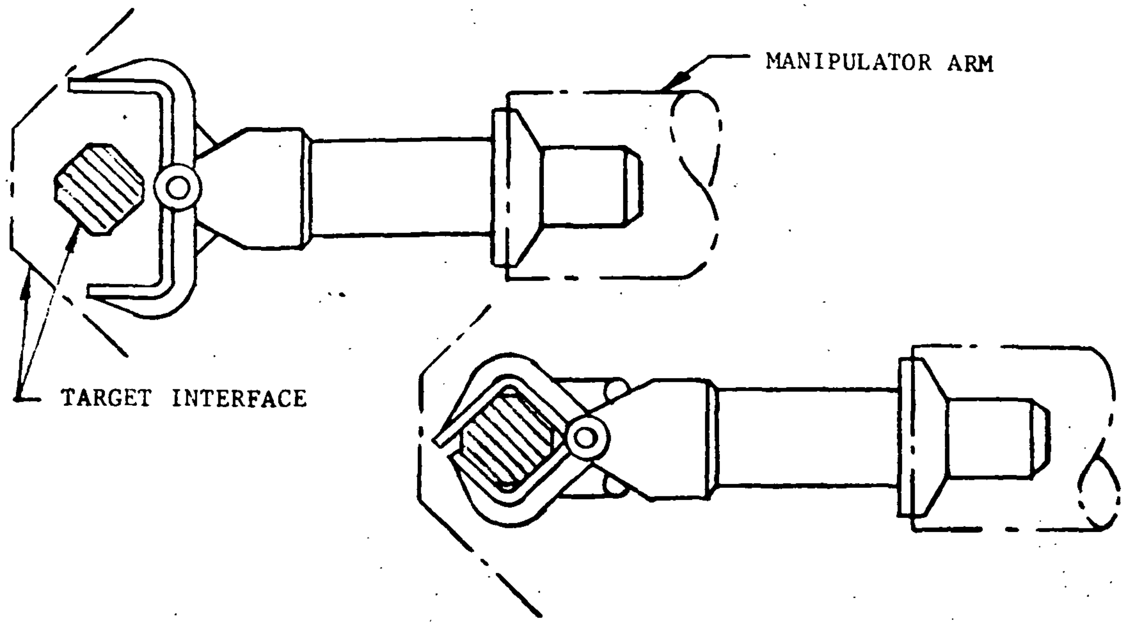


Figure 3-6. Claw End Effector

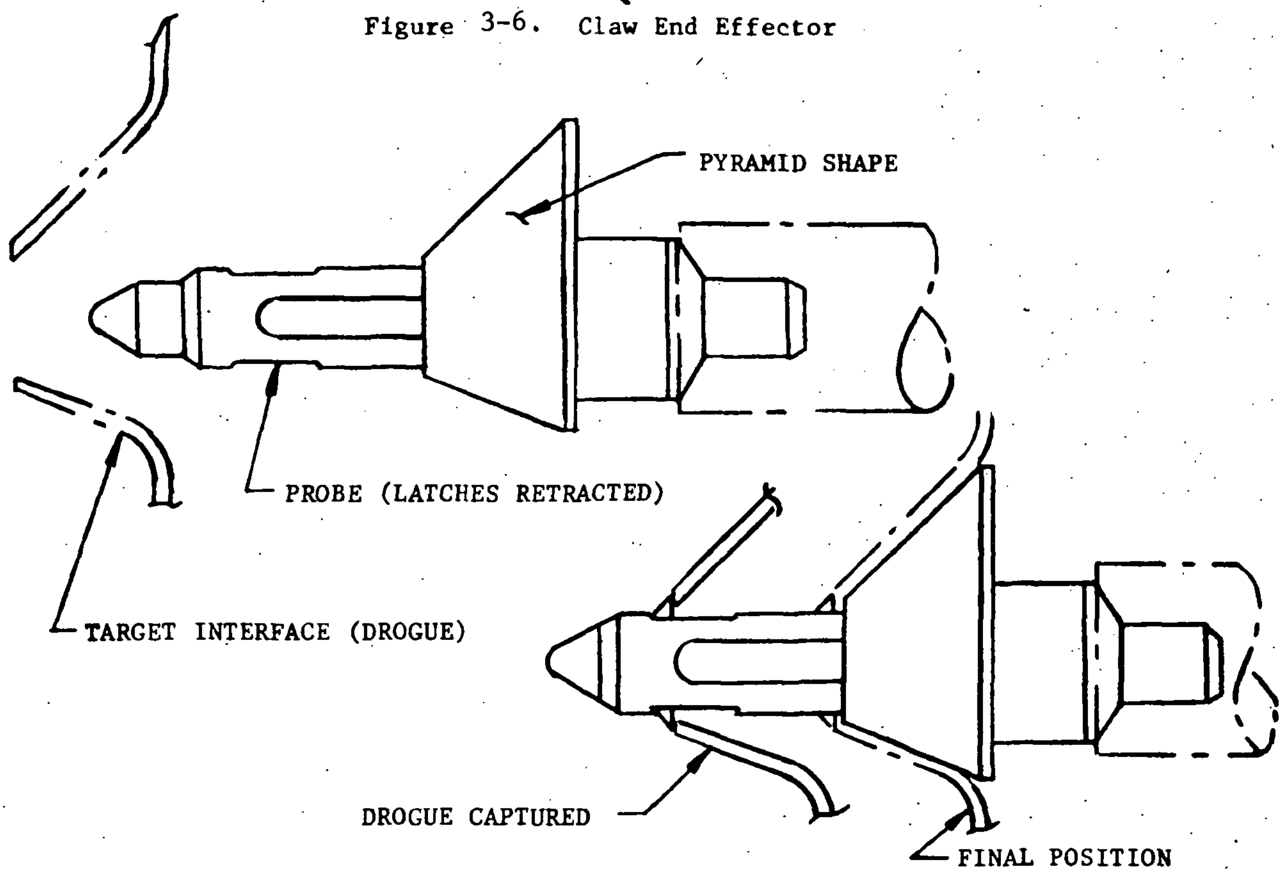


Figure 3-7. Probe End Effector

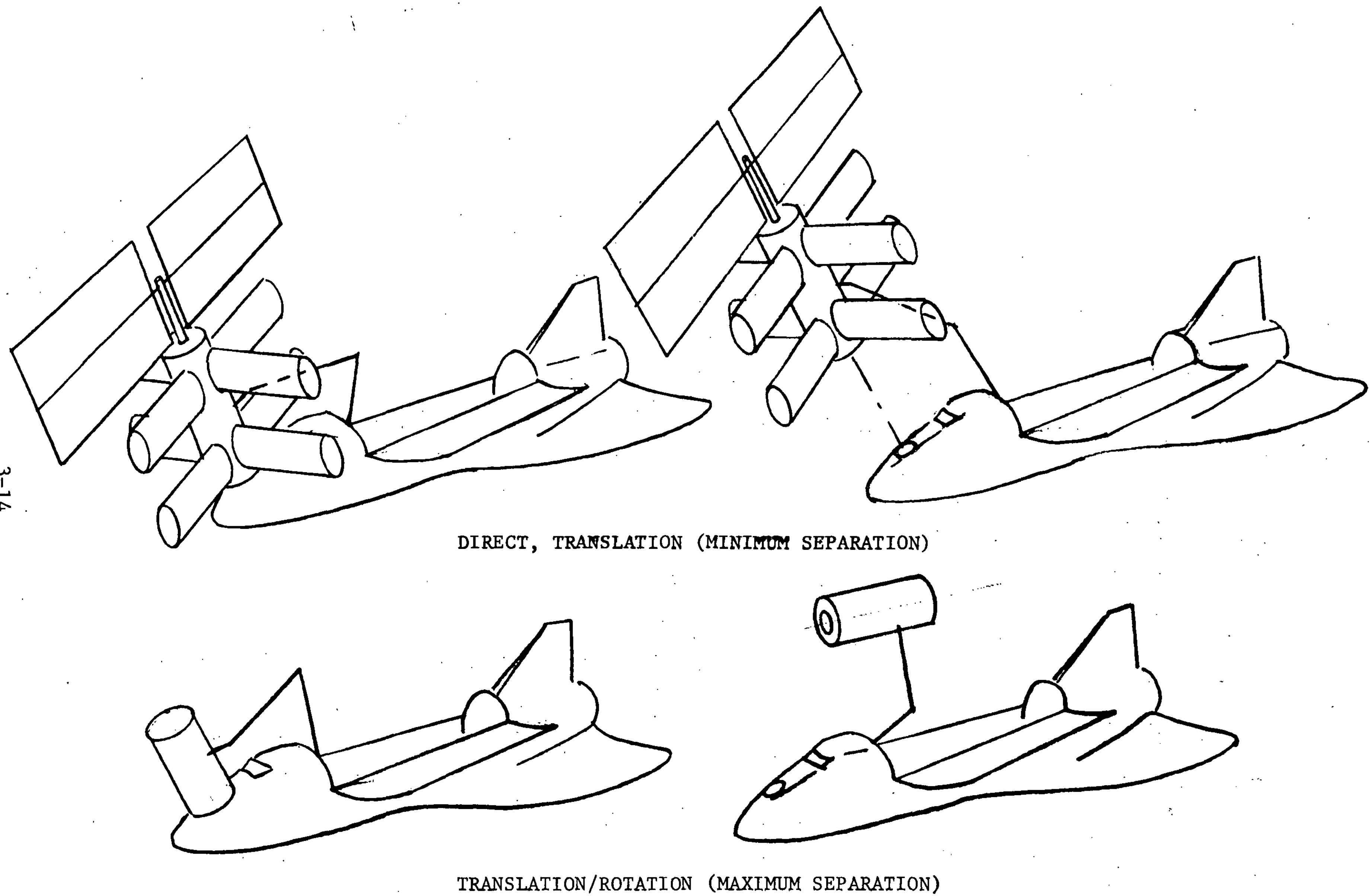


Figure 3-8 Manipulator Separation Concepts

ALIGNMENT MODEL

The alignment criteria for the separation activity is in general not critical except where contact with appendages are possible such as when separating a module from a modular space station. Two alignment concepts are available for use, laser radar system and visual observation. The laser radar concept is actually not viable until the separation distance is such that the laser targets can be acquired (greater than 3.5 feet for a 2 foot diameter target pattern). Not only does the system have to acquire the target, it must recognize and respond to this recognition. If the vehicle misaligns before acquiring the target possible collision could occur before acquisition and realignment is accomplished. It may be that mating can accept the loss of acquisition at some minimum distance due to a mate commitment (point of no return). However, for separation, if appendage clearance is critical, then some type aid must be available to maintain alignment at start of separation. If the separation rate is low enough, visual observation is acceptable for manned elements, however, with a rapid separation rate, reaction time may not be satisfactory and an automatic system that interfaces directly with the control system is required. Because alignment is necessary when separating two unmanned elements and because a laser radar alignment concept is selected for mating, this system should also be the model for jet translation separation. It will be necessary for the system to locate targets and verify alignment interfaces prior to initiating final separation. The system shall also read range such that when the required separation has been achieved independent operations can resume.

With a laser radar system, fully automated separations can be performed. A laser radar will provide precise information on the separation rates of vehicles, real time range data, and the angular alignment between vehicles. This data can be assimilated in a control system computer and resultant commands transmitted to the required thrusters such that a precision separation will be accomplished. During separation, the laser radar on board the vehicle will continuously measure the line-of-sight angles between the docking ports to a precision that will allow the respective vehicle to maneuver such that the line-of-sight angles are nulled. The laser radar concept can utilize an active reflector system or it can utilize a passive reflector system. For this model, the passive system is selected in that the concept relies on less complexity and interfaces and because the separation criteria does not warrant the additional precision afforded by the active reflector concept. With this configuration, all the active components can be placed on one vehicle. Alignment, range, and range rate are determined automatically without an operator. This is accomplished by measuring the range of each corner cube reflector, and the angular separation between the corner cube reflectors, then by using a unique set of geometric equations the relative altitude of the vehicle with respect to the line-of-sight between the two vehicles can be calculated. The relative roll angle can also be calculated using the same set of geometric equations.

For a fully automated separation, either vehicle can be the active element. It is not necessary for the vehicle with the laser radar to assume the active roll. Figure 3-9 illustrates this option for the separation of a space station cargo module using the EOS orbiter as the active element. This concept has the laser radar transceiver installed at the docking port end of the cargo module. This is the preferred location in that this location allows for the direct reading of module misalignment and provides the most commonality with respect to laser radar reflector location.

The laser radar data feeds directly into the EOS Orbiter control computer. If, however, the laser radar is located on the station, the radar data can be computed on board the station and control commands transmitted to the EOS Orbiter control computer or the data can be directly transmitted to the EOS Orbiter control computer with it performing the computations.

Figure 3-10 shows the minimum interfaces within and between the vehicles and the interface with the remote control center for a fully automated system using a laser radar conept. Figure 3-11 shows the same relationships for a manned element separating from an unmanned element, and Figure 3-12 shows the concept utilized between two manned vehicles. Figure 3-13 is a schematic of the laser radar concept. The estimated system performance characteristics for the concept are summarized in Table 3-1.

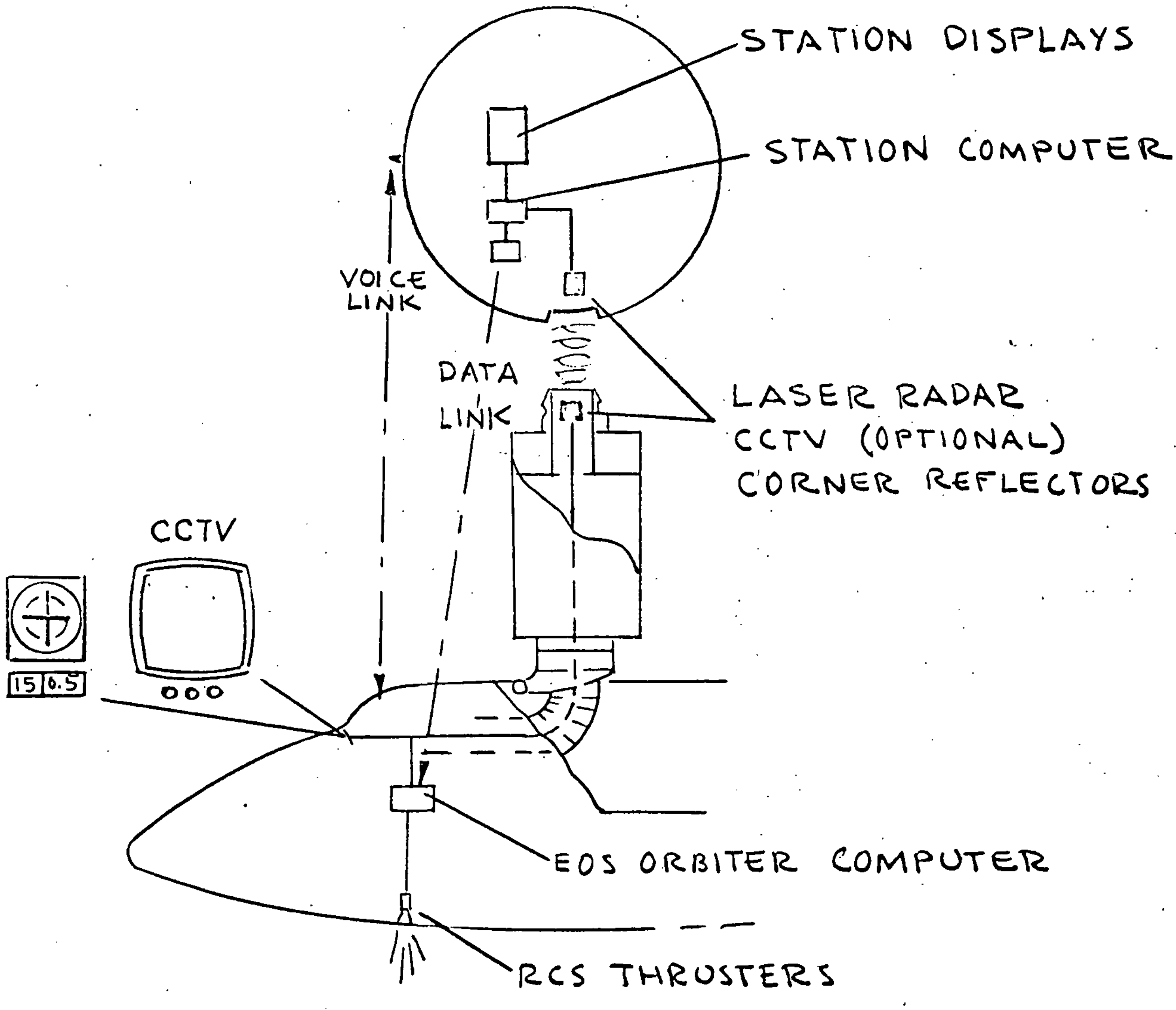


Figure 3-9. Automatic Separation Either Vehicle with Laser Radar

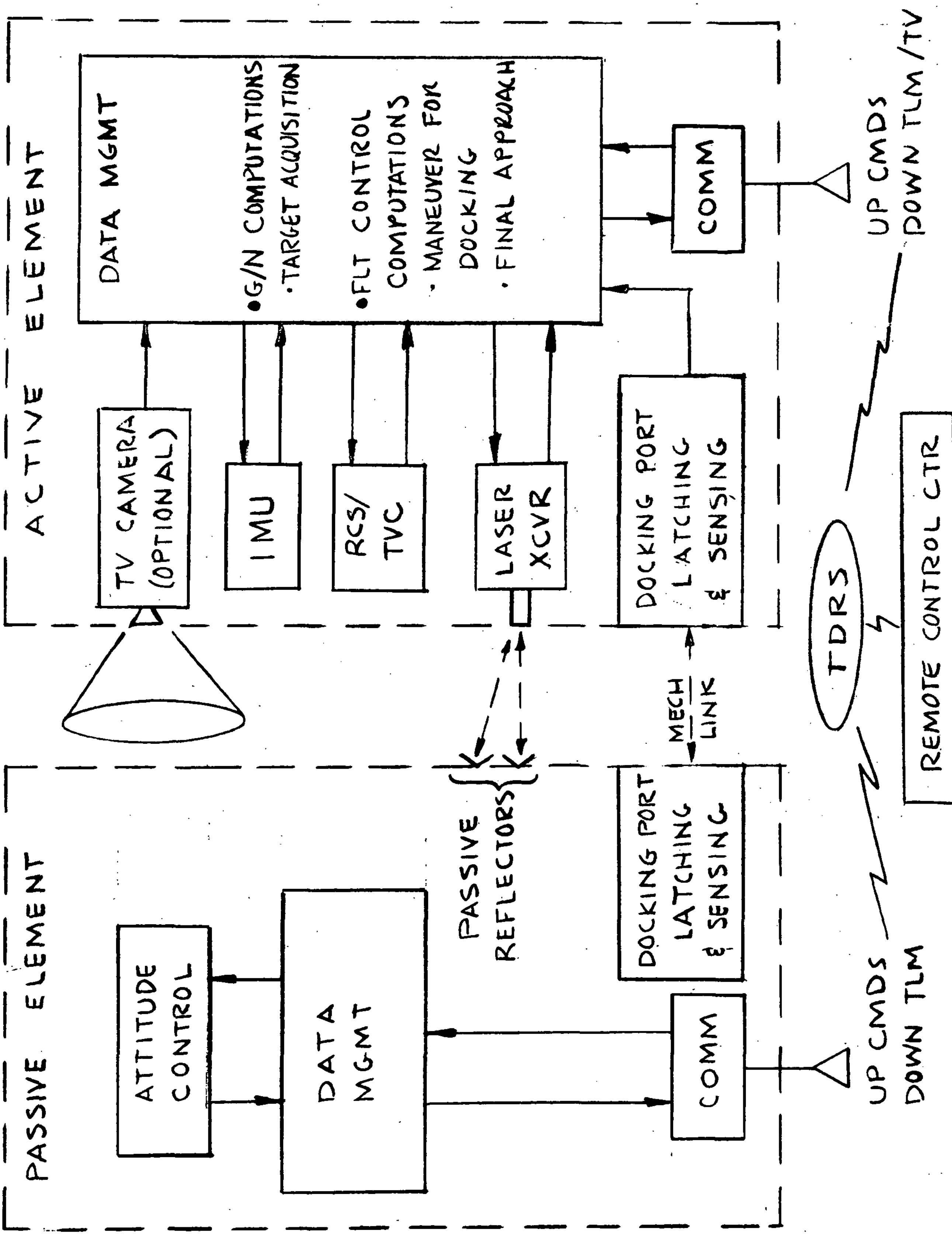


Figure 3-10. Automatic Separation System Interfaces

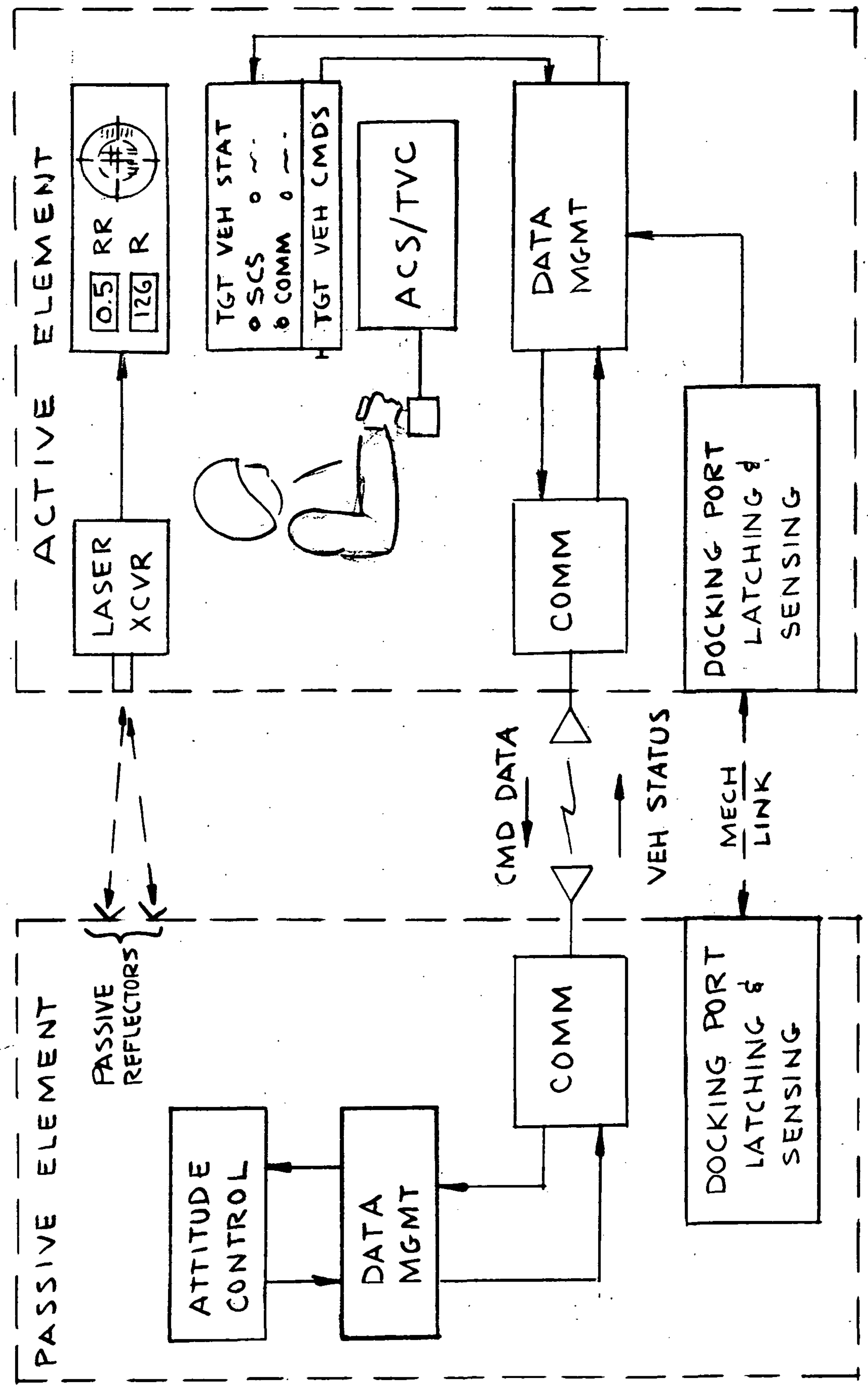


Figure 3-11. Separation--Manned Element from Unmanned Element

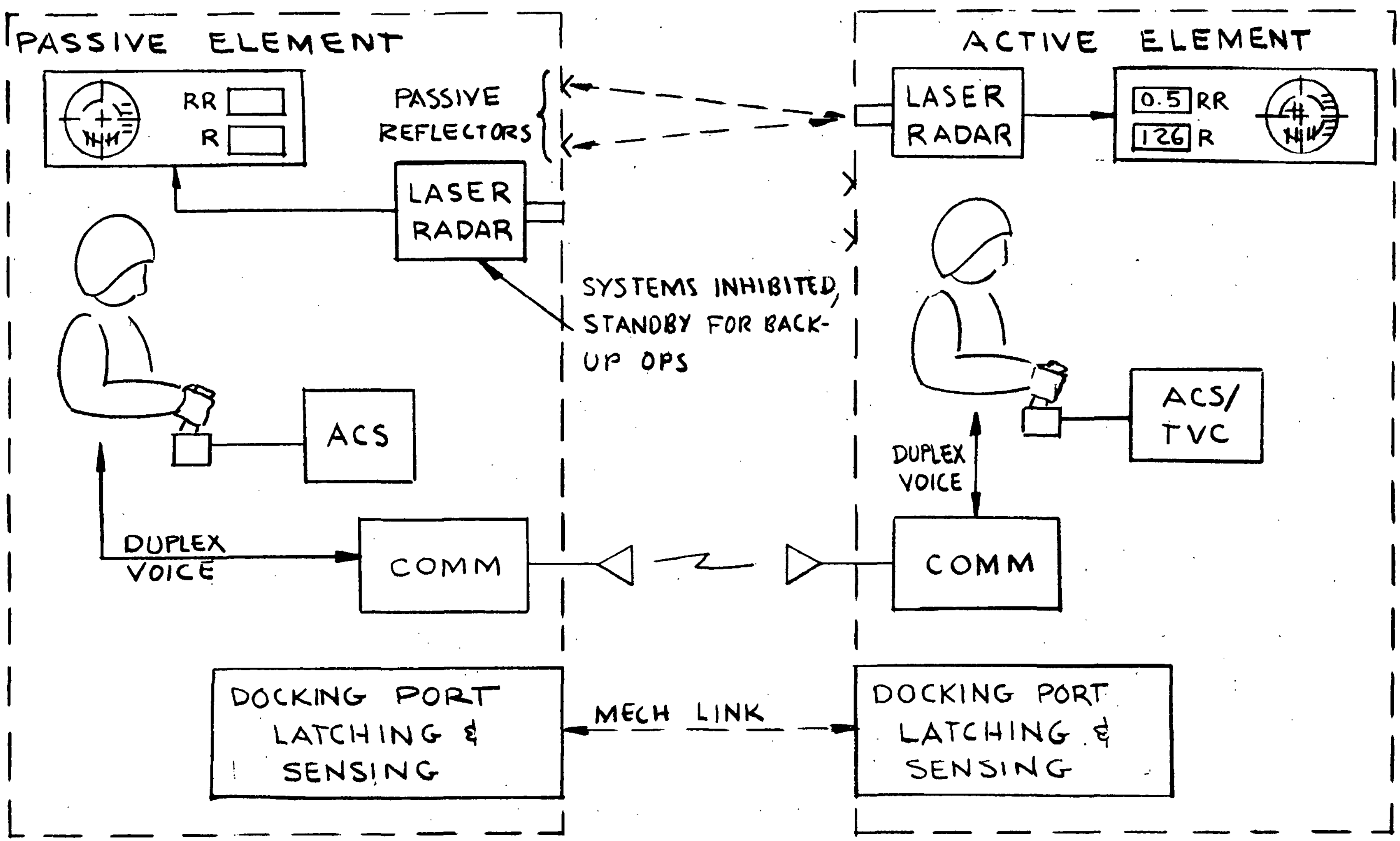


Figure 3-12. Separation--Manned Element from Manned Element

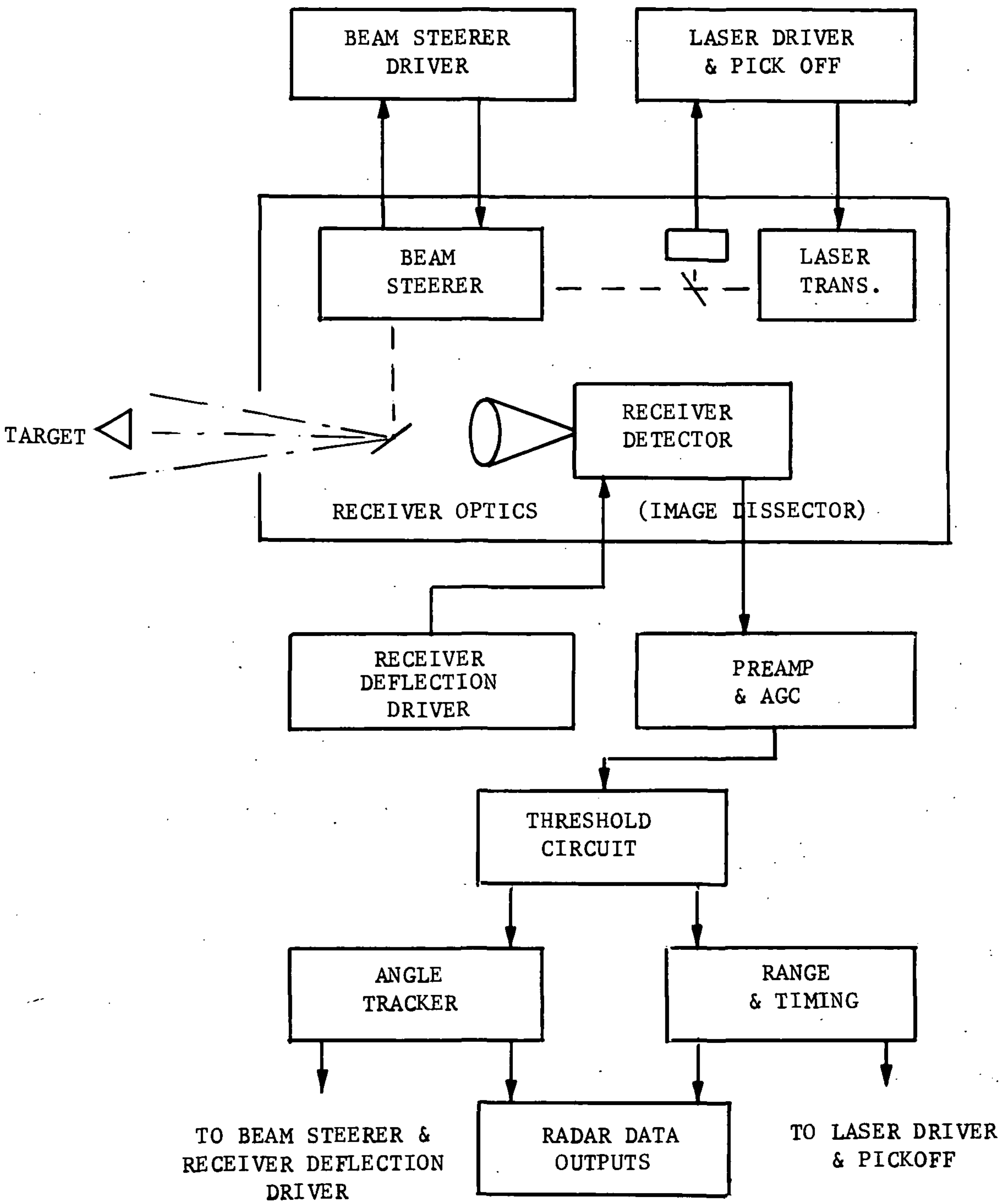


Figure 3-13. Scanning Laser Radar Basic Block Diagram

Table 3-1. Estimated System Performance Characteristics--Scanning Laser Radar

Parameter	Operating Range	Accuracy (3σ)
Range Slant range to target	Low Power Laser: 0-56 km (30 mi), GaAs Semiconductor (1.0 mw Avg. out) Medium Power Laser: 0-167 km (90 mi), Nd:YAG (1 wt Avg. out)	±0.02% of range or ±10 cm whichever is greater
Range-Rate	0-1 km/sec	±1.0% of range-rate or ±1.0 cm/sec whichever is greater
Angle		
Radar-to-target line-of-sight angles (θ_x, θ_y)	0 ± 15° without gimbals	
Relative target attitude Target-to-radar line-of-sight angles (α_{xT}, α_{YT})	0 ± 15° without gimbals (For SLR-3 configuration this is only measured when the range is less than 500-1000 feet.)	
Relative roll angle (ϕ)	0 ± 90° (Measured only at docking)	
Angle-Rate Acquisition Mode		
Radar-to-target LOS angle-rate ($\dot{\theta}_x$, $\dot{\theta}_y$)	For 1 KHz PRF** 0-0.025 deg/sec Worst case--target moving perpendicular to line scan 0-0.303 deg/sec Best case--target moving parallel to line scan	
Relative target attitude rate target to radar LOS angle-rate ($\dot{\alpha}_xT$, $\dot{\alpha}_yT$)	Same as above	
Relative roll angle-rate (ϕ)	Same as above	

RF COMMUNICATIONS

Figure 3-14 is a model of the RF communications in effect when separating various program elements. Manned vehicles will be conversing directly during separation, passing information between vehicles over a duplex voice link. Unmanned vehicles require some type of remote control commands to assume particular attitudes or to activate particular equipment. Unmanned vehicles must be statused before and during the separation activity to verify that subsystems are in accord with the separation operation. Remote control centers, such as ground control, can interface directly with orbiting elements during separation where the vehicles are in line-of-sight, however, since this cannot be guaranteed during all separations, this interface is not considered totally acceptable. Therefore, an interface that utilizes a system such as TDRS is required. An expansion of the communications concepts and trade studies selecting the preferred concepts are documented in Part 3 Section 1.

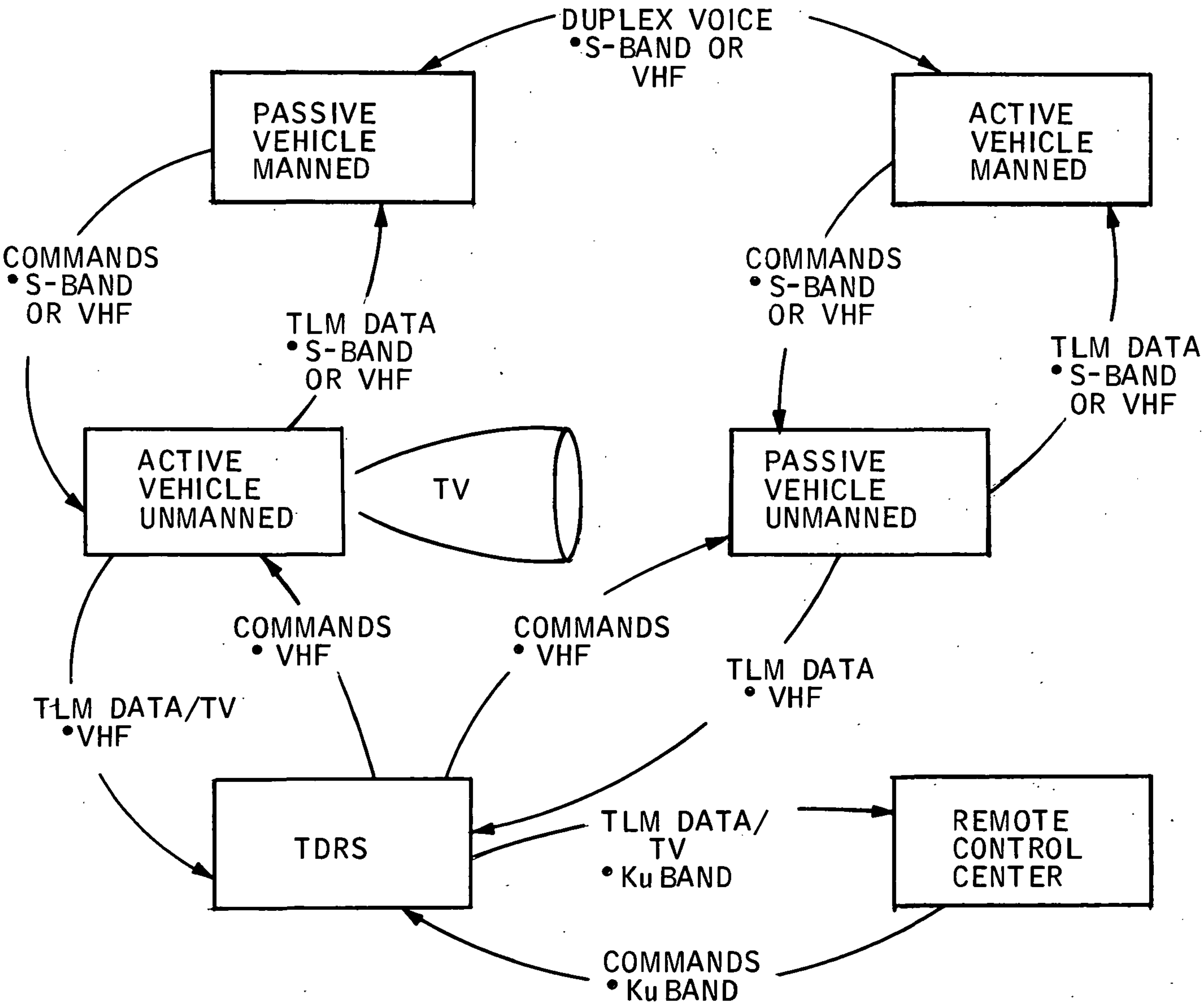


Figure 3-14. Separation Communications Interfaces

3.5 OPERATIONAL PROCEDURES

Separation can occur between manned elements, between unmanned elements, and between manned and unmanned elements. Therefore, it was necesssary to develop procedures that encompassed these three possibilities. Because two different separation concepts are being evaluated; i.e., jet translation separation and manipulator separation, it was necessary that these concepts be applied in the procedures development. If jet translation and manipulator separation are both applicable for the three types of manned and unmanned separations, it would appear that a total of six procedures should be developed. However, by applying the following logic the number was reduced. The first reduction was the elimination of a manipulator separation of two unmanned elements. The need for this procedure was eliminated because manipulators presently being conceived are for man-in-the-loop operations and because those elements that appear to be candidates for manipulators are elements that would probably be manned. The jet translation separation is performed with one element essentially performing a passive roll in that it will only hold attitude while the other element separates and translates clear. Therefore, the operations for a manned element separating from a manned element should be very similar to those of a manned element separating from an unmanned element, and the two procedures could be combined. After developing the initial procedures it was found that the manipulator separation of a manned element from a manned element was very similar to manipulator separation of a manned element from an unmanned element. Therefore, these procedures like the direct docking procedures, were also combined.

Before preparing any procedure it was necessary to select a pair of elements to use as a representative model. By doing this, the procedure would not become so generic that it could fail to uncover detail ambiguities of specific elements that may affect design concepts or be insensitive to particular design requirements. For the manned element separations, the EOS Orbiter was selected as one of the elements because this vehicle would be separating from all of the study elements. The Modular Space Station was selected as the other element in that it presented the most stringent criteria, particularly with alignment problems and the always present interfering appendages that must be avoided during the separation. For the unmanned separating elements, a Space Tug and a detached Research and Applications Module (RAM), both candidates for unmanned operations, were selected for the representative model.

The following matrix shows the final selection for operational procedures development:

Approach	Manned From Manned	Manned From Unmanned	Unmanned From Unmanned
Jet Translation	One procedure EOS Orbiter to MSS		Space tug to DRAM
Manipulator Separation	One procedure EOS Orbiter to MSS		

PROCEDURAL COMPARISON

The separation procedures include configuring of the element-to-element interface for separation, the physical separation of the ports, and the mechanical extension or jet translation operation to provide a safe separation distance between the elements.

Figure 3-15 is a general comparison of a manipulator separation procedure with a jet translation separation procedure. The central bubbles represent common operations with the bubbles on the upper and lower portion of the page representing procedural differences. It can be seen that the only real difference occurs after separation of the mating ports in that the manipulator then performs the separation by extending the arm, whereas, for a jet translation separation, the separation is achieved through jet thrusting by one of the elements until a safe separation distance is achieved. The detailed procedures are located in Appendix B of this document.

PROCEDURES APPLICABILITY

Each procedure that was developed was reviewed for applicability to the feasible separating combinations. The results of these analyses in matrix form are shown in Appendix B.

It is possible to separate all element pairs using either the jet translation or manipulator approach. However, for this analysis it was assumed that manipulators would not be installed on all elements. Those elements that do not appear to be candidates for manipulators are the OIS, CPS, RNS, and OPD. The first three elements which are booster type vehicles are not candidates for manipulators because the secondary advantages gained by manipulators are not applicable to the type missions performed by these vehicles. The OPD is not a candidate because manipulator operations involve a man-in-the-loop concept and the OPD is an unmanned element. All separations, however, could be performed using manipulators if a third element with a manipulator is available to support the operation. Following these ground rules, the matrix indicates that at least two procedures are available for separating each element pair. In all but seven cases, a jet translation or manipulator separation procedure will work. Manipulator separation is not applicable for the seven noted cases because they involve matings between the OIS, CPS, RNS, and OPD.

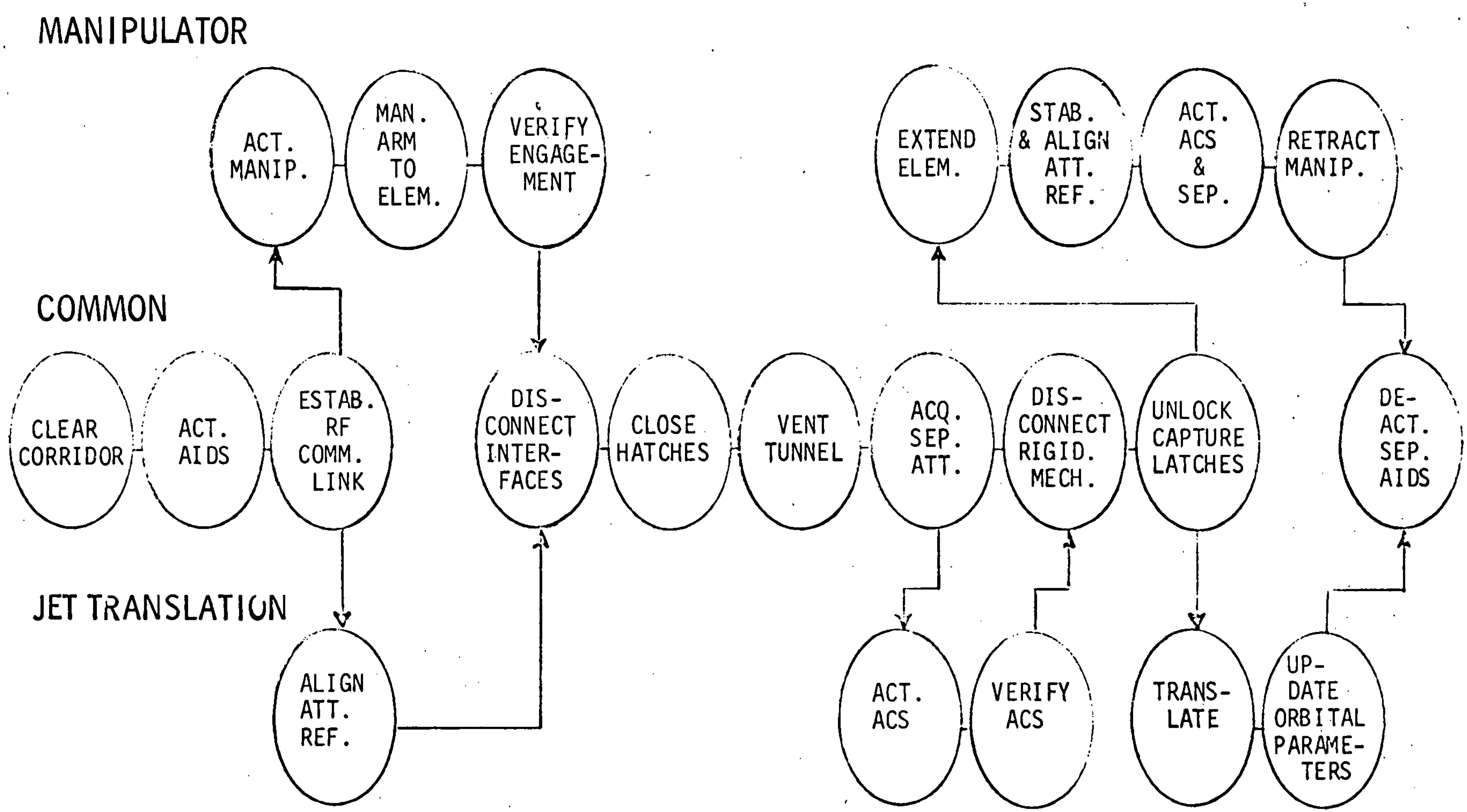


Figure 3-15. Separation Procedural Comparison

3.6 FUNCTIONAL REQUIREMENTS

Functional requirements are presented in this section. These requirements enable the various conceptual separation approaches to be further evaluated against the criteria that will be imposed on the concept or imposed by the concept itself. These requirements are applicable to any orbital separation activity involving either a jet translation separation concept or a manipulator separation concept. In most cases, the requirements are generic in that for any type separation they will apply. This is particularly true for the requirements concerned with interface configuring for separation operations.

The columns on the right hand side of the requirement identify the procedures to which the requirements are applicable. The numbers 3-1, 3-2, and 3-3 refer to the applicable separation procedure located in Appendix B.

Item	Procedure No. Man Jet Trans 3-1	Procedure No. Manip 3-2	Procedure No. Auto Jet Trans 3-2
1. Prior to separation, one element will be maintaining attitude hold control of the mated pair. At separation, both elements will have attitude control capability.			
a. For a jet translation separation, one element will be only holding attitude. The other element will perform the translation maneuver holding a deadband attitude during the separation. The attitude hold alignment driver is that of separating from between two appendages, such as when a module is separated from a MSS. Figure 3-16 depicts allowable deviation from centerline in the plane of the modules for module lengths of 40-foot and 60-foot. With a module length of 60-feet, the allowable angular deviation is 4 degrees. This parameter is based on a module spacing of 5 feet which is the most critical spacing of element appendages identified.	X		X

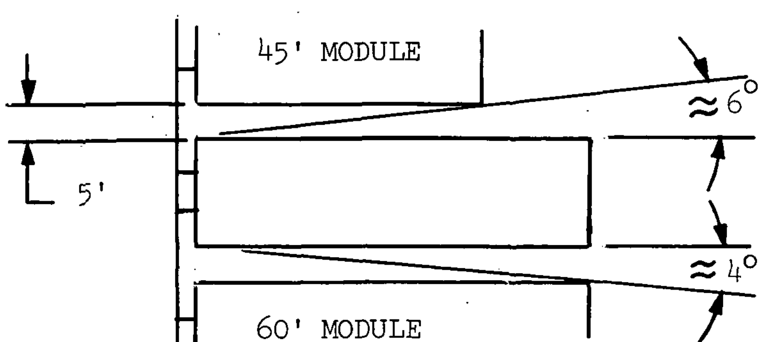


Figure 3-16. Allowable Deviation from Centerline When Separating from Between Element Appendages

	Procedure No.		
	Man Jet Trans	Manip	Auto Jet Trans
	3-1	3-2	3-3
b. For a manipulator separation, both elements could be placed in a free drift mode such that ACS torquing does not occur during the separation. However, if the separating element must be precisely positioned in orbit, then a narrow deadband mode on the manipulator element would be in effect.		X	
2. Separation velocities and angular rates caused by the extension of a shock attenuation system or other energy storage system shall be controlled by delaying release until the extension dynamics cease. For a manipulator separation, the manipulator shall stabilize the separated element and orient it into the prescribed attitude. Stabilization and attitude selection shall be such that the manipulator can be released and retracted without the element recontacting the arm.	X	X	X
3. For a jet translation separation where alignment is critical and alignment aids are utilized, the alignment aids must be active and aligned before separating. For a laser radar alignment system using passive reflectors, the target reflector spacing is critical. Figure 3-17 illustrates this problem. Assuming a 30 inch spacing between the laser transceiver and the reflector location, the diameter spacing of the reflectors must be a maximum of about 16 inches. Any greater than this and the 30 degree scan of the radar beam will not pick up the targets. If the tranceiver is located in the center of the mating ports pointing through a window as shown in the figure, reflector spacing will have to be large enough not to require mounting on the opposing window. Window impingement can be avoided by locating the laser radar and reflectors off the centerline.	X		X

Procedure No.		
Man Jet Trans	Manip	Auto Jet Trans
3-1	3-2	3-3

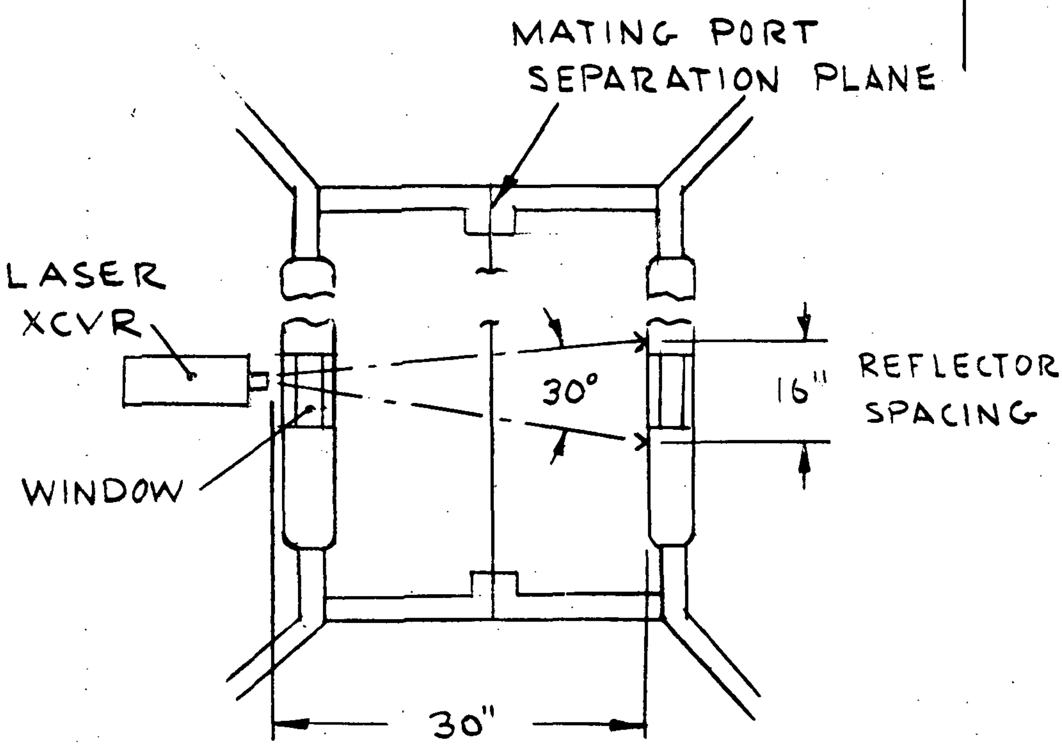


Figure 3-17. Reflector Spacing Example

Because the spacing between the laser radar transceiver and the reflectors is a function of mating port design, the requirement for maximum diameter reflector spacing cannot be specified. However, a review of various mating port designs appears to set the range around 10 inches if the laser is not pointing out a window and about 24 inches if it is viewing out a window. If alignment is not critical and minimum alignment control is all that is necessary, TV coverage or direct viewing is acceptable.

	Procedure No.		
	Man Jet Trans	Manip	Auto Jet Trans
	3-1	3-2	3-3
4. The separation alignment criteria shall be in effect until appendage clearance can be guaranteed or clearance from the command element obtained. The minimum non-recontact separation distance shall be one and one-half times the combined length of the major axis of each element. This will allow a maximum rotation by each element independent of c.g. location (assuming no translation), and still provide clearance between elements. For a manipulator separation, this does not mean the manipulator must provide this full separation; jet translation can also be used. An additional factor that must be considered when defining a separation distance is exhaust plume impingement during maneuvers subsequent to separation. Whereas it may be no problem to perform attitude maneuvers with low thrust engines, a main propulsive engine burn could be catastrophic if there is not adequate separation between the elements and the thrust vector is not properly aligned to avoid plume impingement on the separated element.	X	X	X
5. Throughout the separation maneuver the control systems of both vehicles shall be monitored for indications of control failures such as reaction jet "stuck on" and "stuck off" conditions. Inhibit switches and selectable jet logic may prevent vehicle dynamics from reaching catastrophic proportions and provide time for an element to perform evasive maneuvers.	X	X	X
6. Translation jets utilized for separation shall be selected and propellants utilized so as to minimize the effects of exhaust plume impingement on sensitive areas of interfacing elements. This applies where more than one set of jets can be selected. Solar arrays and experiment sensors are particularly vulnerable to structural damage from direct jet exhaust and degradation through contamination by the reactants.	X		X

	Procedure No.		
	Man Jet Trans	Manip	Auto Jet Trans
	3-1	3-2	3-3
7. Separation sensing shall be provided to ascertain positive separation has occurred at the mating port prior to initiating a jet translation or mechanical extension by a manipulator. If a latch fails to release, firing of RCS engines to translate from the port will cause the elements to pitch or yaw into each other.	X	X	X
8. All separating elements shall be equipped with RF communications systems. The minimum extent of the systems shall be as follows:			
a. When separating unmanned elements from unmanned elements a ground communications link shall be established. Critical operations between the elements will be monitored, real time, by ground control.	X		X
b. When separating manned elements from manned elements a duplex voice link between the elements shall be provided. Element status and voice command information must be transmitted between the elements.	X	X	X
c. When separating manned elements from unmanned elements a data link shall be provided between the elements. The manned element will continuously monitor and status the unmanned element and will transmit commands to the unmanned element.	X	X	
9. Prior to separation of mated elements, the pressurized tunnel between the elements must be pumped down or vented to space. The pressure remaining in the tunnel shall be low enough such that when separation occurs no noticeable delta velocity due to the remaining pressure will be imparted to the separating elements.	X	X	X

	Procedure No.		
	Man Jet Trans	Manip	Auto Jet Trans
	3-1	3-2	3-3
10. Before separating an element utilizing a manipulator, the manipulator end effector engagement must be verified. If the manipulator were to pull free of the receptacle during a separation, possible collision between the elements could occur. One method of verification would be to simulate the actual forces that will be applied during the manipulator separation maneuver before releasing the element from the mating port.		X	
11. Prior to final separation, the attitude reference of the elements will be aligned. Thus, the individual attitude control systems will not generate conflicting commands when both systems are activated. Also, after separation, noncompatible attitude references may cause one element to perform a maneuver that could result in recontact.	X	X	X
12. Propulsive venting of effluents on both vehicles shall be inhibited or controlled during the separation maneuver. The control of venting is not only necessary to prevent attitude control problems, but also should be avoided to prevent effluents from obscurring alignment aids.			
13. The separation technique shall be such that no damage will occur to the mating ports which would prevent succeeding matings and separations. The mating ports shall be left in a condition ready for a subsequent mate, unless remote control configuring of the mating port is available (e.g., the rigidizing latches shall be unlocked and recycled, the drawdown system shall extend the attenuators to the unstrapped position, and the capture latches unlocked and recycled).	X	X	X

Item	Man Jet Trans 3-1	Manip 3-2	Auto Jet Trans 3-3
14. A backup means for release and separation of mated elements in case of failure of the primary method shall be provided. If the backup scheme is a manual disengagement, the technique shall be designed for IVA or shirtsleeve operations rather than requiring EVA. Possible rapid movement at separation by one of the elements could cause a serious accident to an EVA astronaut not protected by vehicle structure.	X	X	X
15. Illumination of the separating element(s) is required for separations where man is involved. or when ground television coverage is required for unmanned elements. Illumination shall be such that appendages of associated elements are independently illuminated by each element or one of the elements can illuminate the opposing element utilizing flood lights. Floodlight usage shall be designed such that it does not blind alignment sensors or opposing pilots.	X	X	X
16. All electrical interfaces shall be deadfaced on both sides of the interface prior to being disconnected. Possible shorting of connector pins during separation can damage hardware or create a hazardous spark that could result in fire or explosion.	X	X	X
17. Electrical and fluid interface connections shall be located, designed, and mounted such that an astronaut can demate the connectors and couplings in a pressurized IVA suit.	X	X	
18. Hazardous fluid interconnects that are to be removed shall be vented or purged with a non-hazardous (inert) gas prior to separation. If residuals remain in interconnects they may spill upon separation, thereby, contaminating the interface area.	X	X	

	Procedure No.		
	Man Jet Trans	Manip	Auto Jet Trans
	3-1	3-2	3-3
19. Prior to initiation of the separation routine those subsystems that will be utilized during the separation activity shall be verified. Where backup systems are available, these shall also be statused. The separation activity involves hazardous operations. Failure of a primary operation will require that a backup system be immediately available to assume the failed function.	X	X	X
20. When hatches between elements are closed such that separation can occur, the hatch seal integrity shall be verified. Failure of the hatch seal after separation could be catastropic. Seal verification prior to separation will allow for repair of the interface or recycling of the door to acquire better seating. The verification can be during tunnel depressurization as long as the depressurization can be terminated and the tunnel repressurized.	X	X	

FUNCTIONAL REQUIREMENTS BY ELEMENT PAIR

Table 3-2 provides a matrix of the requirements as they apply to the various element pairs. The top row of the matrix identifies a primary element. The following row identifies the elements the primary element separates from. The column at the far left is a list of the requirements, numerically corresponding to the functional requirements in the previous paragraphs. A check (√) indicates that the requirement can be valid for the noted interfacing pair and implementation is essentially the responsibility of the primary element. A dash (-) indicates that the primary element is concerned with the requirement, however, the general responsibility lies with the associated element. "NA" indicates that for the noted separating pair, the requirement does not appear to be valid. "X" indicates that the associated element is passive in nature (ARAM, resupply module, and modules of the MSS, OLS, and OPD) and the requirement applies to the two active elements involved in the operation.

Table 3-2. Functional Requirements by Element Pair

Requirement	EOS Orbiter													RTN TUG	SAT	
	EOS	RTN TUG	SPACE TUG	EOS DRAM	MSS ARAM	MSS DRAM	SAT	RESUP MOD	MSS	CPS CLS	RNS	OLS	OPD	EOS	EOS	SPACE TUG
1a. Jet Trans Align	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1b. Manip Align	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–
2. Control of Mech Extension Dynamics	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Prealign of Sep Aids	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–
4. Min Sep Dist	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
5. Cont Sys Monitoring	NA	✓	✓	✓	NA	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
6. Plume Impingement Control	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	NA	–	–
7. Separation Sensing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
8a. Ground Comm Link	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	✓
8b. Duplex Voice Link	✓	NA	✓	NA	X	NA	NA	X	✓	✓	✓	✓	✓	NA	NA	NA

Table 3-2. Functional Requirements by Element Pair

Requirement	EOS Orbiter													RTN TUG	SAT	
	EOS	RTN TUG	SPACE TUG	EOS DRAM	MSS ARAM	MSS DRAM	SAT	RESUP MOD	MSS	CPS CLS	RNS	OLS	OPD	EOS	EOS	SPACE TUG
8c. Data Link	NA	✓	✓	✓	NA	✓	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓
9. Tunnel Pres Vent	✓	NA	✓	✓	NA	NA	NA	NA	✓	✓	✓	✓	✓	NA	NA	NA
10. End Effector Engage Verif	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–
11. Att Ref Alignment	✓	✓	✓	✓	X	✓	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓
12. Prop Venting Control	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
13. Mating Port Protection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14. Backup Release	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15. Illumination	✓	–	✓	–	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓
16. Elect Deadfacing	✓	✓	✓	✓	NA	NA	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓

Table 3-2. Functional Requirements by Element Pair

Requirement	EOS Orbiter													RTN TUG	SAT	
	EOS	RTN TUG	SPACE TUG	EOS DRAM	MSS ARAM	MSS DRAM	SAT	RESUP MOD	MSS	CPS CLS	RNS	OLS	OPD	EOS	EOS	SPACE TUG
17. IVA Dis-connects	✓	✓	✓	✓	NA	NA	✓	NA	✓	✓	✓	✓	✓	✓	-	-
18. Fluid Line Purging	✓	NA	✓	✓	NA	NA	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓
19. System Verification	✓	✓	✓	✓	NA	NA	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓
20. Hatch Seal Verification	✓	NA	✓	✓	NA	NA	NA	NA	✓	✓	✓	✓	✓	NA	-	-

Table 3-2. Functional Requirements by Element Pair

Requirement	Space Based Tug											CPS OIS	EOS DRAM	MSS DRAM		
	SPACE TUG	MSS ARAM	MSS DRAM	SAT	RESUP MOD	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD	SPACE TUG	EOS	EOS	SPACE TUG	MSS
1a. Jet Trans Align	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
1b. Manip Align	√	√	√	√	√	√	√	√	√	√	√	–	–	–	–	–
2. Control of Mech Ext Dynamics	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
3. Prealign of Sep Aids	√	√	√	√	√	√	√	√	√	√	√	√	–	–	–	–
4. Min Sep Dist	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
5. Cont Sys Monitoring	√	X	√	√	NA	√	√	√	√	√	√	√	√	√	√	√
6. Plume Impingement Control	√	√	√	√	√	√	√	√	√	√	√	√	–	–	–	√
7. Separation Sensing	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
8a. Ground Comm Link	NA	X	√	√	X	NA	√	√	√	√	√	√	NA	NA	NA	NA

Table 3-2. Functional Requirements by Element Pair

Requirement	Space Based Tug											CPS OIS	EOS DRAM	MSS DRAM		
	SPACE TUG	MSS ARAM	MSS DRAM	SAT	RESUP MOD	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD	SPACE TUG	EOS	EOS	SPACE TUG	MSS
8b. Duplex Voice Link*	✓	X	NA	NA	X	✓	✓	✓	✓	✓	✓	NA	NA	NA	NA	NA
8c. Data Link	NA	NA	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
9. Tunnel Press Vent	✓	NA	NA	NA	NA	✓	NA	✓	✓	✓	✓	NA	✓	NA	NA	✓
10. End Effector Engage Verif	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	-
11. Att Ref Alignment	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12. Prop Venting Control	NA	✓	✓	✓	X	✓	NA	NA	NA	✓	NA	✓	✓	✓	✓	✓
13. Mating Port Protection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14. Backup Release	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15. Illumination	✓	-	-	-	-	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
16. Elect Deadfacing	✓	NA	NA	✓	NA	✓	NA	✓	✓	✓	✓	NA	✓	NA	NA	✓

*Manned Space Tug

Table 3-2. Functional Requirements by Element Pair (Cont.)

	Space Based Tug											CPS OIS	EOS DRAM	MSS DRAM		
Requirement	SPACE TUG	MSS ARAM	MSS DRAM	SAT	RESUP MOD	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD	SPACE TUG	EOS	EOS	SPACE TUG	MSS
17. IVA Disconnects*	✓	NA	NA	✓	NA	✓	NA	✓	✓	✓	✓	NA	✓	NA	NA	✓
18. Fluid Line Purging	✓	NA	NA	✓	NA	✓	NA	✓	✓	✓	✓	NA	✓	NA	NA	✓
19. System Verification	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
20. Hatch Seal Verification	✓	NA	NA	NA	NA	✓	NA	✓	✓	✓	✓	NA	✓	NA	NA	✓

*Manned Space Tug

Table 3-2. Functional Requirements by Element Pair

Requirement	Low EO MSS						MSS ARAM			CPS CLS						
	EOS	SPACE TUG	MSS ARAM	MSS DRAM	RESUP MOD	MSS	EOS	SPACE TUG	MSS	EOS	SPACE TUG	RESUP MOD	CPS OIS	CPS CLS	OLS	OPD
1a. Jet Trans Alignment	√	√	√	√	√	√	–	–	–	√	√	√	√	√	√	√
1b. Manip Align	√	√	√	√	√	√	–	–	–	–	–	X	NA	X	NA	NA
2. Control of Mech Ext Dynamics	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
3. Prealignment of Sep Aids	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
4. Min Separation Dist	√	√	√	√	√	√	–	–	–	√	√	√	√	√	√	√
5. Cont Sys Monitoring	√	√	X	√	X	X	NA	NA	NA	√	√	X	√	√	√	√
6. Plume Impingement Control	–	–	–	√	NA	–	–	–	NA	√	√	√	√	√	√	√
7. Separation Sensing	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
8a. Ground Comm Link	NA	√	NA	NA	NA	NA	NA	NA	NA	√	X	√	√	√	√	√
8b. Duplex Voice Link	√	√	X	NA	X	X	NA	NA	NA	√	√	X	NA	X	NA	NA

Table 3-2. Functional Requirements by Element Pair

	Low EO MSS						MSS ARAM			CPS CLS						
Requirement	EOS	SPACE TUG	MSS ARAM	MSS DRAM	RESUP MOD	MSS	EOS	SPACE TUG	MSS	EOS	SPACE TUG	RESUP MOD	CPS OIS	CPS CLS	OLS	OPD
8c. Data Link	✓	✓	X	NA	X	X	NA	NA	NA	✓	✓	X	NA	X	NA	✓
9. Tunnel Press Vent	✓	✓	✓	✓	✓	✓	NA	NA	✓	✓	✓	NA	NA	✓	NA	✓
10. End Effector Engage Verif	✓	✓	✓	✓	✓	✓	–	–	–	–	–	X	NA	X	NA	NA
11. Att Ref Alignment	✓	✓	X	✓	X	X	NA	NA	NA	✓	✓	X	✓	✓	✓	✓
12. Prop Venting Control	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
13. Mating Port Protection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14. Backup Release	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15. Illumination	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	–	–	–	–
16. Elect Deadfacing	✓	✓	✓	✓	✓	✓	NA	NA	✓	✓	✓	–	✓	✓	NA	✓
17. IVA Disconnects	✓	✓	✓	✓	✓	✓	NA	NA	✓	✓	✓	✓	NA	✓	NA	✓

Table 3-2. Functional Requirements by Element Pair (Cont.)

Requirement	Low EO MSS						MSS ARAM			CPS CLS						
	EOS	SPACE TUG	MSS ARAM	MSS DRAM	RESUP MOD	MSS	EOS	SPACE TUG	MSS	EOS	SPACE TUG	RESUP MOD	CPS OIS	CPS CLS	OLS	OPD
18. Fluid Line Purging	√	√	√	√	√	√	NA	NA	√	√	√	√	√	√	NA	√
19. System Verification	√	√	√	√	√	√	NA	NA	√	√	√	√	√	√	√	√
20. Hatch Seal Verification	√	√	√	√	√	√	NA	NA	√	√	√	√	NA	√	NA	√

Table 3-2. Functional Requirements by Element Pair

Requirement	RNS							OLS					
	EOS	SPACE TUG	RESUP MOD	CPS OIS	RNS	OLS	OPD	EOS	SPACE TUG	CPS OIS	CPS CLS	RNS	OLS
1a. Jet Trans Alignment	√	√	√	√	√	√	√	√	√	√	√	√	√
1b. Manip Alignment	–	–	X	NA	X	NA	NA	–	–	NA	NA	NA	√
2. Control of Mech Ext Dynamics	√	√	√	√	√	√	√	√	√	√	√	√	√
3. Prealignment of Sep Aids	√	√	√	√	√	√	√	√	√	√	√	√	√
4. Min Sep Dist	√	√	√	√	√	√	√	√	√	√	√	√	√
5. Cont Sys Monitoring	√	√	X	√	√	√	√	√	√	√	√	√	X
6. Plume Impingement Control	√	√	√	√	√	√	√	–	–	–	–	–	–
7. Separation Sensing	√	√	√	√	√	√	√	√	√	√	√	√	√
8a. Ground Comm Link	NA	√	X	√	X	√	√	NA	√	√	√	√	X
8b. Duplex Voice Link	√	√	X	NA	X	NA	NA	√	√	NA	NA	NA	NA

Table 3-2. Functional Requirements by Element Pair

Requirement	RNS							OLS					
	EOS	SPACE TUG	RESUP MOD	CPS OIS	RNS	OLS	OPD	EOS	SPACE TUG	CPS OIS	CPS CLS	RNS	OLS
8c. Data Link	✓	✓	X	NA	X	NA	✓	✓	✓	NA	✓	✓	X
9. Tunnel Press Vent	✓	✓	NA	NA	✓	NA	✓	✓	✓	NA	NA	NA	✓
10. End Effector Engage Verif	✓	✓	X	NA	X	NA	NA	–	–	NA	NA	NA	✓
11. Att Ref Alignment	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
12. Prop Venting Control	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
13. Mating Port Protection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14. Backup Release	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15. Illumination	✓	✓	✓	–	–	–	–	✓	✓	NA	✓	✓	✓
16. Elect Deadfacing	✓	✓	–	✓	✓	NA	✓	✓	✓	NA	NA	NA	✓
17. IVA Disconnects	✓	✓	✓	NA	✓	NA	✓	✓	✓	NA	NA	NA	✓
18. Fluid Line Purging	✓	✓	✓	✓	✓	NA	✓	✓	✓	NA	NA	NA	✓

Table 3-2. Functional Requirements by Element Pair

Requirement	RNS							OLS					
	EOS	SPACE TUG	RESUP MOD	CPS OIS	RNS	OLS	OPD	EOS	SPACE TUG	CPS OIS	CPS CLS	RNS	OLS
19. System Verification	✓	✓	✓	✓	✓	✓	✓	✓	✓	NA	✓	✓	✓
20. Hatch Seal Verification	✓	✓	✓	NA	✓	NA	✓	✓	✓	NA	NA	NA	✓

Table 3-2. Functional Requirements by Element Pair

Requirement	OPD						
	EOS	SPACE TUG	RESUP MOD	CPS OIS	CPS CLS	RNS	OPD
1a. Jet Trans Alignment	✓	✓	✓	✓	✓	✓	✓
1b. Manip Align	–	–	X	NA	NA	NA	X
2. Control of Mech Ext Dynamics	✓	✓	✓	✓	✓	✓	✓
3. Prealignment of Sep Aids	✓	✓	✓	✓	✓	✓	✓
4. Min Sep Dist	✓	✓	✓	✓	✓	✓	✓
5. Cont Sys Monitoring	✓	✓	X	✓	✓	✓	X
6. Plume Impingement Control	✓	✓	X	✓	✓	✓	–
7. Separation Sensing	✓	✓	✓	✓	✓	✓	✓
8a. Ground Comm Link	NA	✓	X	✓	✓	✓	X
8b. Duplex Voice Link	✓	✓	NA	NA	NA	NA	NA

Table 3-2. Functional Requirements by Element Pair

Requirement	OPD						
	EOS	SPACE TUG	RESUP MOD	CPS OIS	CPS CLS	RNS	OPD
8c. Data Link	√	√	X	NA	√	√	X
9. Tunnel Press Vent	√	√	√	NA	NA	NA	√
10. End Effector Engage Verif	-	-	X	NA	NA	NA	X
11. Att Ref Alignment	√	√	X	√	√	√	X
12. Prop Venting Control	√	√	X	√	√	√	X
13. Mating Port Protection	√	√	√	√	√	√	√
14. Backup Release	√	√	√	√	√	√	√
15. Illumination	√	√	X	√	√	√	X
16. Elect Deadfacing	√	√	√	√	√	√	√
17. IVA Disconnects	√	√	√	NA	√	√	√
18. Fluid Line Purging	√	√	√	√	√	√	√

Table 3-2. Functional Requirements by Element Pair

Requirement	OPD						
	EOS	SPACE TUG	RESUP MOD	CPS OIS	CPS CLS	RNS	OPD
19. System Verification	✓	✓	X	NA	✓	✓	X
20. Hatch Seal Verification	✓	✓	✓	NA	✓	✓	✓

3.7 DESIGN INFLUENCES & PREFERRED APPROACH SELECTION

Two approaches to separation have been considered: jet translation and manipulator extension. Both concepts can be performed manually or automatically and both offer significant advantages. The jet translation offers low cost simplicity because at least one of the separating elements for all pairs will be equipped with an RCS system that could be used for the separation task. The manipulator offers a more safe approach in that the elements can be physically separated some distance before independent operations commence. Table 3-3 compares these and additional factors to determine if there are any significant advantages or disadvantages for using one system as opposed to the other.

EVALUATION FACTORS

The following paragraphs are the rationale for the preferences identified in Table 3-3.

Technology

Jet translation separations, both automatic and manual, have been occuring since the start of the space program. The only new problem is the separation of an element within a narrow corridor (e.g., separation of a RAM from a MSS); however, this is not considered a difficult task and should present no real design problem.

Manipulators are new to space. They are made up of numerous mechanisms that will be exposed to the space environment. The manipulator will be required to separate an element from a mating port, maneuver it away from the other element, orient it, and stabilize it is a prescribed position. These tasks are somewhat easier to accomplish than a manipulator capture and berth operation, because unlike the mating operation, for separation the geometry between all elements and components is fixed. However, the hardware technology will still require more development than that required for jet translation.

Table 3-3. Separation Approach Comparison

FACTORS	ALTERNATES			
	JET TRANSLATION		MANIPULATOR	
	MANUAL	AUTOMATIC	MANUAL	AUTOMATIC
Technology	Preferred-state-of-the-art	Acceptable-technology available	Least preferred	Least preferred
C/O Maintenance	Preferred-least parts/complexity	Acceptable-adds alignment/range sensors	Not acceptable-except on elements that periodically return to ground	Not acceptable-except on elements that periodically return to ground
Safety	Acceptable	Acceptable	Preferred-provides a separation before independent operations commence	Preferred-provides a separation before independent operations commence
Reliability	Preferred-least parts	Acceptable-with redundant sensors	Least preferred-Multiple parts	Least preferred-multiple parts
Commonality	Acceptable-still requires automatic jet translation	Preferred-commonality across all element pairs	Least preferred	Least preferred
Relative Cost	Least cost	Low cost	High cost	High cost
Plume Impingement	High	High	Low	Low
Near Term Bias	Preferred	Acceptable	Least Preferred	Least Preferred
Far Term Bias	Preferred	Acceptable	Least Preferred	Least Preferred

Checkout/Maintenance

Elements that return to ground periodically can be easily maintained whether the concept is jet translation separation or manipulator extension. However, if the elements must be maintained in orbit, this maintenance is a rather complex problem. Reaction engines will be used for separation for only short periods. They will be used for much longer periods to maneuver the element for orbital operations. Therefore, their checkout and maintenance is a function of extended operational reliability, and the short separation usage is considered non-scalable over the long term usage. The sensors required for automatic separation are, therefore, the only hardware specifically identifiable for jet translation separation that should be compared. Because this equipment can essentially be protected from the space environment and, for the most part, is constructed using solid state electronics, maintenance time should be relatively low. Also, because the equipment is small and of black box design, maintenance in-orbit should be a simple task. Manipulators on the other hand have to be maintained by EVA or must be returned to ground for maintenance. EVA maintenance of a manipulator does not appear to be within the present state-of-the-art. Sensor replacement or simple plug-in devices are feasible, but, torquing motors, clutch mechanisms, cables, and structural arms do not lend themselves to designs that are EVA repairable and still be suitable to the space environment. If the element that the manipulator is installed on does not periodically return to ground for maintenance, then the manipulator itself must be an IFRU (in-flight replaceable unit). An IFRU designed manipulator will require additional complexity making it even less maintenance free. Therefore, it is considered that for separation alone, manipulators are acceptable only on an element that periodically returns to ground for maintenance.

Safety

Neither the jet translation or the manipulator separation concept is unsafe. The manipulator is a more complex design, but provides the capability of physically separating the elements by some distance before independent operations commence. This separation distance for many elements is great enough that a stuck-on jet applying pure rotation to an element will not result in a collision between the two separated elements. This separation distance also provides additional time for an element to take evasive maneuvers, should a separated element go out of control.

One safety problem is that of latch hangup. Failure of a mating port latch to release at time of separation can result in an angular rotation of the mated elements which if not nulled out results in vehicle collision or, at the very least, the latch will break. With a manipulator available, this problem will not pose an immediate hazard. The manipulator will hold the separating element in place until the latch can be released by some other means or the manipulator can force the element back into a mate and the latch mechanism inspected, repaired, or the separation recycled. In general, the manipulator separation concept is considered to be the more safe alternate. Failure of the manipulator end effector to release is also not considered an immediate hazard. However, the design can incorporate redundant features (i.e., end effector released).

Reliability

As previously pointed out, under checkout and maintenance when we weigh jet translation separation against manipulator separation, we are essentially comparing the sensor devices required for automatic jet translation against a manipulator. Because the sensors are protected within an element and are of solid state design, whereas a manipulator is exposed to space and is comprised of many mechanical mechanisms, there is no doubt that manipulator reliability equivalent to jet translation reliability would be difficult to achieve. Therefore, for the separation activity, manipulators are least preferred. With redundant manipulators, the concept is still not competitive with jet translation.

The reliability of a manual jet translation as opposed to an automated approach gives preference to the manned operation because of the added hardware required for the automatic concept.

Commonality

Because all element pairs that will be separated will have an inherent capability of performing a jet translation separation and all element pairs will not be equipped with a manipulator, the jet translation concept will naturally exhibit the most commonality. The automatic jet translation approach provides the highest commonality between elements because the approach can be used across the full array of mating pairs (manned or unmanned). The manual jet translation separation is relatively similar to automatic jet translation and is, therefore, rated only slightly less common. The manipulator approach is an entirely different concept and is rated least common. The automated manipulator concept could be employed for all element pairs, but a design that is applicable for all element pairs is very unlikely.

Relative Cost

If we assume that a RCS must be available for operations other than separation alone, then the only costs assocaited with jet translation are the alignment and range sensors and their associated interfaces. If a manipulator is used for only separation, then this cost would be very high compared with jet translation. Not only does the manipulator weigh more (reduced payload capability), but its interfaces and complexity far exceed that of the jet translation separation sensors.

For this factor, the manual jet translation is the least cost with the automatic jet translation considered only slightly higher.

Plume Impingement

Although all elements are susceptible to jet plume contamination (radiators, hatch windows, optics, etc.) the ones most susceptible are the MSS, RAMs, and satellites because of their scientific sensors that are exposed to the environment. It is assumed that all free-flying elements are designed to preclude damage to their sensors from their own jets. Therefore, only element pair operations must be evaluated.

The obvious solution to the plume impingment problem is to achieve sufficient physical separation between two elements prior to initiation of any jet thrusting. Use of a manipulator of an appropriate length could achieve this goal for some engine sizes and separation distances. Some of the factors that sufficient physical separation are dependent upon are (1) the susceptibility of the sensors, (2) the propellant used, (3) the thruster size, and (4) the location of the jets. The results of the plume impingement analysis (Trade Study A4, Appendix A) as they pertain to the MSS, RAM's and satellites are summarized below.

Contractor configurations of the EOS have included jet clusters on the wing tips, tail, nose, and main fuselage. The various locations were proposed to achieve efficient EOS translation as well as minimize plume impingement on EOS payloads such as RAMs and satellites. All configurations that were examined precluded plume impingement on payloads in the cargo bay. However, upon deployment some configurations did expose the payload to EOS jet plume. Figure 3-18 illustrates one of the configurations. Note that the payload is not in the exhaust stream until it is more than 30 feet from the cargo bay of the EOS.

Results of tests with 25-pound hydrazine thrusters indicated that there was minor degradation in performance of some sensors mounted 10 feet axially from the jet. Extrapolation of these tests results to correspond to the 1000-pound jets proposed for minor translation (separation) maneuvers of the EOS indicated similar contamination would occur at distances of approximately 60 feet from the EOS engines. The jet locations illustrated in Figure 3-18 result in separation distances between a deployed payload and EOS jets of 90 to 100 feet. Also, the payloads are not in line with the centerline of the jets. Thus, the contamination on deployed payloads would be significantly reduced from that evidenced in the 25-pound thruster tests. However, some contamination would still occur. Use of a manipulator in this configuration would not alleviate the potential problem.

Figure 3-19 illustrates another EOS jet configuration that essentially provides a core of contamination-free operational volume directly above the cargo bay. This volume is not dependent upon the use of the manipulator; rather, it is a result of the judicious placement of the EOS jets.

In the case of the MSS, the elements that interface with it and may cause plume impingement problems are the EOS, tug, and DRAMs. The MSS contamination problem can readily be avoided in the case of the EOS and tug by performing mating and separation maneuvers at an isolated port such as at the end of the core module. DRAMs may dock to side ports on a core module and contamination of adjacent modules could occur. If a manipulator

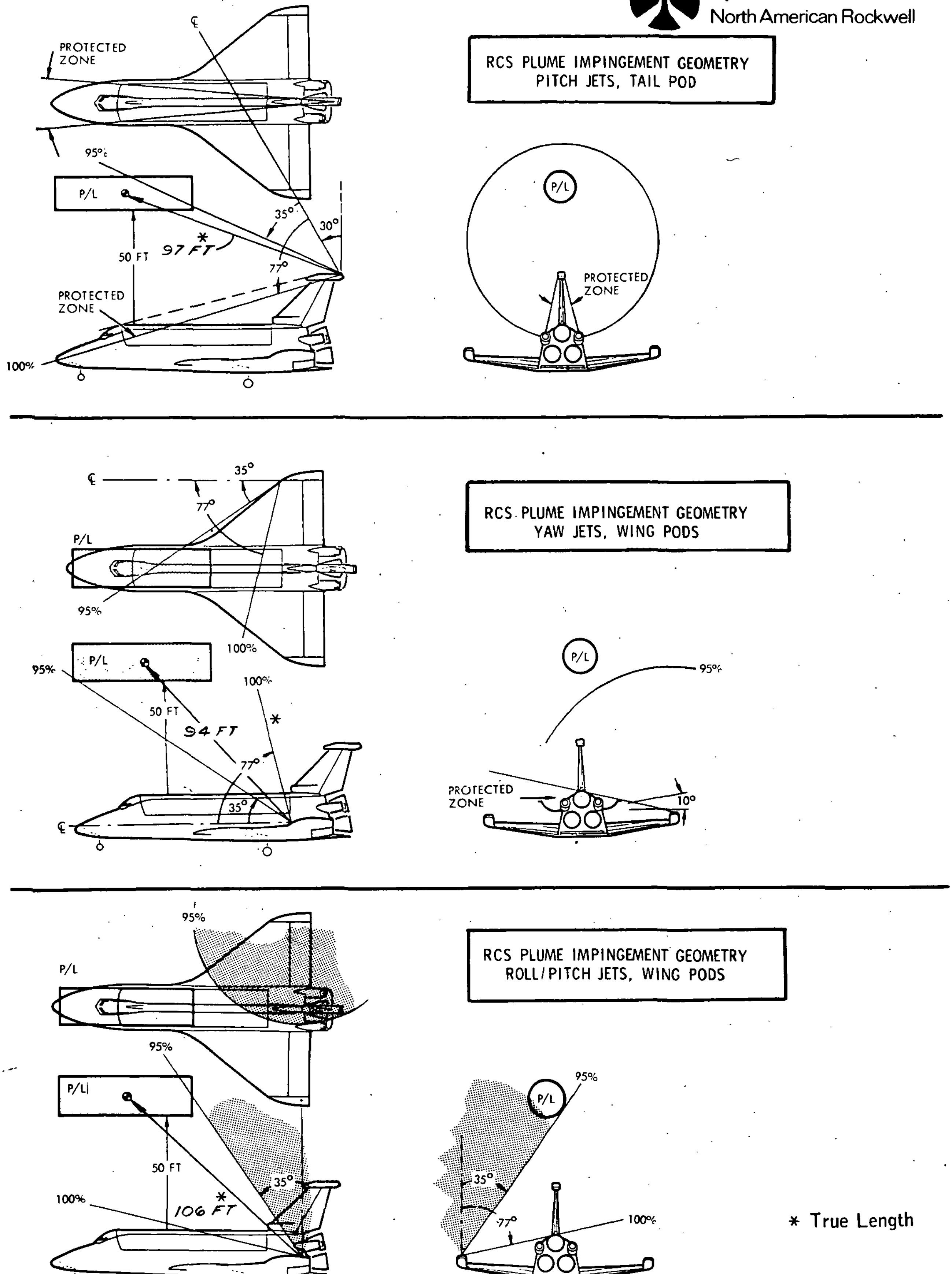


Figure 3-18. Basic Shuttle Jet Configuration

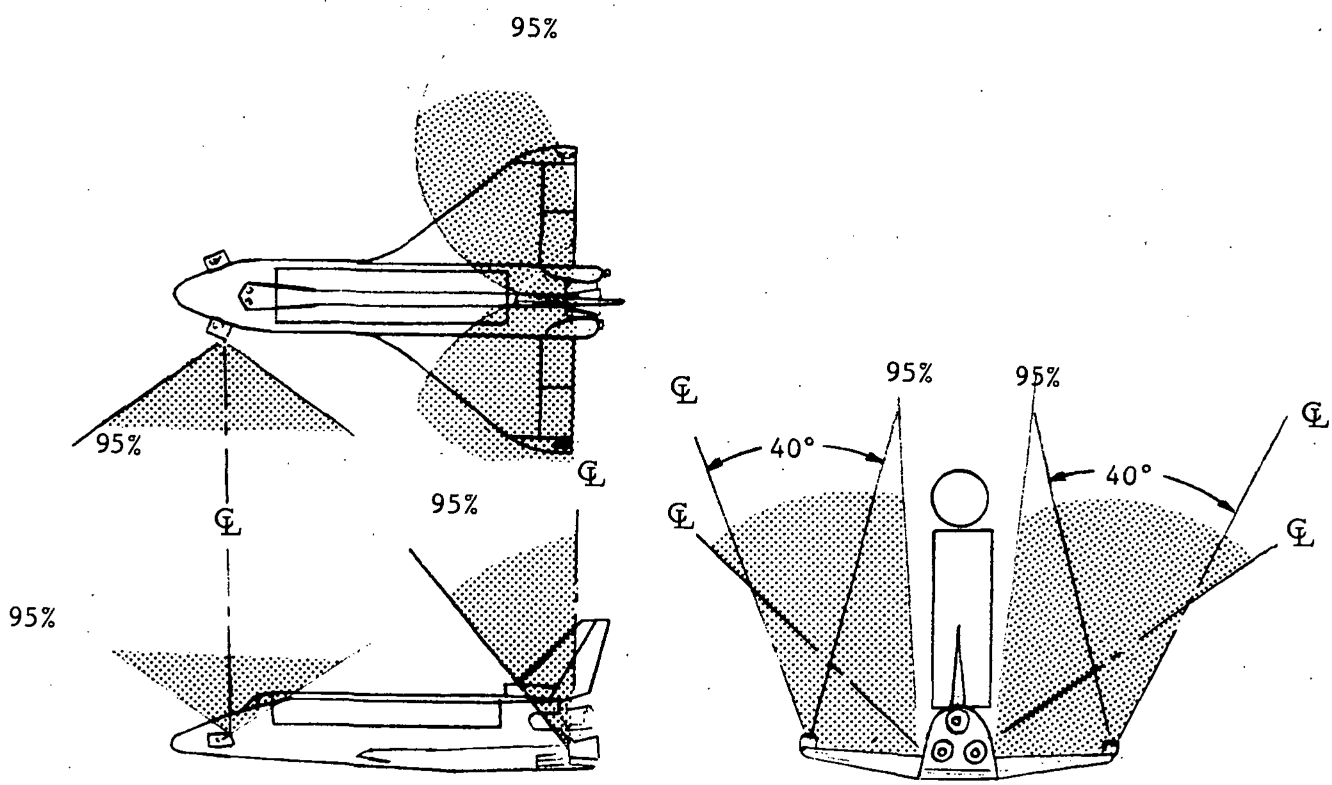


Figure 3-19. Modified EOS Jet Configuration

were included on the MSS, the DRAM could be separated and positioned some 50 feet away before jet translation is initiated. If jet translation is used the service ports for DRAM's must be carefully designated to preclude damage to adjacent modules. That is, DRAM ports on the MSS would be adjacent to MSS modules that do not contain exposed sensors. The same placement criteria would apply to RAM modules integral to the MSS complex.

RAM's that interface with tugs must be designed to be compatible with the tug jet plume during transport and attitude control operations. At separation the free-flying RAM could perform the translation maneuver. Similar criteria apply to the tug-satellite interface.

Although a manipulator or extension device could provide a limited distance between elements prior to separation maneuvers it would not necessarily preclude jet plume impingement problems. Required thrusting during mating and attached operations as well as separation operations must be considered. The most effective and efficient method to circumvent the problem is the careful selection of jet locations.

Near Term Bias

The near term bias is essentially a function of the programmatic implications for each of the approaches. Jet translation for separation is a demonstrated concept and can be readily implemented. Manipulators are currently under development. It would appear that the demonstrated concept, jet translation, that requires no additional element hardware would be the least risk approach.

Far Term Bias

There is no evidence to evaluate that a manipulator will prove to be more beneficial over the long term program than it is for the short term program considering separation applications only. All factors will remain essentially the same because the critical elements, RAM's and satellites--are included throughout the projected 10-year space program. Therefore, the far term bias also prefers jet translation as the selected approach.

Conclusion

Jet translation is the preferred approach for all separation operations. It is less costly, requires little or no additional equipment than already included in the elements, has been demonstrated to be a safe concept, and can be utilized for all element pairs. If a manipulator is included in the program and especially as part of the EOS it could be used for separation with negligible impact on elements originally defined for separation by jet translation.

SYNERGISTIC INFLUENCES

As pointed out previously the jet translation concept does make multiple use of a single set of equipment. Translation (for mating as well as separation), attitude orientation, and stabilization all use the same equipment. Trade study A-5 in Appendix A indicate potential synergistic benefits derived from inclusion of a manipulator in the EOS. It could be readily used for separation and does provide a margin of safety over that of the jet translation concept. However, manipulator separation is not practical for all element pairs. The jet translation concept would still be required. Thus the preferred approach for separation even upon consideration of other interfacing activities is still jet translation. Note that this selection does not preclude the use of the manipulator if it is available for other reasons.

DESIGN INFLUENCES

The selection of jet translation will have the minimum influence on the design of any element. The hardware required for separation is essentially only jet translation capability which will be available on at least one vehicle of all mated element pairs for normal orbital operations. The manipulator end effector receptacle and the laser radar transceiver are extensions of the mating hardware.

Table 3-4 identifies the preferred hardware for each noted element based on the preferred conceptual approaches for separating the various element pairs. The following paragraphs are a synopsis of why each piece of hardware was allocated to the noted elements.

Manipulator End Effector Receptacle

This is the interfacing receptacle for a manipulator if it is included on the EOS orbiter. It is allocated to those elements that are most probable to be plume impingement sensitive.

Jet Translation Capability

This capability is allocated to the logistics vehicles. Each of these elements perform jet translation separations from multiple elements. The single exception is the MSS supported DRAM which may be required to free fly between the MSS and its operational orbit. For such a case, the DRAM will perform the translational separation with the MSS providing backup assistance, if required.

Laser Radar Transceiver

As noted, the only time alignment maintenance during separation is critical is when a module is separated from between other modules on an MSS or OLS. Because manned logistics elements can successfully perform a separation using direct visual alignment aids, where man is available, as in the case of an EOS orbiter, this will be the mode. For elements that may or may not include a man, such as the space based tug, the laser radar concept is recommended. The MSS is provided a laser radar as a backup tool for the critical separations and for guiding a free flying DRAM during its separation. The OLS is not equipped with a transceiver because it will be unmanned during most of its low earth orbital assembly operations. It may be that its operations in lunar orbit will include the requirement; however, it is not necessary for low earth orbital operations.

Passive Laser Radar Reflectors

The radar reflectors are installed on elements that will be separating from an element that is equipped with a laser radar transceiver.

TV Camera

An option to the information provided by a laser radar system is a TV camera directly viewing the separation and transmitting the data to a remote control center. The accuracy of the information is much less, however, if general characteristics are acceptable, the TV camera is the least cost. Because the unmanned logistics elements (return tug, space based tug, CPS, and RNS) all perform non-critical alignment separation, the TV camera will efficiently provide any necessary data.

Table 3-4. Separation Hardware Preference

HARDWARE	ELEMENT													
	EOS	RTN Tug	Space Based Tug	EOS DRAM	MSS ARAM	MSS DRAM	SAT	EO Resup Mod	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD
Separation Extension Device	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Extension Device Recept	-	-	-	X	-	X	X	-	-	-	-	-	-	-
Jet Translation Capability	X	X	X	-	-	Note 1	-	-	-	X	X	X	-	-
Laser Radar XCVR	-	-	X	-	-	-	-	-	X	-	-	-	X	-
Passive Laser Radar Reflect	-	-	X	-	X	X	-	X	X	-	-	-	X	-
TV Camera (Note 2)	-	X	X	-	-	-	-	-	-	X	X	X	-	-
Direct Visual Align Scope	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Visual Alignment Targets	-	-	-	-	-	-	-	-	X	-	-	-	X	-

NOTE 1: The MSS-supported DRAM requires translation capability if it is to free-fly and direct-dock to the MSS.

NOTE 2: TV camera is an option to the laser radar and passive reflectors. TV coverage to a remote site will provide the same information at lesser accuracy than radar alignment sensors, but vehicle control can be directly integrated with the laser radar concept and not with TV.

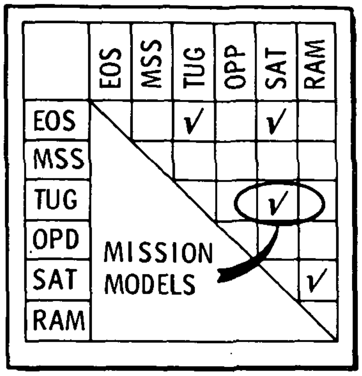
Direct Visual Alignment Scope

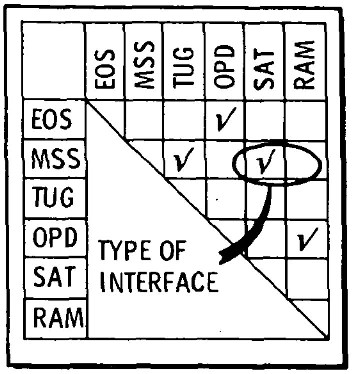
This hardware is allocated to the EOS orbiter only because it is the single logistics element that is always manned and does not require the more expensive laser radar hardware to perform a jet translation separation. If the laser radar equipment is available for mating, it should be implemented for separation as well.

Visual Alignment Targets

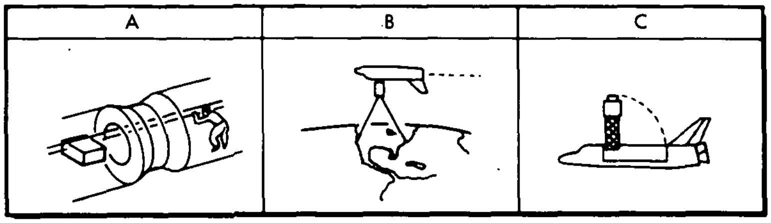
Visual alignment targets are required on the MSS and OLS only. These are the elements which the EOS orbiter separates from and can involve a relatively critical alignment during the separation.

ELEMENT INTERFACES

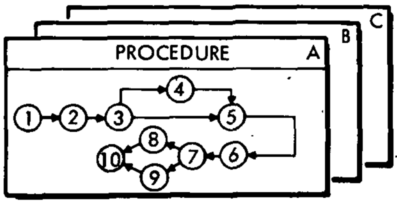


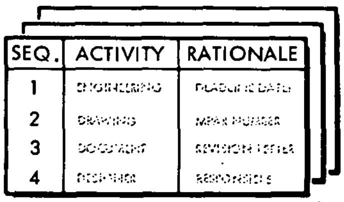


ALTERNATE APPROACHES AND DESIGN CONCEPTS

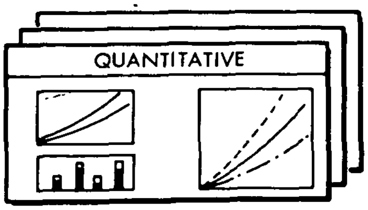


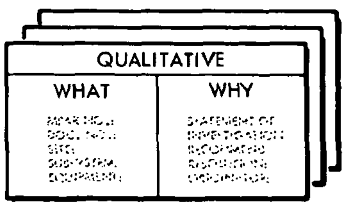
OPERATIONAL PROCEDURES



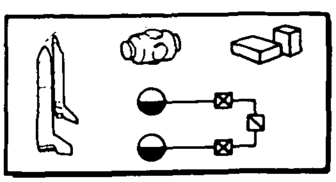


FUNCTIONAL REQUIREMENTS





DESIGN INFLUENCES AND APPROACH SELECTION



	SAFETY	COST	PERF
A	√	√	
B		√	
C			√

4.0 EOS PAYLOAD DEPLOYMENT

4.0 EOS PAYLOAD DEPLOYMENT

4.0 EOS PAYLOAD DEPLOYMENT

A major objective of many earth orbital shuttle (EOS) missions is the delivery of a payload from the earth's surface to a specified earth orbit. Attainment of this objective necessitates removal of the payload from the EOS orbiter cargo bay and readying it for separation and/or operation. The group of actions associated with this activity have been designated as EOS payload deployment interfaces. Because the EOS will be the principal means of delivery of satellites, tugs, and modular space systems to earth orbit, this interface will occur on some of the earliest EOS flights and will become more frequent as the EOS program progresses.

EOS payload deployment is closely related to another interfacing activity designated as EOS payload retraction and stowage. The obvious weight advantage makes it highly desirable that, if possible, both activities be performed with common hardware. Thus, approaches and requirements for both activities must be evaluated to determine if commonality can be accomplished.

4.1 SUMMARY

Within the interfacing activity of Earth Orbital Shuttle (EOS) payload deployment there are 23 possible element-to-element interactions relating to the 24 elements of the space vehicle inventory. This high vehicle involvement made commonality and adaptability prime considerations in the evaluation and determination of a preferred approach selection. This high level of EOS involvement was also evident in the mission models. In all but two of the mission models (MM-6 and MM-9) EOS payload deployment may be involved.

Five deployment approaches were identified as potential candidates to handle the deployment of payloads from the EOS cargo bay. Three of the original choices were eliminated considering safety, technology, and similarity to operational characteristics of other candidates. The two approaches selected for further study were (1) on-board manipulation and (2) pivot mechanism.

It is necessary to define design concept models to be able to evaluate the applicability of each approach for all elements of the vehicle inventory. Models were defined for the principal hardware concepts of the manipulator and the pivot mechanism. While at a lower level than the two approaches being evaluated; payload retention concepts were considered important enough to have design models defined for evaluation. The analysis of the retention devices was conducted not to select the "best" retention method but to assess the impact that both approaches would have on payload retention requirements.

Two operational procedures were developed for EOS payload deployment, one for each of the alternate approaches selected for further study. These procedures were used in the approach selection analysis and were evaluated along with their hardware concepts to select a preferred approach for each element pair. Analysis was made of the applicability of these two procedures to each element pair and also across the interfacing activities of deployment and retraction/stowage. The third part of this analysis was the examination of the commonality and applicability that exists between the two approaches. This applicability analysis is especially important because it is envisioned that the majority of EOS flights will have requirements that both deployment and retraction be performed on the same mission. A combined EOS payload deployment/retraction and stowage procedure was developed and used in the evaluation.

A preferred approach selection cannot be completed without an understanding of what requirements have to be met to accomplish the task; therefore, functional requirements were developed for a wide range of payload types. Some of the requirements developed related only to the EOS and in particular to the manipulator.

Selection of a preferred approch for EOS payload deployment was made with the commonality between this interfacing activity and EOS payload retraction and stowage being a primary consideration. Another equally important consideration was the ability of each approach to handle payloads that are unique in some respect such as those design-sensitive payloads that require a specific launch configuration (satellite that must be launched with one specific end vertical). The deployment approach selected had to be capable of meeting a wide spectrum of payload types and requirements.

Also included in the selection process was the interrelationship between deployment and mating, separation and orbital assembly. The ability of each approach to support these activities was added to the selection process to enlarge the scope of the commonality and applicability analysis. If these selections were made independently of the potential commonality between activities, then the choices might have varied significantly. An important point that must be considered when reviewing the selection made was that this interfacing activity includes only the interactions and interfaces of the EOS to each payload element. Therefore, when an analysis was made of the adaptability of each approach to another activity (i.e., orbital assembly), it was made with the ground rule that the EOS would be on orbit to assist in this orbital assembly. It did not consider the aspects of orbital assembly between vehicles like an OPD and a tug.

The analysis of EOS payload deployment requirements indicated that both approaches are necessary. The selection was not made based entirely on the requirements of deployment alone. It had a wider scope. Also included in the analysis were the requirements of other interfacing activities, namely, Mating, Separation and Retraction and Stowage. The selection made for the deployment or retrieval of single payloads is the pivot mechanism. It was selected primarily because of its simplicity and lower cost. With the addition of an extension/retraction device and special latches it can be adapted to handle the deployment and retrieval (mating) of small satellites.

The selection of a manipulator to be used in EOS payload deployment was driven by the handling of multiple payloads. Developing a rack or strong back mechanism for multiple payloads would reduce the effective diameter of the bay (from its present 15 feet). The manipulator would be utilized to deploy these payloads sequentially and would represent a minimum impact on the payloads themselves. If developed, the manipulator would have increased benefits to small satellites in both their deployment and retrieval. It would eliminate the necessity for mating ports on some of the satellites. For those that function with a tug or kick stage the end effector receptacle (6 - 10 lb weight penalty) would be an additional aid in the retraction of these small satellites because the problems associated with the satellite and orbiter mass differences is significantly reduced. These retrieval (mating) and retraction/stowage benefits were evaluated because of the anticipated necessity of performing both deployment and retraction on the same mission (i.e., satellite recovery, servicing and redeployment missions.

4.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

Because the orbiter is capable of carrying and assemblying modules of the CPS, RNS, and other large elements in orbit, EOS payload deployment activities could involve 24 of the 25 elements in the space vehicle inventory. Only the orbital insertion stage and the orbiter itself cannot be considered as a potential EOS payload. By definition, the orbiter is always one of the elements involved in the interface. Thus, there are 23 possible element-to-element interactions relating to EOS payload deployment. These are indicated in the top row of the matrix displayed in Figure 4-1.

Figure 4-2 utilizes the same matrix that was used to identify EOS payload deployment interactions to identify the types of missions where this activity may be involved. Eleven reference missions have been identified for this study and are described in detail in Appendix C. The matrix cross-references the applicable mission using the corresponding mission identification numbers 1 through 11. Mission models 1, 2, and 5 are the most frequently mentioned. In Missions 1 and 2 the EOS is the delivery vehicle. They are emplacement and logistics/retrieval missions and, as expected involve EOS payload deployment. Mission model 5 utilizes the Space Based Tug as the delivery vehicle. It is a logistics mission and again as expected there is frequent EOS payload deployment activity.

In all but two of the mission models, MM-6 and MM-9 (ref. DS530), EOS payload deployment may be involved. Neither of these two mission models, which relate to tug disposal missions and insertion of heavy payloads into orbit using an OIS, involve the EOS orbiter. The matrix shown in Figure 4-2 contains the mission model numbers that identify particular payload deployment interactions between the orbiter and the other elements in the inventory. A total of 86 such interactions were identified.

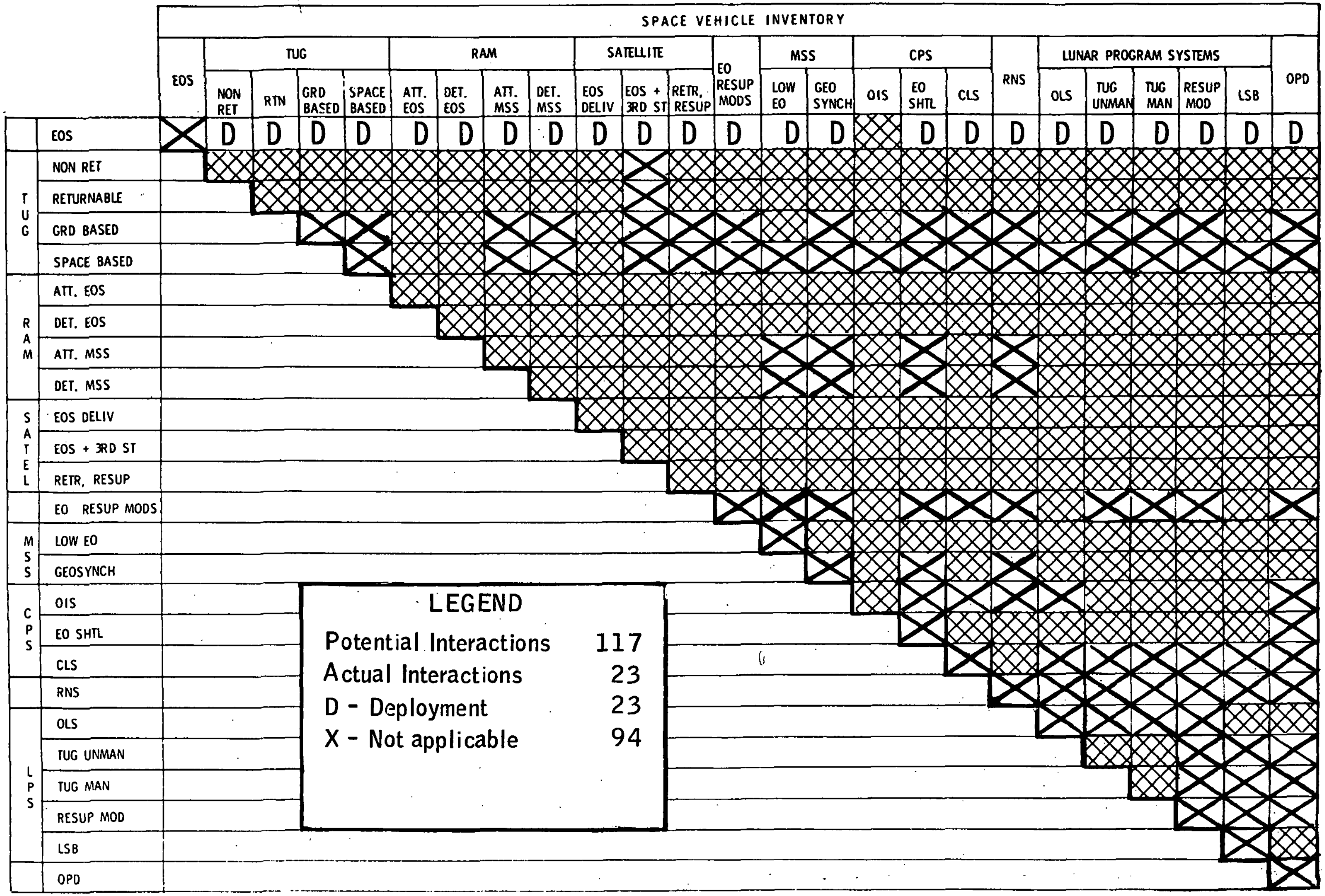


Figure 4-1. EOS Payload Deployment Interactions

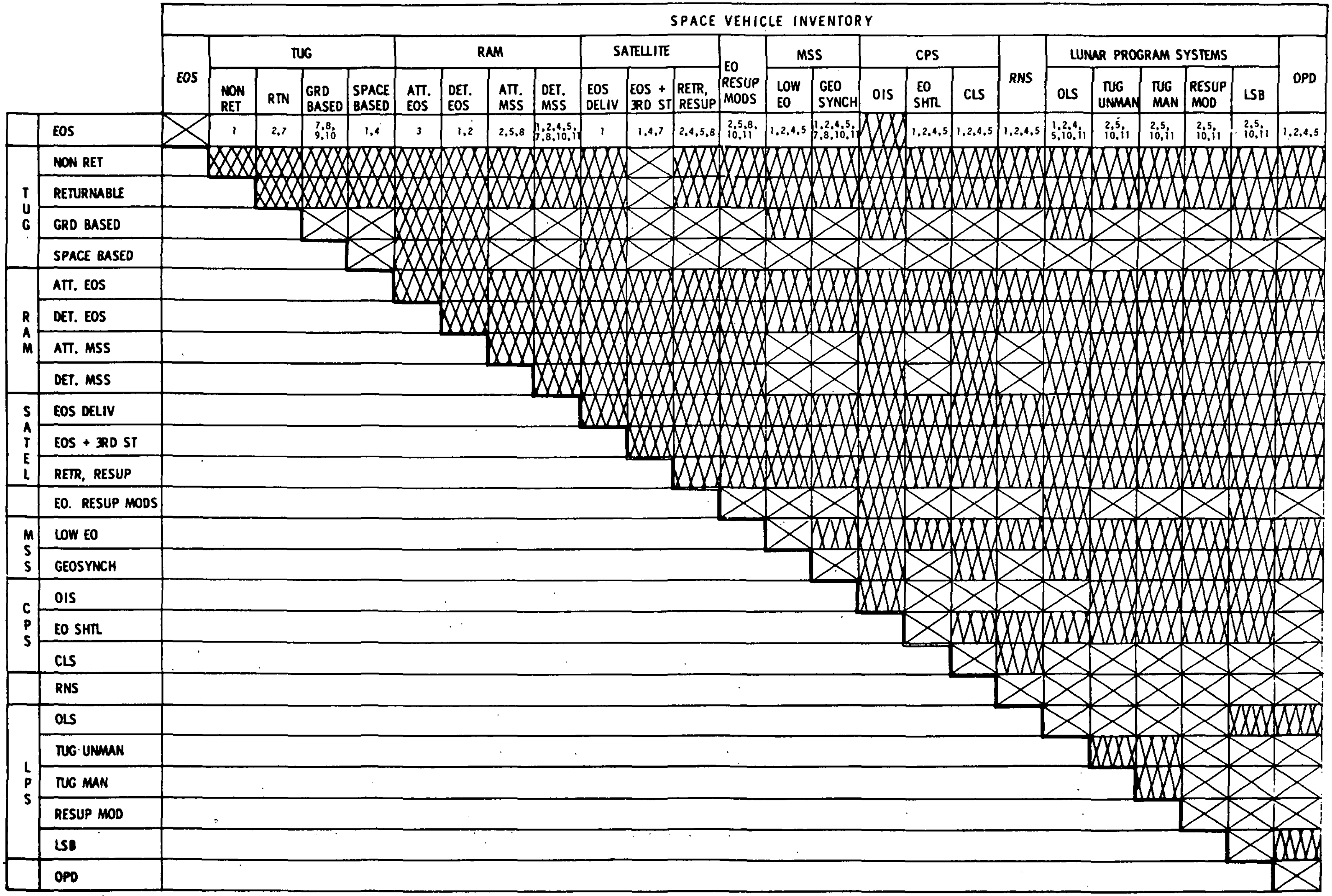


Figure 4-2. Applicable Mission Models for EOS Payload Deployment

4.3 ALTERNATE APPROACHES

There were five alternate approaches studied as possible candidates for deployment of a payload from the orbiter cargo bay. The approaches for EOS deployment are illustrated in Figure 4-3. The five are:

1. manipulator
2. teleoperator
3. EVA and AMU
4. lateral translation
5. pivot mechanism

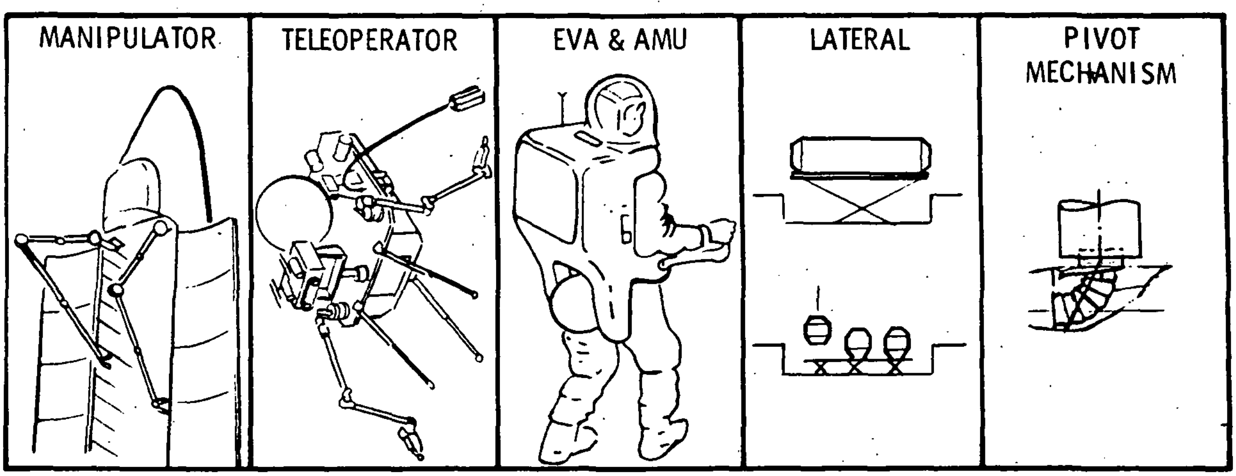


Figure 4-3. Alternate Approach

The deployment function can be accomplished in either of two modes, (1) extracting the payload with a manipulator or (2) pivoting and/or elevating it to a position outside the orbiter moldline where it can be operated or released. The following paragraphs are a description of each approach.

MANIPULATOR

The manipulator is an articulating boom with multiple degrees of freedom provided by joints, elbows, and pivots. The manipulator approach has three major assemblies: (1) a support platform - the EOS orbiter, (2) articulated arms - 2, and (3) tools. Power, command, and control must be provided by the orbiter for each assembly. The support platform maneuvers the arm assemblies into a position to perform the desired deployment functions. The manipulator arms produce the tool positioning motions and forces. They characteristically have multiple degrees of freedom; from three in simple systems to as many as eight in complex sophisticated installations. The control and skill requirements and mechanization complexity increases proportionally to the number of degrees of freedom.

TELEOPERATOR

The teleoperator approach is a system level concept and would be a separate spacecraft in element inventory. The teleoperator spacecraft illustrated in Figure 4-3, consists of a structure housing the spacecraft systems, a propellant supply tank, four sets of quad thrusters, a two axis camera mount, binocular TV cameras and lights, a single close-up TV camera, two manipulator arms with interchangeable end effectors, and three docking arms. Control of the teleoperator will be accomplished from a control station within the orbiter.

EVA AND AMU

The use of EVA and a orbiter crewman in an Astronaut Maneuvering Unit (AMU) is the most restricted of the five approaches. It utilizes, as illustrated in Figure 4-3, a suited crewman with a back pack. The back pack contains the crewman's life support, propulsion, attitude control, electrical power and communications/data. Attached to the back pack is the oxygen storage bottle. The front of the unit has two hand controllers, one for translation, the other for attitude hold. The hand controllers rotate down when not in use.

LATERAL TRANSLATION

The lateral translation approach provides a carriage assembly mounted on rails, screw jacks, etc., that laterally extend the payload beyond the moldline of the orbiter.

PIVOT MECHANISM

The pivot mechanism is a roational approach that pivots the payload 90 degrees with respect to the orbiter centerline. The pivot point can be located at either the forward or aft bulkhead of the cargo bay. There are options for flexible tunnels that can be added to the pivot mechanism to provide shirt-sleeve crew passage to the payload in either the stowed or deployed positions.

SELECTED APPROACHES

The five candidate approaches were reviewed and the following factors were used to select two approaches for further study.

	Approaches Eliminated	Rationale
(1)	Teleoperator	Because numerous Orbiter missions do not involve an element already on orbit, the teleoperator would have to "deploy" itself and therefore it reduces the effective cargo bay volume. It also adds another element to the vehicle inventory requiring an additional development program. It also has no signficant advantages over an EOS manipulator approach.
(2)	EVA with AMU	The EVA with AMU was rejected because of its potential hazardous operations. It was also severely limited in the size of payloads that could be handled. It also has the further disadvantage of being a new development.
(3)	Lateral translation	The lateral translation approach has been eliminated from further study consideration because all of the functional requirements, operational procedures and alternates associated with lateral translation devices do not vary sufficiently from the pivot mechanism to offer any significant advantage to studying this alternative.

Therefore the approaches that were selected for further study and analysis were: (1) pivot mechanism and (2) manipulator. The data is the remaining sections of EOS payload deployment were established utilizing these two approaches.

PRECEDING PAGE BLANK NOT FILMED

4.4 DESIGN CONCEPT MODELS

To be able to analyze the approaches that were developed specific hardware concepts were synthesized. They were used to evaluate the approaches and the viability of any hardware designs. In the interfacing activity of EOS payload deployment the EOS will be involved in 23 element-to-element interactions with the 24 elements of the space vehicle inventory. It is because of this principal involvement of the EOS that design concept models had to be defined for some of the major EOS/payload interfaces. The following are the models of EOS payload handling and servicing equipment that were utilized in the selection of a preferred element pair approach.

PAYLOAD ENVELOPE

Figure 4-4 shows the dimensions of the orbiter payload bay. Within this bay the payloads are accommodated. A 60-foot module would have 27 inches total clearance for its length and if it were 15-feet in diameter it would have a 3 inch clearance at the bottom of the bay and 5 inches on each side of the bay.

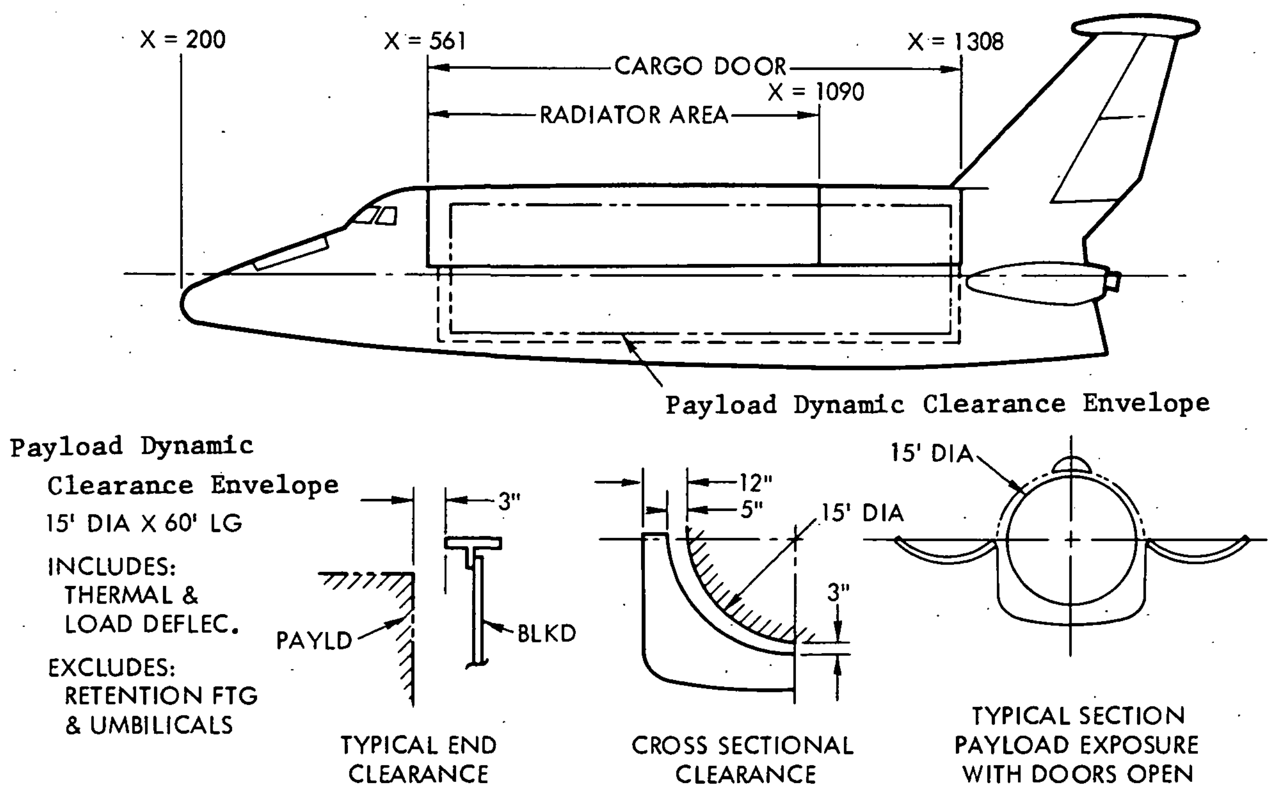


Figure 4-4. Orbiter/Payload Envelope

MANIPULATOR

The EOS manipulator approach (Figure 4-5) is a system consisting of two manipulator arms, a manipulator operator station, a payload retention assembly and IVA tunnel connecting the payload bay and the crew compartment. In their stowed position the arms are above the payload. Each arm is 50 feet long (from shoulder joint to tip of end effector), with a maximum diameter of 15 inches.

Although the manipulator concept is a system with two arms, each arm is sized to accomplish the functional requirements. Manipulator systems generally have three major assemblies: (1) a support platform (EOS orbiter), (2) articulated arms (3) and tools. Power, command, and control capability are supplied by the orbiter.

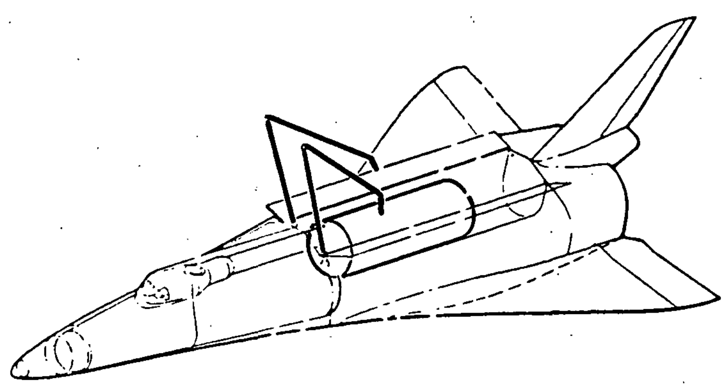


Figure 4-5. Manipulator/Payload Handling

Each arm has a shoulder, elbow, and wrist joint with two-degrees of rotational freedom at the shoulder, one degree of rotational freedom at the elbow, and three degrees at the wrist. The entire arm is capable of being jettisoned to allow closure of the cargo bay doors. Each joint is driven by redundant motors and is torque limited to prevent damage to the manipulator arm.

End effector tools (Figure 4-6) may be changed to accommodate specialized tasks. One TV camera and one floodlight are mounted near the end effector to illuminate and televise the work area.

Each arm is sized to individually deploy a 65,000-pound payload (15 feet in diameter by 60 feet) a distance of 50 feet vertically out of the cargo bay, and rotate it 90 degrees. This operation is completed in a maximum of 5.2 minutes (Figure 4-7).

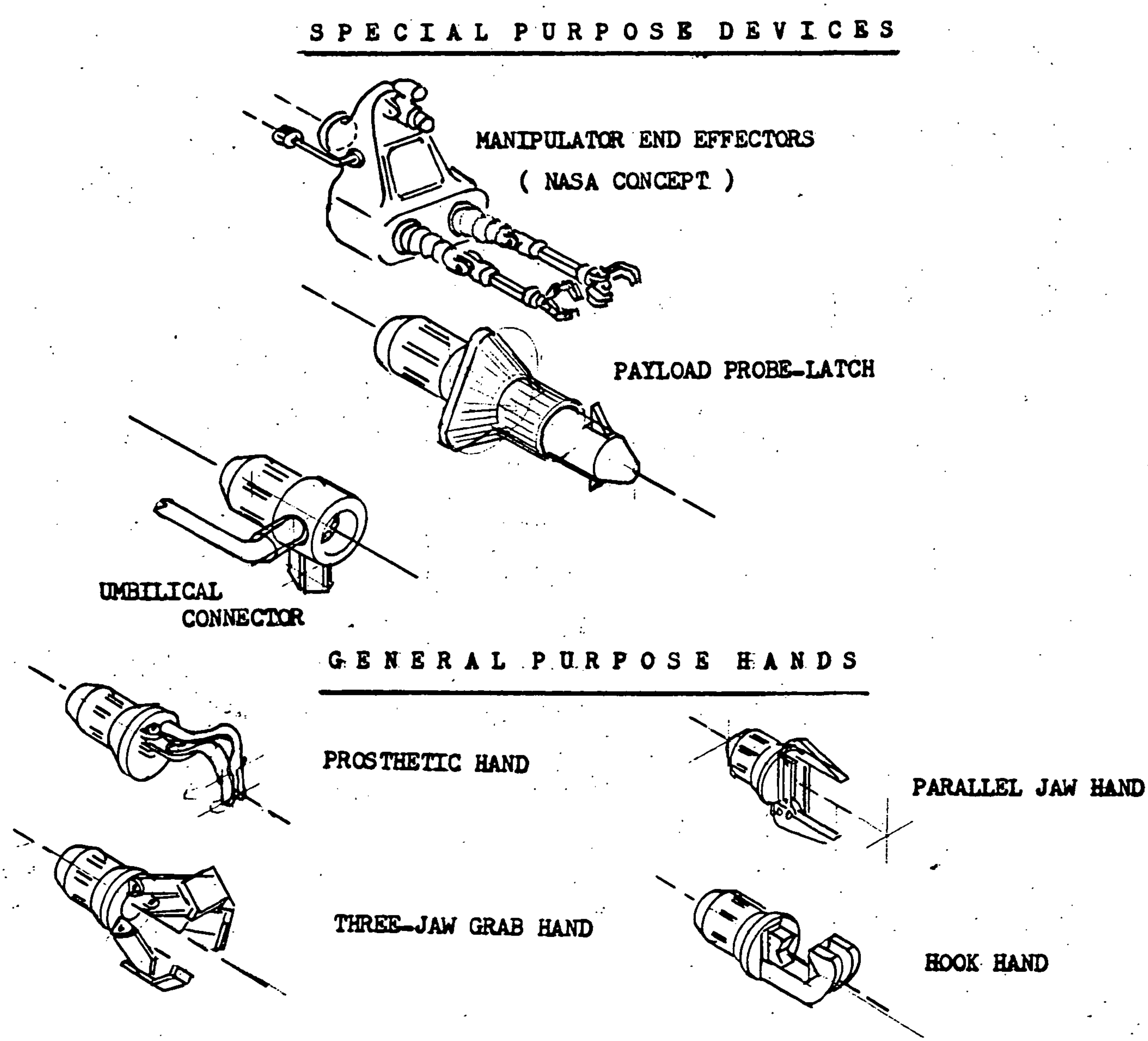


Figure 4-6. Classes of End Effectors

CENTER OF GRAVITY	DEPLOYMENT TIME (MINUTES) PAYLOAD WEIGHT			
	65K LBS.	45K LBS.	25K LBS.	10K LBS.
A	5.2	4.3	3.2	2.5
B	7.0	5.8	4.3	3.4
C	9.7	8.0	6.0	5.0

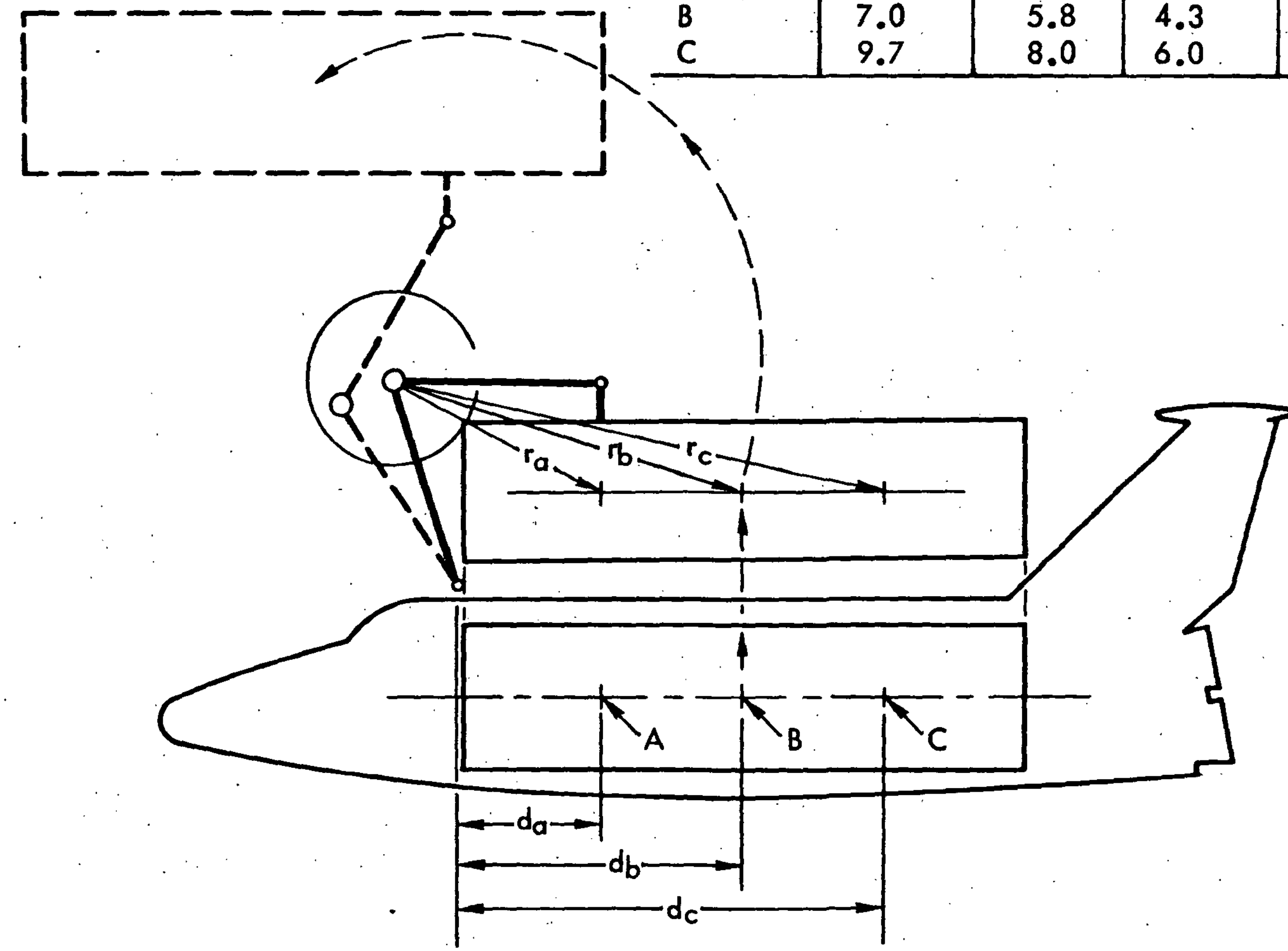


Figure 4-7. Manipulator Deployment Rates

RETENTION CONCEPTS

There are a wide variety of possible payload retention assemblies. The payload retention assembly accommodates payloads 15 feet in diameter by a length that can vary from payload to payload. Payloads that are smaller in diameter than 15 feet will be retained by standardized pallets. Retention includes payload center-of-gravity (c.g.) control, as required by aerodynamic entry. Of the many potential candidates that exist each is characterized by the number of retention attach points, their location (side wall or bottom of the cargo bay) and whether each attach point utilizes latches or simply reacts loads in a slot or channel. Figure 4-8 describes the type defined by MSS and OOS studies and a three point system that was under study for possible orbiter use. The figure also shows two options for the attach point at the bottom of the payload and two possible EOS/payload latching interfaces.

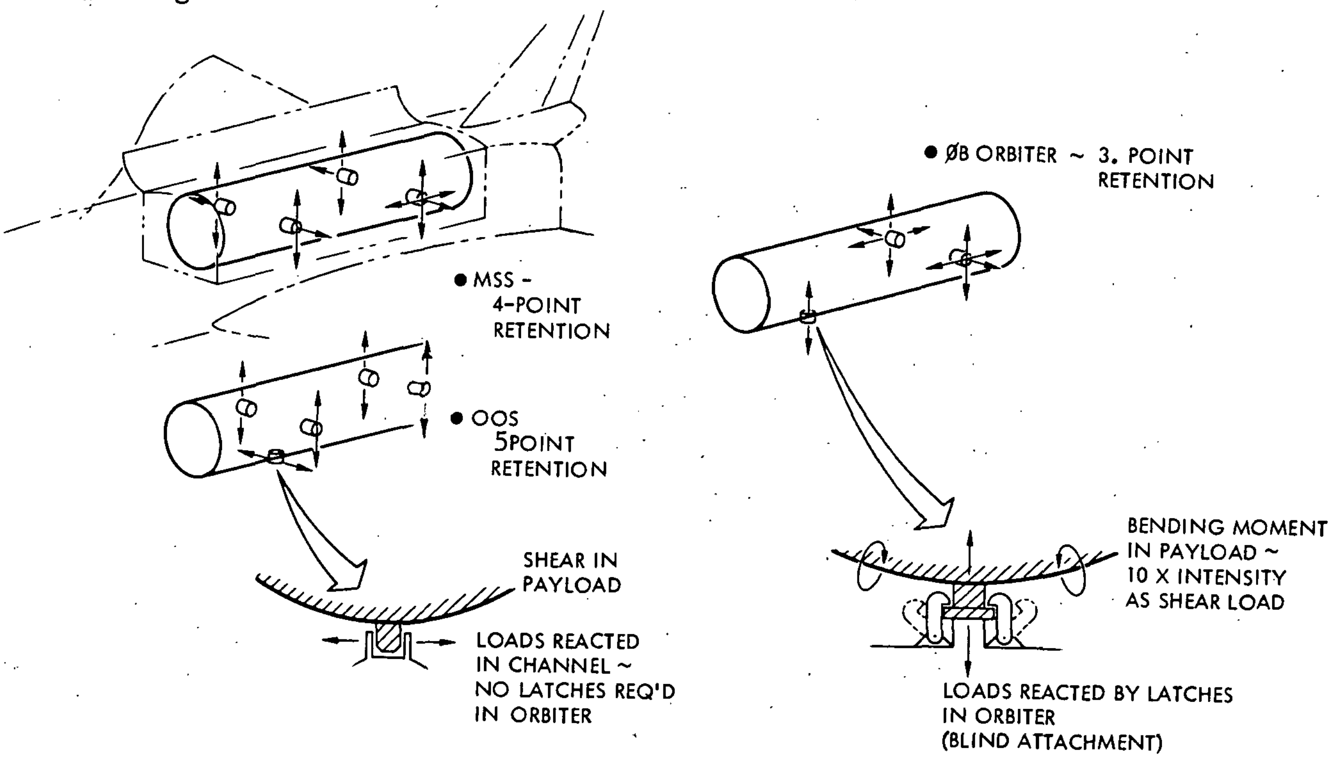


Figure 4- 8. Payload Retention Systems

There are some large payloads that because of their particular design requirements cannot easily adapt to the retention concept of Figure 4-8, and as a result must utilize a large clamp or a cylinder hinge and rotating mechanisms (see Figures 4-9 and 4-10). Several of the tug concepts have indicated a preference for the large clamp or hinge approach. The applicability of these retention devices to the wide spectrum of payloads is obviously limited and a commonality analysis would eliminate them from consideration as a baseline concept. They are discussed in more detail in the selection approach section (4.7).

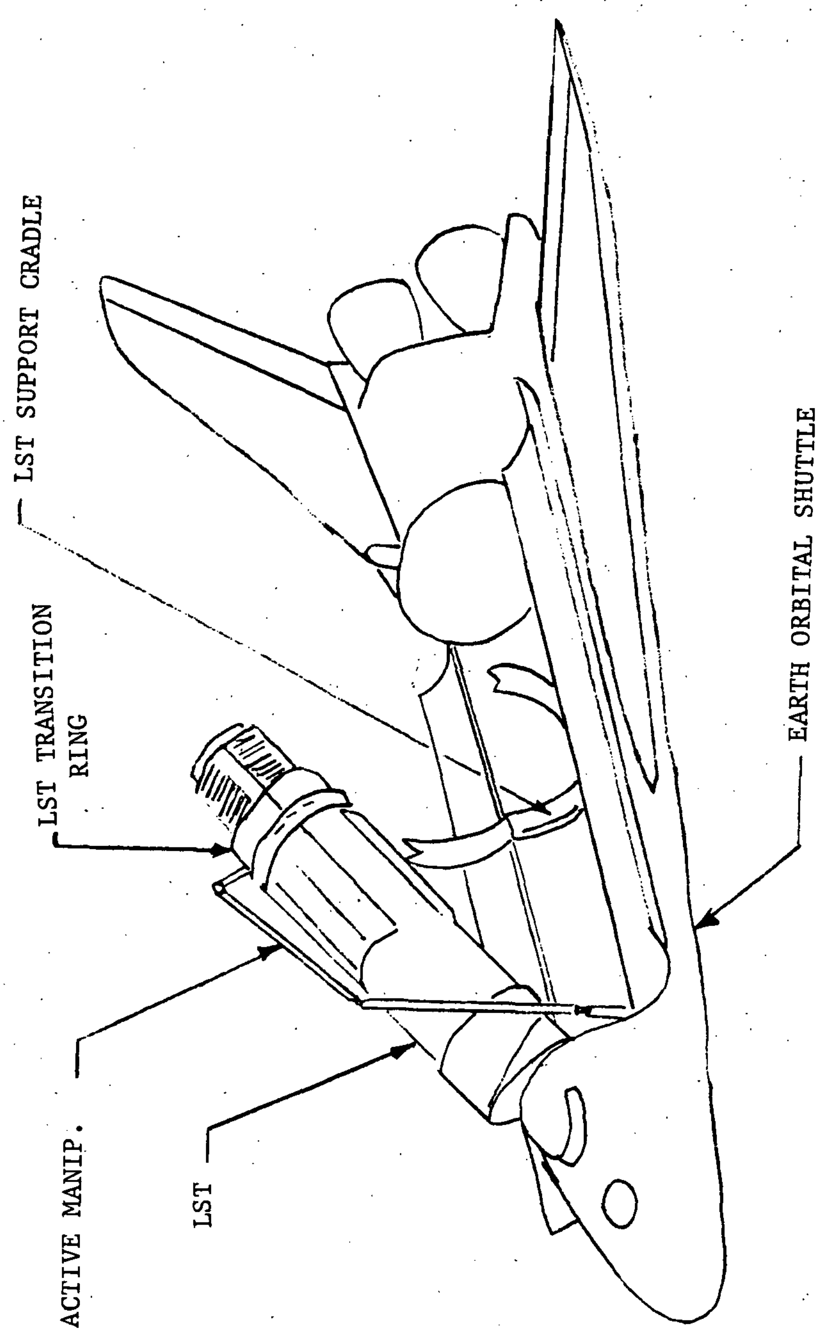


Figure 4-9. Clamp Retention Concept

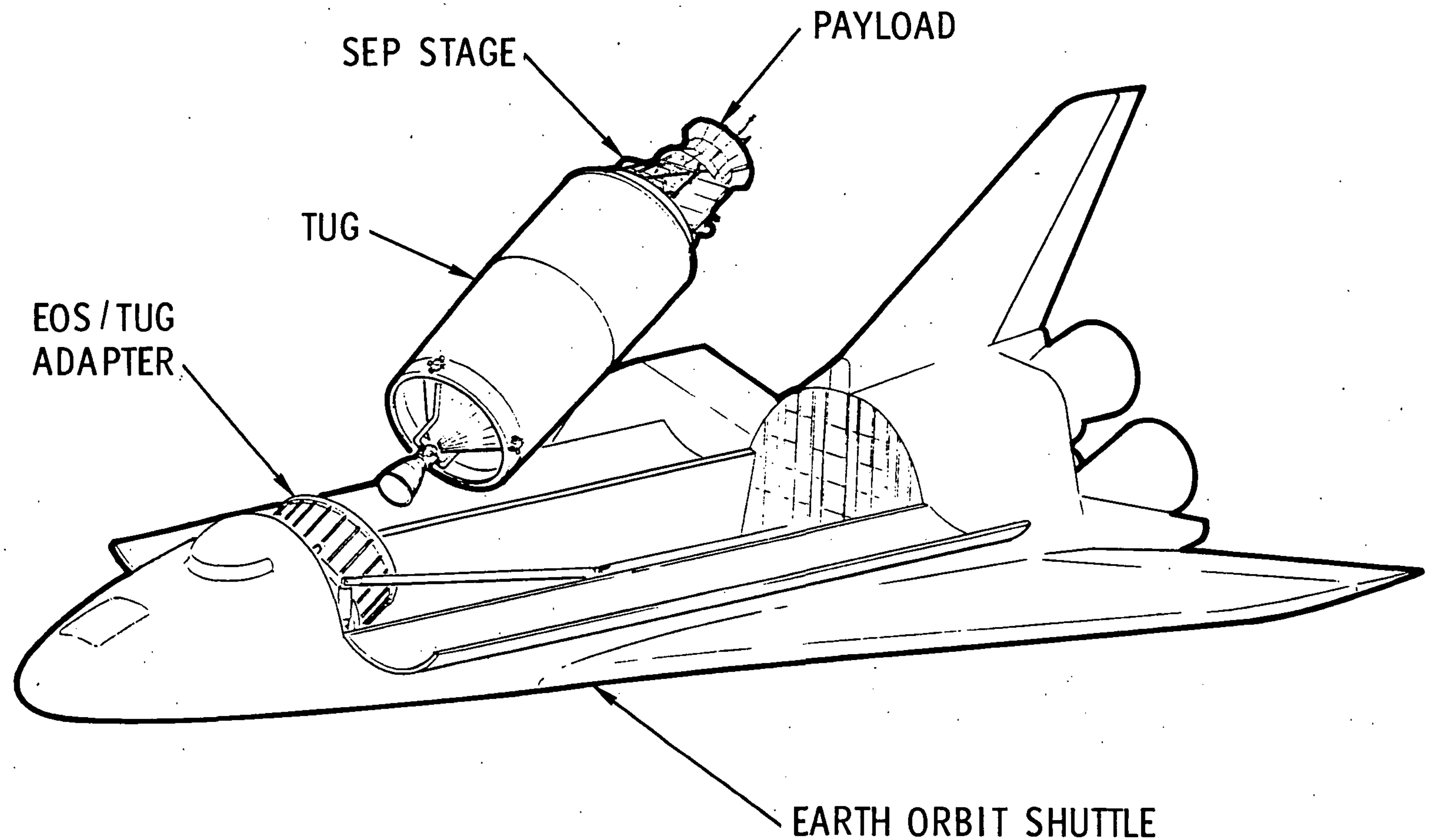


Figure 4-10. Rotating Hinge Retention Concept

Figure 4-11 shows the selected retention concept. The advantages of this selected concept are: (a) it employs a simple latch design, (b) no orbiter loads are transmitted to the P/L, (c) the P/L is not affected by the flexibility of the orbiter, (d) the side load in the keel saves 500 pounds in orbiter structure, (e) the lower fitting is a passive mechanism (slot).

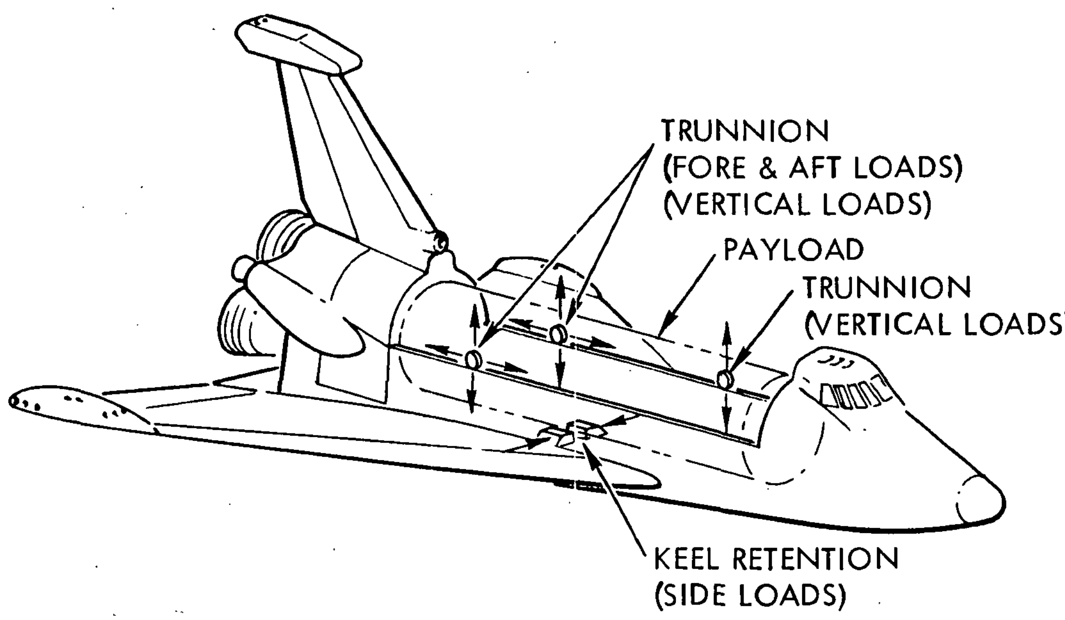
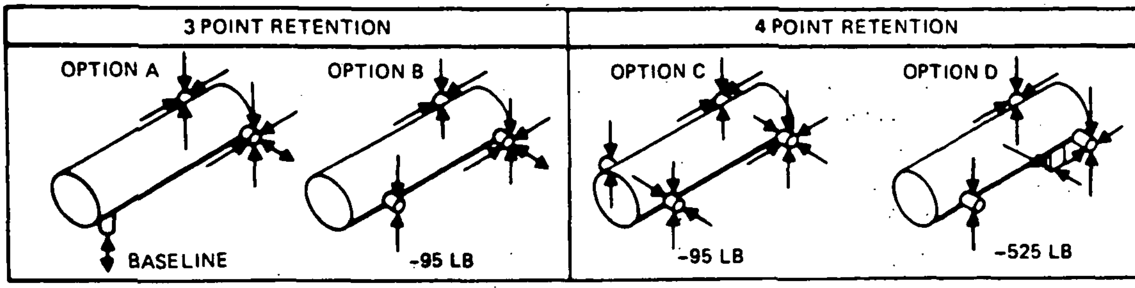
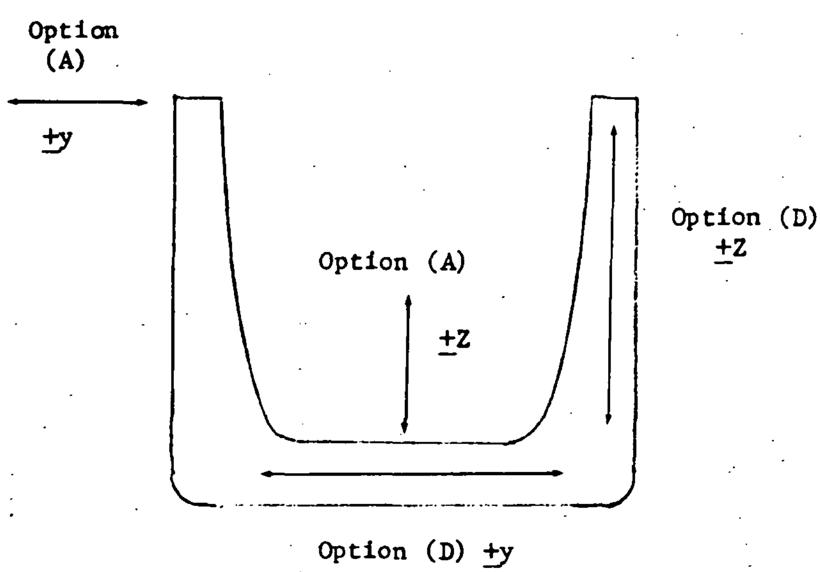


Figure 4-11. Selected Payload Retention Concept

The sketch below illustrates the weight savings the selected concept had over the baseline and other alternatives.



One contractor's initial retention concept corresponded to Option A which was acceptable if only a singular payload location was provided. Alternate concepts B, C, and D were evaluated in order to accommodate multiple retention location in the cargo bay. If it is assumed that (5) five retention locations are required, then Option D is approximately 500 pounds lighter than Option A. In Option A the vertical loads were reacted on the lower centerline of the bay (see sketch below) resulting in an inefficient load path. This concept would have required additional stiffening of beam members. By moving the retention point location to the side of the bay the loads were then taken out by the side walls in shear, which is an inherent load path. The other significant comparison was the method in which the side loads were taken out. In Option A these loads were introduced normal to the side walls which resulted in bending moments in the frames. Option D moved this load path to the bottom of the bay and reacted them by a keel through the frames (in shear).



PIVOT MECHANISM

This system for the deploying of payloads is shown in Figure 4-12. The model used had redundant actuators and payload deployment drive mechanisms. It also contained a flexible passenger transfer tunnel. All deployment mechanisms have a manual override capability that the crew can actuate from the crew compartment. The actuators are located inside the airlock providing accessibility for possible in-orbit maintenance or emergency manual operation (IVA). Torque shafts and adjustable push rod systems are routed through the airlock wall to latching and actuation points. All actuations have lock/unlock indicators and are inspectable by line-of-sight systems from the airlock aft viewing port. Crew transfer (shirtsleeve) is provided into the payload bay at the centerline by a flexible tunnel. This tunnel allows pressurized transfer into habitable payloads in either the stowed or deployed position. Hardwire power, communications, and monitoring interface connectors, and other fluids/gases interfaces are located inside the connecting tunnel/hatch area (see item I, Docking Port and Hatch Locations) and are accessible (IVA) for payloads that provide a matching seal. Payload deployment is a simple 90-degree rotation out of the cargo bay.

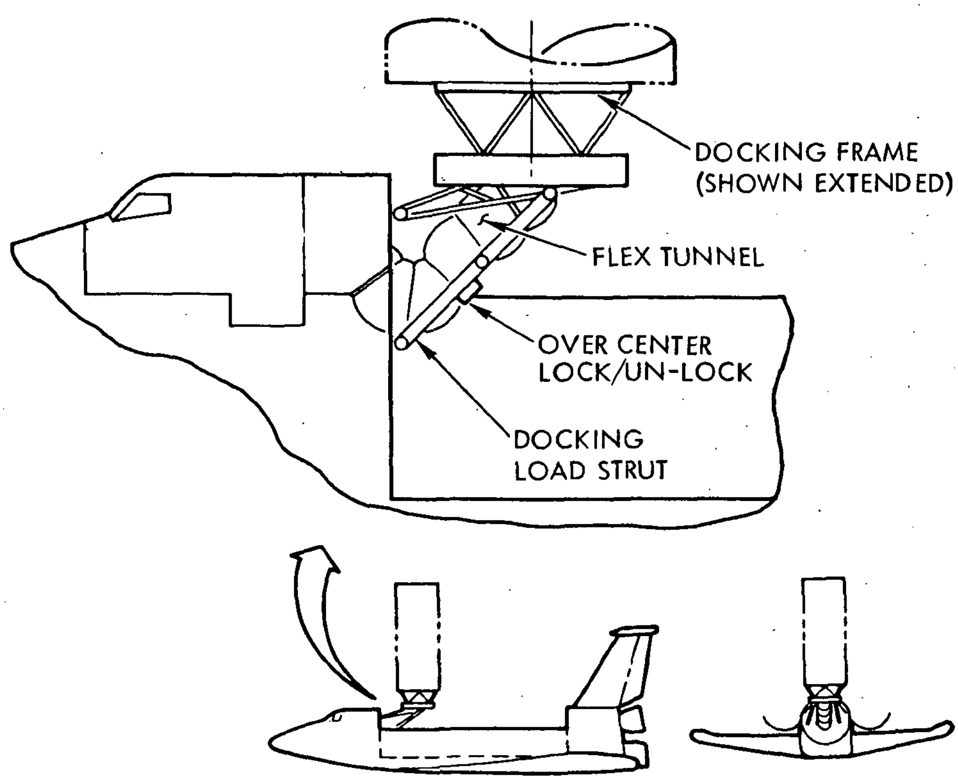


Figure 4-12. Pivot Mechanism

4.5 OPERATIONAL PROCEDURES

Two operational procedures were developed for EOS payload deployment, one for each of the conceptual approaches. Procedure number 7-1 applies to the EOS equipped with a manipulator. Procedure number 7-2 is applicable to the EOS with a pivoting mechanism in the cargo bay. Both procedural approaches have operations that potentially involve other interfacing activities (mating, attached element operations, and separation). These interfaces were handled by reference only. The following two paragraphs are descriptions of each procedure.

Procedure No. 7-1 (Manipulator Approach)

This procedure contains 30 operations that commence with activation of the manipulator subsystems through the stowing of the manipulator and the deactivation of the subsystem. There are three BY-PASSES (see Appendix B) in the logic flow. These By-Passes relate to the adapter and are utilized if the intention of the mission is strictly payload deployment without a requirement for crew ingress. The charts that follow the flow diagram contain remarks and rationale relating to each operations step of the procedure. The procedure was written to handle all activities associated with deployment of EOS cargo bay compatible payloads. It also has a recycle feature designed to the payload to facilitate the missions that involve multiple payload deployments.

Procedure No. 7-2 (Pivot Mechanism)

This procedure (7-2) contains nine operations that commence with reading the cargo bay for deployment through the securing of the pivot mechanism for Earth return. As in the procedure that was developed for the manipulator approach, this procedure contains a By-Pass that is utilized if no crew ingress is required prior to deployment. It also contains a recycling to allow for multiple deployments. A description of the remarks and rationale for each operation of the procedure is contained on the pages that follow the flow diagram.

Procedure Commonality Analysis

Since the majority of EOS flights might involve both deployment and retraction on the same mission, a commonality evaluation of EOS payload deployment and EOS payload retraction was performed. A combined deployment/retraction and stowage procedure was developed and used for this task (see Appendix A, trade A-2). The combined procedure has five operational options.

1. Deploy payload only
2. Retract and stow payload only
3. Deploy one payload, then retract and stow a second payload
4. Retract and stow one payload, then deploy a second payload
5. Retract a payload (service) then redeploy same payload

PRECEDING PAGE BLANK NOT FILMED

4.6 FUNCTIONAL REQUIREMENTS

The functional requirements for the interfacing activity of EOS payload deployment are unique in that the majority of these functional requirements relate specifically to the EOS. Since the EOS is the active element in the deployment of each payload, it is understandable that most requirements would be directed toward the EOS. Major considerations in the establishment of functional requirements relating to EOS payload deployment are the type of payloads to be handled, the operations involved in moving the payload clear of the cargo bay (erection), and safety. The majority of the requirements are independent of the approach taken to accomplish deployment.

The columns on the right-hand side of the requirement identify the operational procedure to which the requirement is applicable. The 7-1 and 7-2 are the manipulator and pivot mechanism approaches, respectively.

Requirement	Manipulator 7-1	Pivot Mech. 7-2
1. Deploy Multiple Payloads	X	X
2. Deployment Time Constraint	X	X

1. Deploy Multiple Payloads - The EOS shall be capable of deploying multiple payloads during a single mission.

   Maximum Weight: 65,000 lb (including cargo bay provisions)

   Maximum Size: 15 ft diameter by 58 ft length (including retention/storage mechanisms)

   The requirement for multiple payload deployment is derived from (1) economy of operations and (2) space station flights that require a DRAM that may be retrieved and delivered to the station in conjunction with a cargo module exchange.

2. Deployment Time Constraint - The orbiter must be capable of deploying any single payload within a given period of time. The most rapid deployment requirement currently identified is 5 minutes (Reference section 6.0, SD-136). A 10-minute deployment criteria also has been identified as a result of safety analyses. A failure of the vent valve of a liquid oxygen resupply module in the closed position could cause a pressure buildup to a hazardous level in approximately 10 minutes. Damage to the orbiter and other payloads could be avoided by rapid deployment and separation from the module.

Item	Manipulator 7-1	Pivot Mech. 7-2
3. <u>Conduct Orbital Maneuvers</u> - The EOS will be required to provide attitude maneuvers for an attached payload to verify proper response of payload attitude control and orientation devices. Selected payloads will require on-orbit service and checkout prior to deployment. During the checkout operations attitude control and orientation mechanisms may be required to be placed in a deactivated or standby mode. Proper response of the attitude control and solar array positioning must be verified prior to deployment as a failure of either mode can result in mission discontinuation. Illumination of the cargo bay for selected steps in the deployment operation may require shuttle maneuvers as a backup to floodlights.	X	X
4. <u>Manage Contamination</u> - The EOS shall be capable of selectively inhibiting the firing of attitude control engines and the venting of cabin effluents. Certain subsystem and scientific equipment are extremely sensitive to engine impingement and contamination. Solar arrays, antennas, and optical sensors should be exposed to a minimum of contamination.	X	X
5. <u>Release of Manipulator Attachment</u> - The EOS shall provide an alternate means of physical separation from the payload if the manipulator effector end fails to release. The failure of a manipulator end effector release can result in a potential safety hazard to the EOS.	X	
6. <u>Payload Separation</u> - The EOS shall provide a separate and independent means for separating the payload from physical attachment external to the cargo bay. A payload that cannot be separated from an external port represents a catastrophic mission failure preventing Earth return.	X	X

	Manipulator 7-1	Pivot Mech. 7-2
7. <u>Provide Electrical Power</u> - The EOS shall provide limited electrical power and grounding to the payload while in the cargo bay and connected to an external port. Electrical power may be required to condition subsystem and scientific equipment during the predeployment operations. EOS supplied power may also be required to pacify subsystems and provide habitable environment and safety monitoring.	X	X
8. <u>Provide Venting</u>. The EOS shall provide payload service panels for in-flight fluid venting and dumping. Many payloads will contain hazardous liquids and gases such as: . UDMH . Liquid Oxygen . IRFNA . Liquid Helium . Hydrazine . Freon . Hydrogen Peroxide . Gaseous Nitrogen . Liquid Hydrogen . Gaseous Helium During the on-orbit phase of the mission the shuttle/payload vent system interfaces will need to be safely broken prior to release of a deployed payload, and connections remade and verified with retrieved payloads if residuals are on board. This implies a need for automatic, remotely controlled connecting hardware to preclude EVA activity.	X	X
9. <u>Hardwire Communication and Data</u> - The EOS and payload shall collectively provide the capability to monitor the health and safety status of the payload. A data bus tie for commands and responses shall be provided. Payloads may contain propellant liquids and gases that can result in potential safety hazards requiring rapid venting and or redeployment of the payload. Conditioning signals may be required to activate or pacify subsystem equipment. Voice and alarm status is a mandatory crew safety requirement for all activities requiring ingress into a payload.	X	X

Requirement	Manipulator 7-1	Pivot Mech. 7-2
10. <u>RF Data and Command</u> - The EOS shall be capable of establishing a RF link and transmitting command signals to condition the payloads for normal operation. Selected payloads will require single or multiple RF commands to initiate the following responses: a. Initiate spin b. Enable and/or change attitude control modes c. Extend external appendages (solar arrays, antenna) d. Enable orientation of sensors e. Activate protective doors and shutters	X	X
11. <u>Monitoring</u> - Means shall be provided for monitoring the various steps in the deployment sequence (e.g., clearance of the cargo bay, separation of wiring and plumbing stability of payload, and either direct or television viewing of the operations). The information obtained from this monitoring must be available to the operator and/or controller of the deployment mechanism.	X	X
12. <u>Stability</u> - The deployment mechanism must hold the payload stable until it is physically released from the orbiter. There are two reasons for maintaining stability of the payload during deployment. First, stabilization is a safety measure which can prevent bumping of the payload and orbiter structure. Second, some payloads will be mated to other elements before release and stabilization if required for effective operations during mating.	X	X
13. <u>Separation</u> - Separation of plumbing and wiring connections shall leave them in a state such that, if needed they can be reconnected to and function with either the deployed payload or another payload retrieval on the same mission. Some missions require retrieval of the same payload as deployed on that mission (e.g., ground-based tug missions). In these cases, hardware communication links and propellant purge and vent lines would be reconnected.	X	X

	Manipulator 7-1	Pivot Mech. 7-2
There shall be a positive, safe separation of any plumbing and/or wiring connections between the payload and the orbiter. This separation may occur at any time after the initial check indicating that the payload is ready for deployment. Different connections may be separated at different times during the deployment sequence.		
14. <u>Payload Shirtsleeve Access</u> - Shirtsleeve access is required from the EOS passenger compartment to pressurized payloads in the cargo bay.		X
Access to all payloads shall be on the payload module centerline to allow use of the berthing port hatches for crew access. The passageway or tunnel shall be sized to allow transfer of a suited crewman wearing a portable life support system (PLSS), excluding utility runs, lighting, and crew mobility aids. Additional volume could be considered for the rescue of a disabled crewman from the payload module. The requirement to preclude the intrusion of the tunnel or passageway into the 15 x 60-foot clear volume of the cargo bay implies that part of the tunnel may be flexible to accommodate payload modules attached at different cargo bay locations (see Figure 4-13). This is a potential trade area - payload access accommodation with a single flexible tunnel vs. detachable nonflexible adaptors of various lengths. Capability to dump or pump-down the tunnel atmosphere shall be provided to accommodate IVA crew access to an unpressurized payload.		

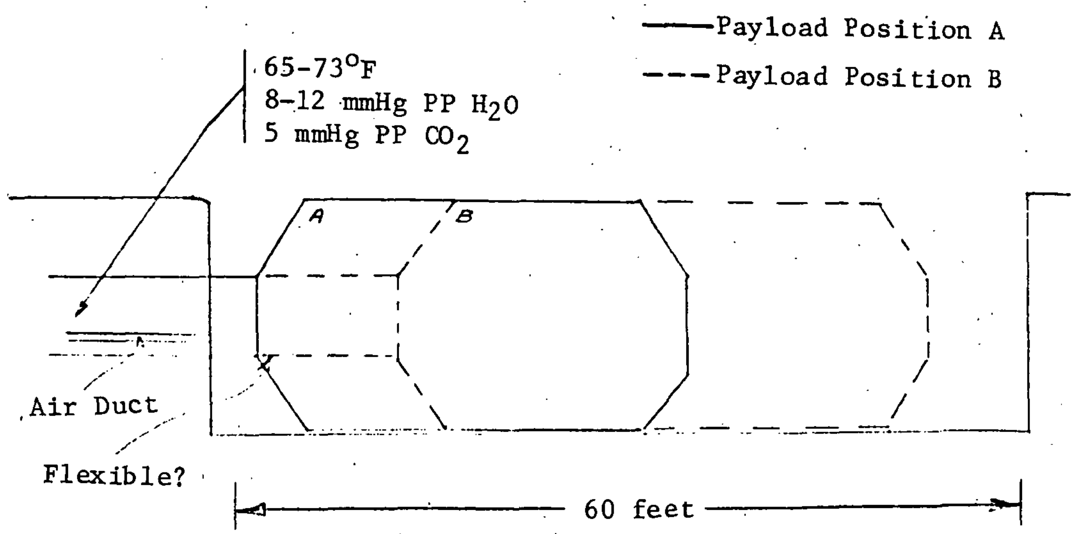


Figure 4-13. Payload Shirtsleeve Access

ELEMENT PAIR REQUIREMENTS

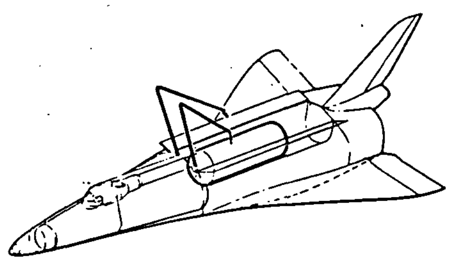
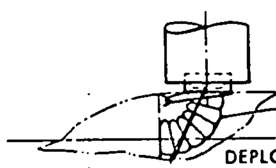
The development of functional requirements for the interfacing activity of EOS Payload Deployment were unique in the respect that they relate almost exclusively to the orbiter. The majority of the requirements are independent of the approach taken to accomplish deployment. Except for compatible communications, between the EOS and the payload, required to monitor the health and safety of the payload (see functional requirement 9), all of the requirements were developed for the two alternate deployment approaches of one vehicle element, the EOS. In the other interfacing activities there were hardware choices that could be made as a function of distinct element pairs where the requirements could then be developed by element within an activity. In EOS payload deployment there is one element that interfaces with almost (23 of 24) all elements of the inventory (CPS/OIS not affected because of incompatible diameter). Since the EOS was selected as the active element of the activity all functional requirements became primarily an EOS model that all payloads, requiring use of the shuttle for deployment, would be required to be compatible with. Therefore, the entire functional requirements section forms a model of EOS capability for deployment that payloads must be compatible with. For these reasons no separate functional requirement choices were made for all element pairs.

4.7 DESIGN INFLUENCES & PREFERRED APPROACH SELECTION

In order to properly select the preferred approach for EOS Payload Deployment it was necessary to go beyond this interfacing activity and include the requirements of EOS Payload Retention and Stowage. The two activities are so closely related that an attempt was made to see if the same hardware could accomplish both functions. Therefore in the analysis that was made the functional requirements were expanded and analyzed along with consideration of, Mating (Section 1.0), Orbital Assembly (Section 2.0), and EOS Payload Retraction & Storage (Section 5.0).

PRIMARY ALTERNATIVES

Five alternates were identified as potential candidates to handle the deployment of payloads from the EOS cargo bay. The two choices selected for further study were the pivot mechanism and on-board manipulation. Paragraph 4.3 (Alternative Approaches) contains a description of each the five alternatives and the rationale used to select the two approaches that were evaluated further. The two approaches are:

MANIPULATOR	PIVOTING MECHANISM
	

It was necessary to construct models (see paragraph 4.4) of both approaches and evaluate them against the functional requirements. This was necessary to be able to analyze these two approaches and select a preferred approach for payload deployment. Added to this comparison of requirements against model capability were the additional characteristics of each alternative. These unique characteristics form a basis for the additional considerations of the systems level impact that these approaches would have on both the payload and the orbiter.

An additional step of this evaluation/selection process was an assessment of each approach and how it was effected by the operational procedures of paragraph 4.5. This comparison of approach to procedure also included the combined deployment/retraction and stowage procedure. This last comparison was made because the procedural applicability efforts conducted for this study showed that there would be a high probability that both deployment/retraction and stowage operations would be required on many shuttle flights. Table 4-3 (Approach Selection) contains a summary of how each approach meets the functional requirements of deployment and how they compare for the eight additional evaluation factors considered.

Handle Payload in the Bay

This requirement covers the possible repositioning of a payload prior to deployment and the activation of the release mechanisms. A manual backup is required for all release operations to prevent a mission continuation failure.

The ability of the manipulator to perform these functions is excellent. The payload retention system can be designed to utilize the capability of the manipulator as a backup release mechanism.

The ability of the pivot mechanism to perform these functions is good. The pivot mechanism model utilized in the evaluation had mechanical and manual backup for the deployment of the payload and the release of the retention devices at the mating interface (forward end of cargo bay), however, the ability to reposition a payload in the bay prior to its deployment does not exist in this alternative. The pivot mechanism does have the added ability to provide a well controlled motion path when moving a payload into or out of the bay.

Disconnect Umbilicals

This function will be handled mechanically for both the manipulator and the pivot mechanism. Actuator drive mechanisms will separate the interface panel in the cargo bay from the mating panel on the payload. The pivot mechanism has the additional advantage that these umbilical connections can remain intact during the erection sequence of the deployment operation has been completed.

Table 4-1. Approach Selection

Functional Requirement	Manipulator	Pivot Mechanism	Remarks
Handle payload in EOS bay	Excellent	Good	Flexibility of movement with manipulator
Disconnect umbilicals	Good	Good	Pivot mechanism can maintain continuous connection through erection
*Deploy multiple payloads	Good	Poor	
*Deployment rate	10 minutes	10 minutes	
Provide cargo bay illumination	Excellent	Good	Manipulator can move light source easily
Release attachments Separate payload	Mech. devices at end effector attachment	Mech. devices at mating interface	Manipulator can use second arm as backup
Provide utilities	Mult. service panels	Service panel on pivot	
Monitor payload status	Through ISS hardware	Through ISS hardware	
Maintain payload stability	Good	Excellent	
Place in proper orientation	Excellent	Good	Pivot mechanism utilizes EOS ACPS
*Extend payload from orbiter	Excellent up to 50 ft	Minimum distance	
Release payload	Best	Good	Distance allows for improved checkout and verification of deployment readiness
Provide manned entry to payload	Good (flex. tunnel kit)	Best	Pivot can provide manned entry in both deployed and stowed position
Evaluation Factor			
Technology	Slightly beyond the state of the art	State of the art	
Maintenance	Limited to EVA	Good	Some degree of maintenance can be designed into pivot mechanism
Operational complexity	Least	Slightly higher	
Reliability	Good	Best	
Commonality	Best	Poor	Pivot requires special adapters for many payloads
Relative cost	Slightly higher	Lowest	
Crew interface complexity	Highest	Lowest	Special training and high levels of crew involvement
Center-of-gravity control	Best	Poor	Attach point on pivot mechanism limited to ends of cargo bay

*Evaluated for intra-activity applicability

Deploy Multiple Payloads

There will be some missions of the EOS that will require the deployment of more than one payload on a single mission. The flexibility of the manipulator to handle this function is excellent. It can be accomplished without an additional design complexity being added to the manipulator model. A pivot mechanism (or strong back) can be designed to handle this requirement and would perform the functions adequately. A concept is illustrated in Figure 4-14 . It would, however, require additional weight and volume and thereby reduce the dynamic clearance evelope in the cargo bay from the 15-ft diameter that is presently available to payloads. However, from strictly a deployment standpoint both approaches can meet the requirement. Retraction of multiple payloads (on the same mission) is discussed in section 5.0 (EOS Payload Retraction and Stowage).

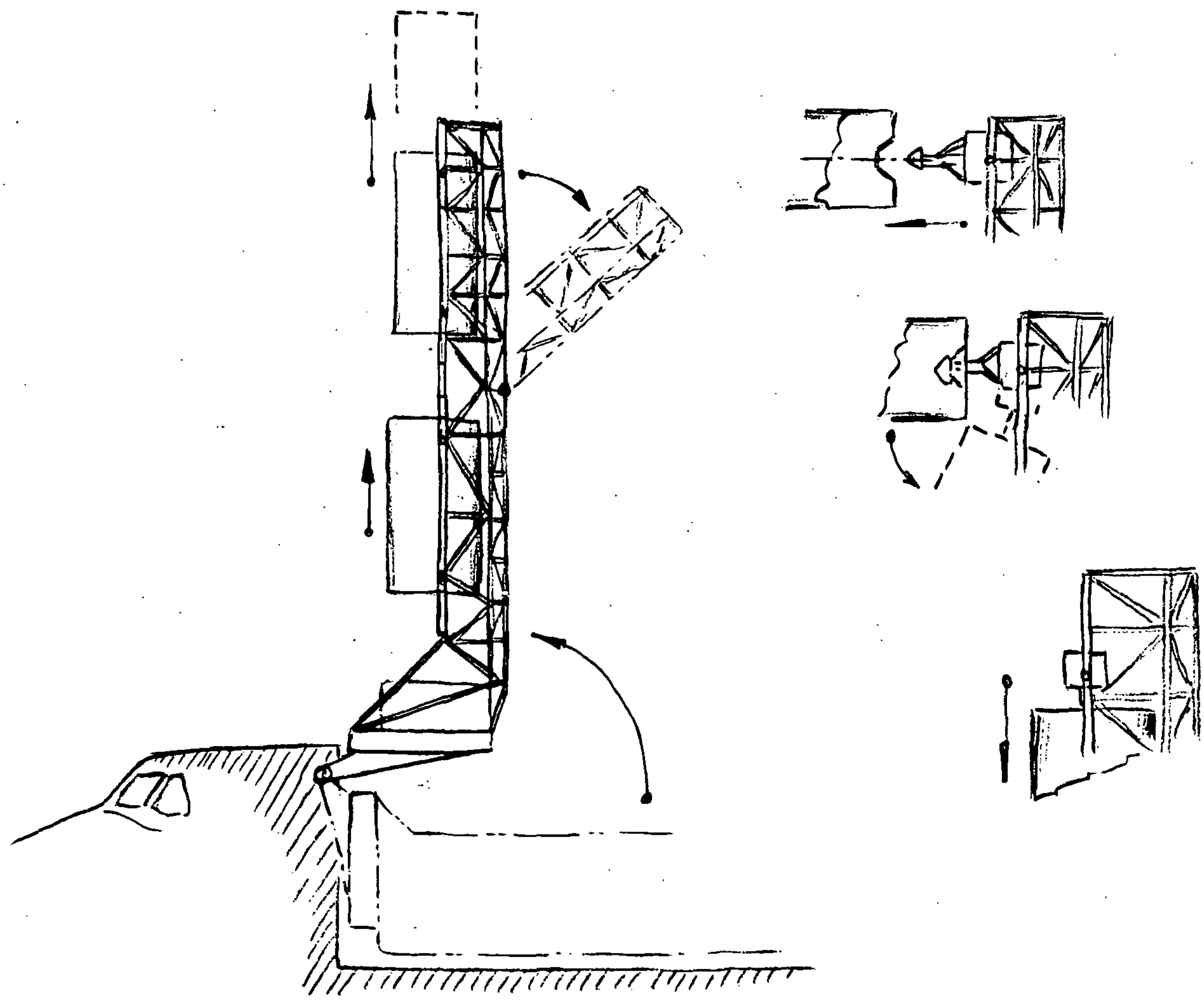


Figure 4-14. Multiple Payload Handling Concept

Deploy Tug Payloads

The ability to use a universal retention concept is highly unlikely. Some payloads designs will be such that structural penetrations to react loads will either be impractical or prohibitive from a weight standpoint. These payloads (TUG for example) will require a clamp device or rotating hinge mechanism to provide the load distribution path between the payload and the EOS attachment points.

The selection of either (1) rotating hinge or (2) clamp for Tug retention in the EOS cargo bay is greatly influenced by the main propulsion LOX tank location as follows:

LOX Tank Location	Retention Concept	
	Clamp	Hinge
Aft	(1) X	(2) Preferred
Forward	(2) Preferred	(4) X

(1) Aft LOX Tank and Clamp Mechanism. Not selected due to unfavorable dynamic response created by large c.g. to retention location moment arm.

(2) Aft LOX Tank and Hinge Mechanism. Preferred because the rotating hinge mechanism is located close to combined Tug/Payload c.g., thereby reacting the principal $\pm X$ axis loads. The $\pm Y$ and $\pm Z$ axis loads can be reacted using the universal retentions.

(3) Forward LOX Tank and Clamp Mechanism. Minimizes the dynamic response by locating the retention device on the LOX tank support. The resultant loads are reacted near the c.g. and using an existing structural member.

(4) Forward LOX Tank and Hinge Mechanism. Not selected primarily due to the large separation between retention device and Tug/Payload c.g.

The selections between items (2) and (3) will be determined in the current DOD Upper Stage/Shuttle System study.

Selection of the rotary hinge concept would eliminate the need for the manipulator since the rotating hinge can perform the same functions as the pivot mechanism. The selection of the large clamp will favor use of the manipulator.

Deployment Rate

The orbiter must be capable of deploying any single payload within 5 minutes. This requirement is applicable for certain DOD payloads. Both approaches can meet this requirement and therefore, it was not a basis for the selection.

Provide Cargo Bay Illumination

This requirement must be satisfied prior to the initiation of the deployment sequence. The manipulator has the advantage over the pivot mechanism in that the second arm can be used to position flood lights in any number of locations making the illumination portable and flexible. This portability can be extended not only to the payload attach points but also to the verification that external appendages (i.e., solar arrays, antennas, windows, lens covers) have not been damaged and/or were deployed correctly.

Separate Payload

The EOS shall provide a separate and independent means for separating the payload from physical attachments external to the cargo bay. The manipulator and the pivot mechanism can both equally meet this requirement. The pivot mechanism can have manual backup release mechanisms in the IVA tunnel near the mating interface. The manipulator can use either mechanical means to effect the backup for separation, or the second manipulator arm.

Provide Utilities

Both approaches can provide an equal quantity and type of utilities. There is an advantage for the pivot mechanism in that it is potentially capable of maintaining these utilities throughout the erection phase for selected payloads.

Maintain Payload Stability

The deployment mechanism must hold the payload stable until it is physically released from the orbiter. Primarily it will avoid possible bumping between the orbiter bay and the P/L. A second advantage to deployment stability comes from the ability to mate another element to the payload prior to its release. The pivot mechanism has an advantage over the manipulator in that it provides a much more rigid deployment device that will move a payload over a more controlled, predictable motion path than a manipulator. (See the manipulator and pivot mechanism models for system capabilities.)

Place in Proper Orientation

Many payloads will have specific mission requirements that they be deployed in a specific orientation or attitude. The requirements develop from the accommodation needs of either experiments, external appendages, or a payload sensitivity to solar orientation for arrays, sensors, and thermal control, or possibly a minimum propellant mode. The manipulator with its seven degrees of freedom (DOF) movement is capable of providing this required payload orientation with a minimum impact on either the payload or the orbiter. To accomplish this same requirement the pivot mechanism must either rely on the orbiter ACPS or place the payload in an other than optimum orientation. For final orientation the payload reaction control system would be required to perform the final attitude maneuvers.

Extend Payload from Orbiter

After the payload has been erected from its stowed position in the bay, and the service/monitoring functions have been completed then the payload should be extended as far as possible from the orbiter prior to release. The manipulator in the fully extended position can separate the payload and the orbiter almost fifty feet before releasing it. The pivot mechanism is restricted to releasing the payload at the mating interface. If it is mandatory that a separation distance be established prior to firing some main engines or deploying external appendages (solar arrays, antennas) then either the payload or the orbiter ACPS will have to provide the final separation distance. The manipulator has specific advantages in the accomplishment of this requirement. It can move the payload through a range of orientations to verify proper response of attitude control and orientation devices. It can also be used as an aid to completing a thorough visual inspection of the payload prior to deployment.

Release Payload

Both approaches can equally meet the requirement of separate and independent means of releasing a payload. They can also both maintain the plumbing and wiring connections in a state such that, if need be, they can be reconnected.

Provide Manned Entry to Payload

While the payload is in the stowed position in the bay both approaches will utilize the same concept to provide manned access to the payload, a flexible tunnel. The pivot mechanism has the specific advantage of being capable of connecting the tunnel to the frame of the mating/deployment structure. Thus this manned entry capability can be continuous in both the stowed and erected positions. In the manipulator case if shirtsleeve access is required for a stowed payload then the utilities connections and the monitoring of the habitable condition of the P/L will be broken when the payload is erected. The effect of the operational complexity will be most evident during the attached EOS - RAM missions.

Technology

The technology status of the two approaches is slightly different. In the pivot mechanism the mechanical devices and actuator drive assemblies are well within the state of the art even though a prototype has to be completed. With the manipulator the same status (within the state of the art) exists for the mechanical portions (drive motors, clutches, actuators, basic arm design) of the concept. There is still some development work required in areas of stiffness, and force feedbacks for the anticipated wide range of payload masses.

Maintenance

The pivot mechanism has a potential design advantage over the manipulator. Its actuators can be located inside the crew tunnel where they would be accessible for on-orbit maintenance or emergency manual operation. The torque shaft and adjustable push rod systems could be routed through the pressure wall to latching and actuation points. Maintenance on some of the components of the pivot mechanism and the manipulator will require IVA/EVA operations. However, neither concept has identified on-orbit maintenance requirements. All normal maintenance would be performed upon return of the EOS to ground.

Safety

Basically both approaches can be made safe. The question resolves itself then to what potential hazards exist with each alternative. The pivot mechanism with its more controlled motion paths would be the easiest of the two options to make safe. It represents a simpliar concept with fewer potential hazard than the manipulator. The major safety problem with the pivot would be a failure of the activation system with a payload practically deployed. This could be handled with redundant drive motors backed-up with a manual override capability.

The manipulator has four potential hazards that would create significant safety problems, namely: (1) once motion of the payload has been initiated failure to the control, and/or brake mechanisms could result in damage to either the orbiter, payload or manipulator, (2) there is the potential problem of having failures in the manipulator cause it to "hang-up such that it cannot retract a payload from the bay", (3) the manipulator end effector could become engaged in a receptacle and fail to release, thus the cargo bay doors could not be closed until the release was affected, (4) the final potential major problem is one in which during the final motions prior to engagement of the end effector and the receptacle either a mechanical failure (to the manipulator and/or the attitude control system of either vehicle) or an operator error could cause an inadvertent movement of the end effector or arm; damaging the payload or its appendages.

While these potential failure modes are significant all of them can be compensated for by adding redundancy in design and force feedback capability. Therefore since both approaches can be made safe, safety did not drive the decision between the two approaches. It did, however, establish a bias toward the pivot mechanism since it appears to be the easiest of the two to make safe.

Operational Complexity

There are operational activities where the complexity of the pivot mechanism is greater than that of a manipulator. An example that can serve to illustrate this is the exchange of a space station cargo module including crew transfer. The basic differences between the two approaches are summarized below:

Step	Pivot Mechanism	Step	Manipulator
1.	Hard Dock EOS to Station (through payload)	1.	Berth EOS to Station
2.	Transfer Crew to Station	2.	Transfer Crew to Station through EOS Mating Port
3.	Undock EOS from Cargo Module	3.	Utilizing Manipulator to Effect Exchange of Cargo Modules
4.	Redock EOS to Cargo Module that is to be returned		

Thus, the use of the manipulator approach to affect the exchange of modules at an orbital facility involves only one berthing as opposed to the pivot mechanism mode of a docking followed by a near proximity maneuvering, stationkeeping and redock (at an estimated propellant penalty of 350 pounds per redock).

The use of manipulators for payload deployment has the potential for additional operational simplicity in that it can minimize the complexity of operations concerned with the preparation of a payload for final checkout prior to separation. The manipulator can assist in deployment of appendages, and with TV cameras it can perform a visual inspection of the payload.

Although these operations can be adequately performed with the pivotal mechanism concept, a manipulator is favored for delivery and exchange of modules at a facility and the deployment of satellites and unmanned payloads.

Reliability

Inherent in the two approaches is the basic simplicity of the pivot mechanism approach as compared to the manipulator. It will require more cost to bring the level of reliability of the manipulator to that of the pivot. Although there are problems in designing the manipulator approach there are no elements that cannot be made as reliable as required.

Commonality

The pivotal mechanism concept is compatible with the direct docking preferred approaches for mating and orbital assembly. A common docking mechanism can be incorporated on the pivotal mechanism that would mate with all elements except some satellites. An adapter would be required for the deployment of satellites. It could be the same adapter identified for the case of a tug mating with a satellite.

Use of the manipulator as the deployment concept could provide an equal degree of commonality with respect to EOS payload operations. However, payloads that must subsequently be mated with other elements not equipped with a manipulator would still require a docking port(s). Incorporation of the attachment mechanism on EOS payload for manipulators spectrum is not a significant weight problem (6 - 10 lbs). A docking mechanism adapter would not be required for satellites associated soley with the EOS and thus the manipulator would provide the most common concept for payload deployment.

Relative Cost

Cost studies of comparable manipulator and pivot mechanism approaches that have evaluated the weight estimates of both the mechanism for costs and also included the costs of enlarging or shrinking the shuttle to maintain constant payload weight have concluded the manipulator approach more expensive than the pivot mechanism approach.

Bias

The near term bias would have to be with a pivot mechanism system since the early shuttle flight would primarily be restricted initially to the deployment of attached RAM payloads and the placement in orbit of satellites. These missions can be used as flight tests for the manipulator at a time when the functional requirements of the missions would be relatively simple. As the complexity of the missions increases and the flight test results of the manipulator are expanded this manipulator capability can be utilized most effectively.

Conclusions

Based upon the analyses and evaluations selection of a singular approach for EOS payload deployment is not warranted. If only this interfacing activity were considered a preference for the pivotal concept is evidenced. It is less complex, lighter, less costly, and facilitates manned access to the payload. However, when consideration of the synergistic benefits that can be achieved by the use of the manipulator in assembly of the station, handling of multiple payload, and potential on orbit maintenance operations is included the manipulator is a highly desirable concept.

In addition to the added margin of safety inherent in the use of the manipulator for station module assembly operations (more positive control of modules in close proximity) the manipulator can be used for attaching modular packages such as an airlock laboratory or antenna package. Handling multiple payloads can be readily accomplished with the manipulator. The sequence of operations is not restricted and free flying close proximity operations can be avoided.

The principal advantages of the pivotal mechanism concept are:

1. It consists of a single system that can be readily used for single payload deployment and retrieval operations (adapter required for some satellites).

2. It provides a conventional and common on axis docking capability for mating with the orbiter or payloads with other elements.

3. It provides the potential for continuous shirtsleeve access to habitable payloads during cargo bay stowage and deployed payload operations without interruption of EOS-payload interface.

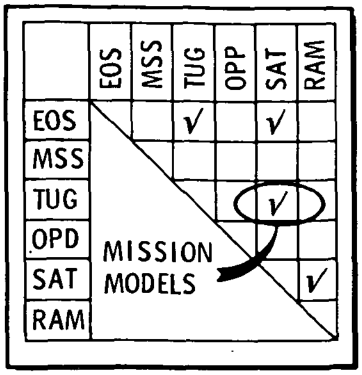
4. It provides the potential for shirtsleeve access (if necessary) to the deployment/retraction activities and the interface connections.

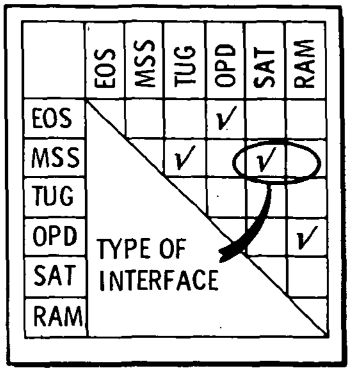
5. It provides a more positive control of the payload during erection and retraction operations.

Thus each approach has highly desirable features. Also each approach can be adapted to meet all the operational requirements identified. For example the pivotal mechanism concept could include a "rack" as illustrated in Figure 4-15 which would permit the handling of multiple payloads.

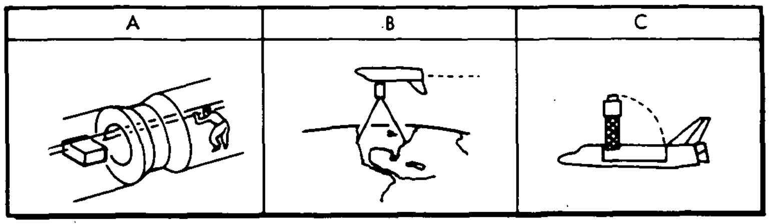
It is recommended that both the pivotal mechanism and the manipulator concept be developed. EOS programmatic considerations - cost, schedule, payload traffic models - rather than operational operations should determine the selection of the baseline concept. Development options include (1)selection of one as a baseline and kit installation of the other, 2) provisions for kit installation of both concepts, or 3) if the EOS traffic model permits, a sequential development of concepts on successive orbiters.

ELEMENT INTERFACES

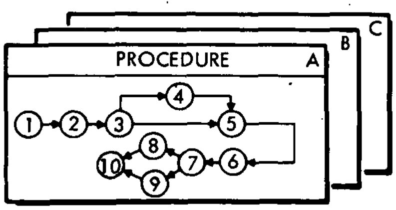


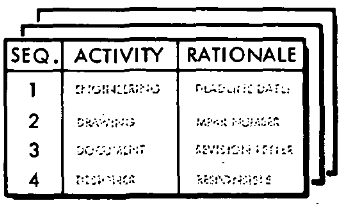


ALTERNATE APPROACHES AND DESIGN CONCEPTS

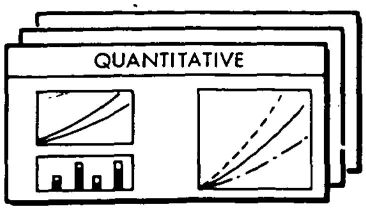


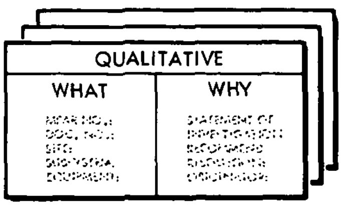
OPERATIONAL PROCEDURES



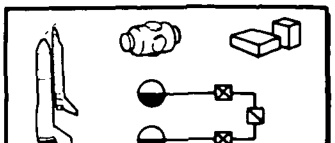


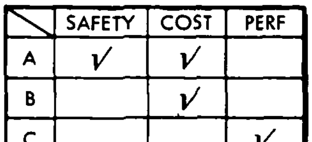
FUNCTIONAL REQUIREMENTS





DESIGN INFLUENCES AND APPROACH SELECTION





5.0 EOS PAYLOAD RETRACTION

5.0 EOS PAYLOAD RETRACTION

5.0 EOS PAYLOAD RETRACTION AND STOWAGE

The converse operation to payload deployment from the orbiter is designated EOS payload retraction and stowage. In this study, this interfacing activity is considered to comprise all those actions occuring between physical attachment of the payload to a deployment/retrieval mechanism and tie-down in the orbiter cargo bay. Payload retraction normally would be preceded by mating and/or shutdown of the payload subsystems. In some cases, retraction and stowage would be followed by orbiter transport of the payload during some thrusting maneuver. Monitoring of the payload during these operations would probably be required. As pointed out in Section 4, the weight saving advantage of using the same mechanism for retraction as is used for deployment results in common operating procedures and requirements for the two activities. Thus, EOS payload retraction and stowage is related to some of the interfacing activities denoted as EOS payload deployment, mating, separation and orbital assembly.

5.1 SUMMARY

The interfacing activity of EOS payload retraction and stowage has 20 possible element-to-element interactions relating to the 24 elements of the space inventory. As with Section 4, EOS Payload Deployment, this high vehicle involvement made commonality and adaptability prime considerations in the evaluation and determination of a preferred approach selection. A similar analysis determined that utilizing the mission models and the vehicle inventory, there are 71 occasions when retraction and stowage interaction could occur.

Five approaches were identified as potential candidates to handle the retraction and stowage of payloads into the EOS cargo bay.

1. Manipulator
2. Teleoperator
3. EVA with AMU
4. Lateral Translation
5. Pivot Mechanism

Three of these original choices: (1) Teleoperator, (2) EVA with AMU, and (3) Lateral Translation were eliminated for considerations of safety, technology and similarity of operational characteristics to other alternates. The two approaches selected for further study were (1) On-Board Manipulation and (2) the Pivot Mechanism.

Design concept models were defined for the principal hardware concepts utilized by each of the two approaches. The applicability of each approach to all the elements of the vehicle inventory could not be completed without the design concept models. Models of payload retraction and stowage devices were also defined. While at a lower level than the two approaches being evaluted, payload retention concepts were considered important enough to warrant having design concept models defined for evaluation. The analysis of the retention device was conducted not to select the "best" retention method, but to assess the impact that retention devices would have on payload retraction requirements.

Two operational procedures were developed for EOS payload retraction and stowage, one for each of the alternate approaches selected for further study. These procedures were used in the approach selection analysis and were evaluated along with their hardware concepts to select a preferred approach for each element pair. Analysis was made of the applicability of these two procedures to each element pair and also across the interfacing activities to both Deployment and Retraction/Stowage. The third part of this analysis was the examination of the commonality and applicability that exists between the two approaches. This applicability analysis is especially important because it is envisioned that the majority of EOS flights will have requirements that both deployment and retraction be performed on the same mission. A combined EOS Payload Deployment/Retraction and Stowage procedure was developed and used in the evaluation.

Selection of a preferred approach for EOS payload retraction and stowage considered the ability of each approach to handle payloads that are unique in some respect such as those design sensitive payloads that require specific launch and reentry configurations (satellites that must be launched in one orientation and reversed for entry). The retraction/stowage approach selected had to be capable of meeting a wide spectrum of payload types and requirements.

Also included in the selection process was the interrelationship between retraction/stowage and mating, and separation and orbital assembly. The ability of each approach to support these activities was added to the selection process to enlarge the scope of the commonality and applicability analysis. If these selections were made independently of the potential commonality between activities then the choices might have varied significantly. An important point that must be considered when reviewing the selection made was that this interfacing activity includes only the interactions and interfaces of the EOS to each payload element. Therefore when an analysis was made of the adaptability of each approach to another activity (i.e., orbital assembly) it was made with the ground rule that the EOS would be on orbit to assist in this orbital activity. It did not consider the aspects of orbital assembly between vehicles like an OPD and a tug.

The EOS payload retraction and stowage analysis of the requirements of the interfacing activity and the capabilities of both approaches indicated that both the pivot mechanism and the manipulator are necessary. As in the analysis of a preferred payload deployment approach, the analysis was expanded to include not just the retraction and stowage functions, but also deployment. Because of the need to perform both a deployment and a retraction operation on some mission both activities were included in the analyses.

The selection for the retrieval of single payloads is the pivot mechanism. It was selected primarily because of its simplicity and lower cost. With the addition of an extension/retraction device and special latches it can be adapted to handle the deployment and retrieval (mating) of a small satellite.

The selection of a manipulator to be used in EOS payload retraction and stowage was driven by the handling of multiple payloads. Developing a rack or strong back mechanism for multiple payloads would reduce the effective diameter of the bay (from its present 15 feet). The manipulator could be used to retract and stow multiple payloads in or out of sequence and would represent a minimum impact on the payloads themselves.

PRECEDING PAGE BLANK NOT FILMED

5.2 ELEMENT INTERFACES AND MISSION MODEL MATRICES

The orbiter should be capable of retracting and stowing most of the elements or modules of elements given in the space vehicle inventory. Consequently, the orbiter's retraction and stowage activities could involve interfacing interactions with 20 other elements. These are indicated in the top row of the matrix in Figure 5-1. For this interfacing activity no interaction is possible between two orbiters, because it is not modular in design, and thus no part of one would be carried in the cargo bay of another. Likewise, there would be no interaction with the CPS used as an orbital injection stage. Further, no retraction and stowage interaction would occur between the orbiter and non-returnable tug or the first two satellite categories, which would not be retrieved. Satellite retrieval is covered in the third satellite category. Retraction and stowage would occur with the EOS attached RAM, even though it is never physically separated from the orbiter.

Figure 5-2 utilizes the same matrix, that was used to identify the EOS payload retraction and stowage interactions, to identify the types of missions where the activity may be involved. Eleven reference missions have been identified for this study and are described in detail in Appendix C. The matrix cross-references the applicable missions using the corresponding mission identification numbers 1 through 11. Mission Models 2 and 5 are the most frequently mentioned. In Mission Model 2 the EOS is the delivery vehicle. It is a logistics/retrieval mission and as expected involves EOS payload retraction and stowage. Mission Model 5 utilizes the Space Based Tug as the delivery vehicle. It is a logistics missions and again as expected there is frequent EOS payload and retraction activity.

In all but three of the mission models, MM-1, MM-6 and MM-9 (reference DS530), EOS payload retraction and stowage may be involved. In MM-1 the EOS is the delivery vehicle but these are emplacement missions and there no retraction and stowage is anticipated. In Mission Models 6 and 9 neither of these two missions, which relate to tug disposal missions and insertion of large payloads into orbit using an OIS, involve the EOS orbiter. The matrix shown in Figure 5-2 contains the mission model numbers that identify particular payload retraction and stowage interactions between the orbiter and the other elements in the inventory. A total of 71 such interactions were identified. By definition, the EOS is one element of the interaction on all 71 occasions. RAM's operated detached from space stations and modules of the geosynchronous MSS were involved in retraction and stowage six times each in the mission models. RAM's attached to space stations, earth orbital resupply modules, OLS modules, and the manned lunar tug were each involved five times.

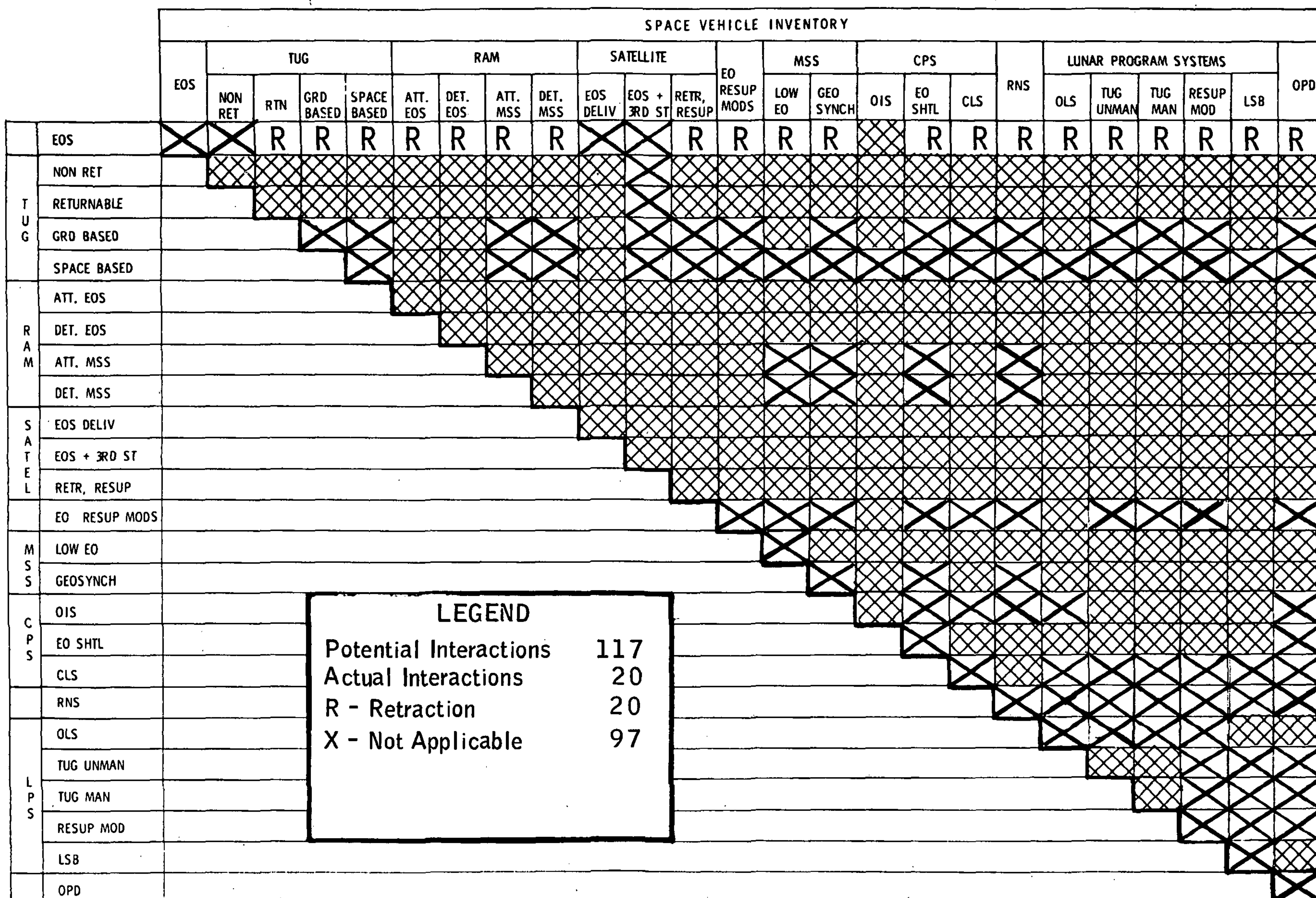


Figure 5-1. EOS Payload Retraction and Stowage Interactions

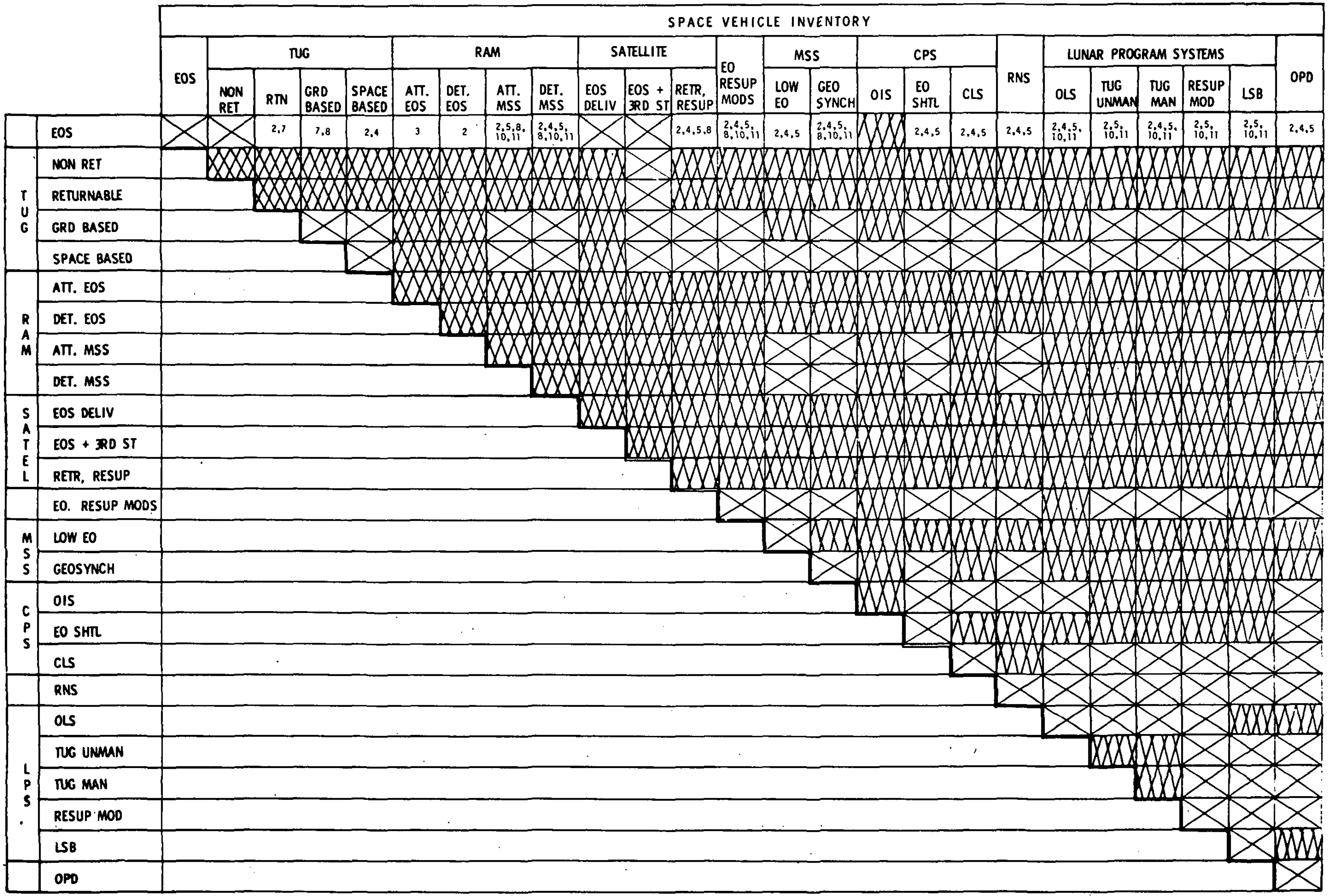


Figure 5-2. Applicable Mission Models for EOS Payload Retraction and Stowage

PRECEDING PAGE BLANK NOT FILMED

5.3 ALTERNATE APPROACHES

There were five alternate approaches studied as possible candidates for retraction and stowage of a payload into the orbiter cargo bay. The approaches for EOS deployment are illustrated in Figure 5-3. The five are:

1. Manipulator
2. Teleoperator
3. EVA and AMU
4. Lateral Translation
5. Pivot Mechanism

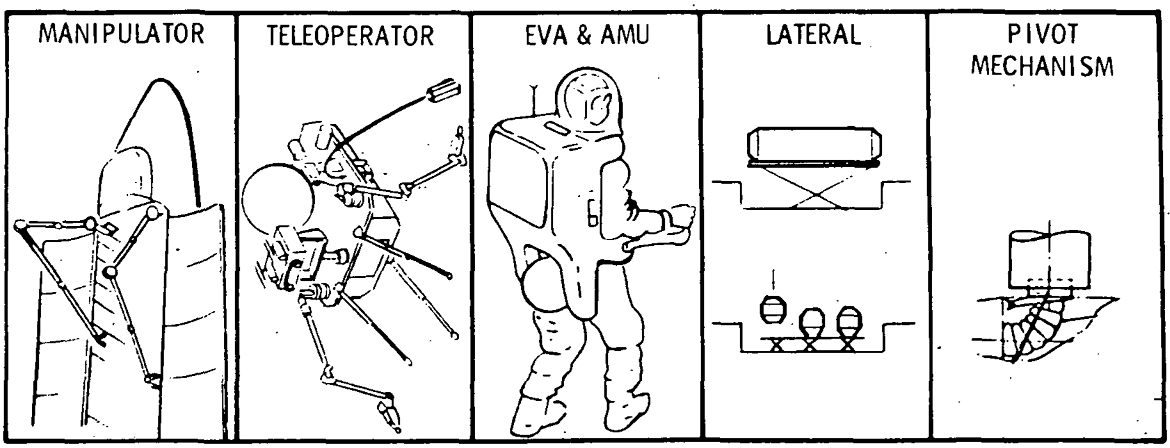


Figure 5-3. Alternate Approaches

The retraction and stowage function can be accomplished in either of two modes: (1) retracting the payload with a manipulator or (2) direct docking the payload to a pivot mechanism or lateral translation device and lowering it into the orbiter cargo bay. The following paragraphs are a description of each approach.

MANIPULATOR

The manipulator is an articulating boom with multiple degrees of freedom provided by joints, elbows, and pivots. The manipulator approach has three major assemblies: (1) a support platform - the EOS orbiter, (2) articulated arms - 2, and (3) tools. Power, command, and control must be provided by the orbiter for each assembly. The support platform maneuvers the arm assemblies into a position to perform the desired retraction functions. The manipulator arms produce the tool positioning motions and forces. They characteristically have multiple degrees of freedom; from three in simple systems to as many as eight in complex sophisticated installations. The control and skill requirements and mechanization complexity increases proportionally to the number of degrees of freedom.

TELEOPERATOR

The teleoperator approach is a system level concept and would be a separate spacecraft in element inventory. The teleoperator spacecraft illustrated in Figure 5-3, consists of a structure housing the spacecraft systems, a propellent supply tank, four sets of quad thrusters, a two axis camera mount, binocular TV cameras and lights, a single close-up TV camera, two manipulator arms with interchangeable end effectors, and three docking arms. Control of the teleoperator will be accomplished from a control station within the orbiter.

EVA AND AMU

The use of EVA and a orbiter crewman in an Astronaut Maneuvering Unit (AMU) is the most restricted of the five approaches. It utilizes, as illustrated in Figure 5-3, a suited crewman with a back pack. The back pack contains the crewman's life support, propulsion, attitude control, electrical power and communications/data. Attached to the back pack is the oxygen storage bottle. The front of the units has two hand controllers, one for translation, the other for attitude hold. The hand controllers rotate down when not in use.

LATERAL TRANSLATION

The lateral translation approach provides a carriage assembly mounted on rails, screw jacks, etc., that laterally retracts the payload into the cargo bay of the orbiter.

PIVOT MECHANISM

The pivot mechanism is a rotational approach that pivots the payload 90 degrees with respect to the orbiter centerline. The pivot points can be located at either the forward or aft bulkhead of the cargo bay. There are options for flexible tunnels that can be added to the pivot mechanism to provide shirtsleeve crew passage to the payload either outside of the orbiter or in the stowed position in the bay.

SELECTED APPROACHES

The five candidate approaches were reviewed and the following factors were used to eliminate three approaches from further study.

Approaches Eliminated	Rationale
(1) Teleoperator	Because numerous orbiter missions do not involve an element already on orbit, the teleoperator would have to "deploy" itself and therefore it reduces the effective cargo bay volume. It also adds another element to the vehicle inventory requiring an additional development program. It also has no significant advantages over an EOS manipulator approach.
(2) EVA with AMU	The EVA with the AMU was rejected because of its potential hazardous operations. It was also severely limited in the size of payloads that could be handled. It also has the further disadvantage of being a new development.
(3) Lateral Translation	The lateral translation approach has been eliminated from further study consideration because all of the functional requirements, operational procedures and alternates associated with lateral translation devices do not vary sufficiently from the pivot mechanism to offer any significant advantage to studying this alternative.

Therefore, the approaches that were selected for further study and analysis were: (1) pivot mechanism and (2) manipulator. The data in the remaining sections of EOS payload retraction and stowage were established utilizing these two approaches.

5.4 DESIGN CONCEPT MODELS

To be able to analyze the approaches that were developed, specific hardware concepts were synthesized. They were used to evaluate the approaches and the viability of any hardware designs. In the interfacing activity of EOS payload retraction and stowage, the EOS will be involved in 20 element-to-element interactions with the 24 elements of the space vehicle inventory. It is because of this principal involvement of the EOS that design concept models had to be defined for some of the major EOS/payload interfaces. The following are the models of EOS payload accommodations and equipment that were utilized in the selection of a preferred element pair approach.

PAYLOAD ENVELOPE

Figure 5-4 shows the dimensions of the orbiter payload bay. Within this bay the payloads are accommodated. A 60-foot module would have 27 inches total clearance for its length and if it were 15-feet in diameter it would have a 3-inch clearance at the bottom of the bay and 5 inches on each side of the bay.

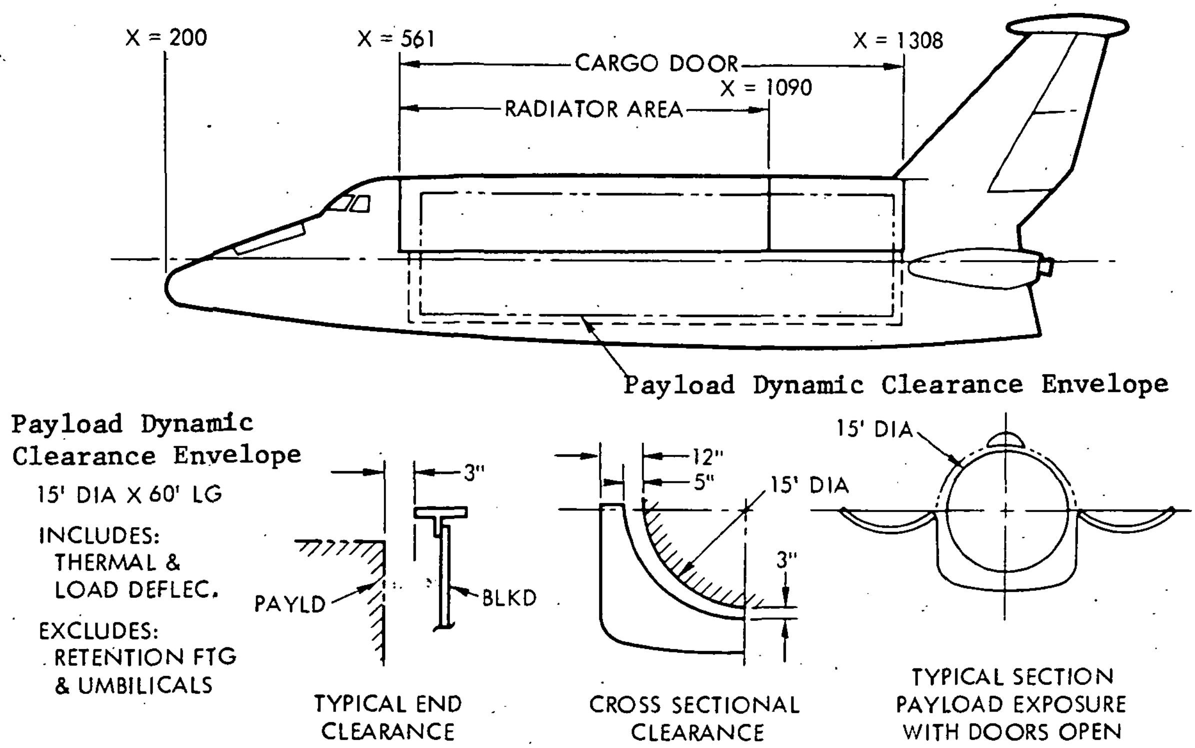


Figure 5-4. Orbiter/Payload Envelope

MANIPULATOR

The EOS manipulator approach (Figure 5-5) is a system consisting of two manipulator arms, a manipulator operator station, and payload retention assembly. In their stowed position the arms are above the payload. Each arm is 50 feet long (from should joint to tip of end effector), with a maximum diameter of 15 inches.

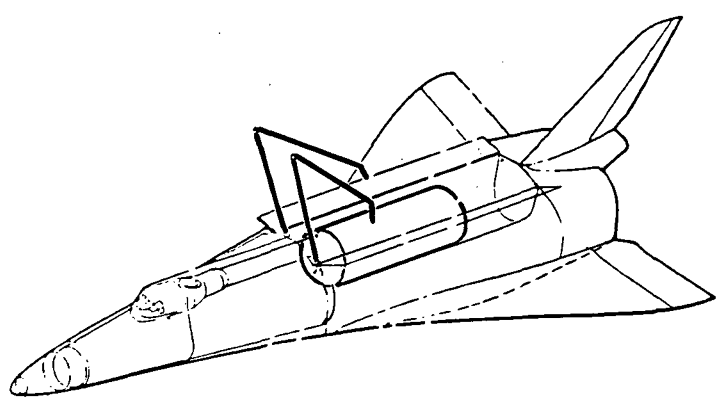


Figure 5-5. Manipulator/Payload Handling

Each arm has a shoulder, elbow, and wrist joint with two degrees of rotational freedom at the shoulder, one degree of rotational freedom at the elbow, and three degrees at the wrist. The entire arm is capable of being jettisoned to allow closure of the cargo bay doors. Each joint is driven by redundant motors and is torque limited to prevent damage to the manipulator arm. Figure 5-7 lists the rates at which the manipulator model can deploy specific payloads, for example, following a retraction and servicing.

End effector tools (Figure 5-6) may be changed to accommodate specialized tasks. One TV camera and one floodlight are mounted near the end effector to illuminate and televise the work area.

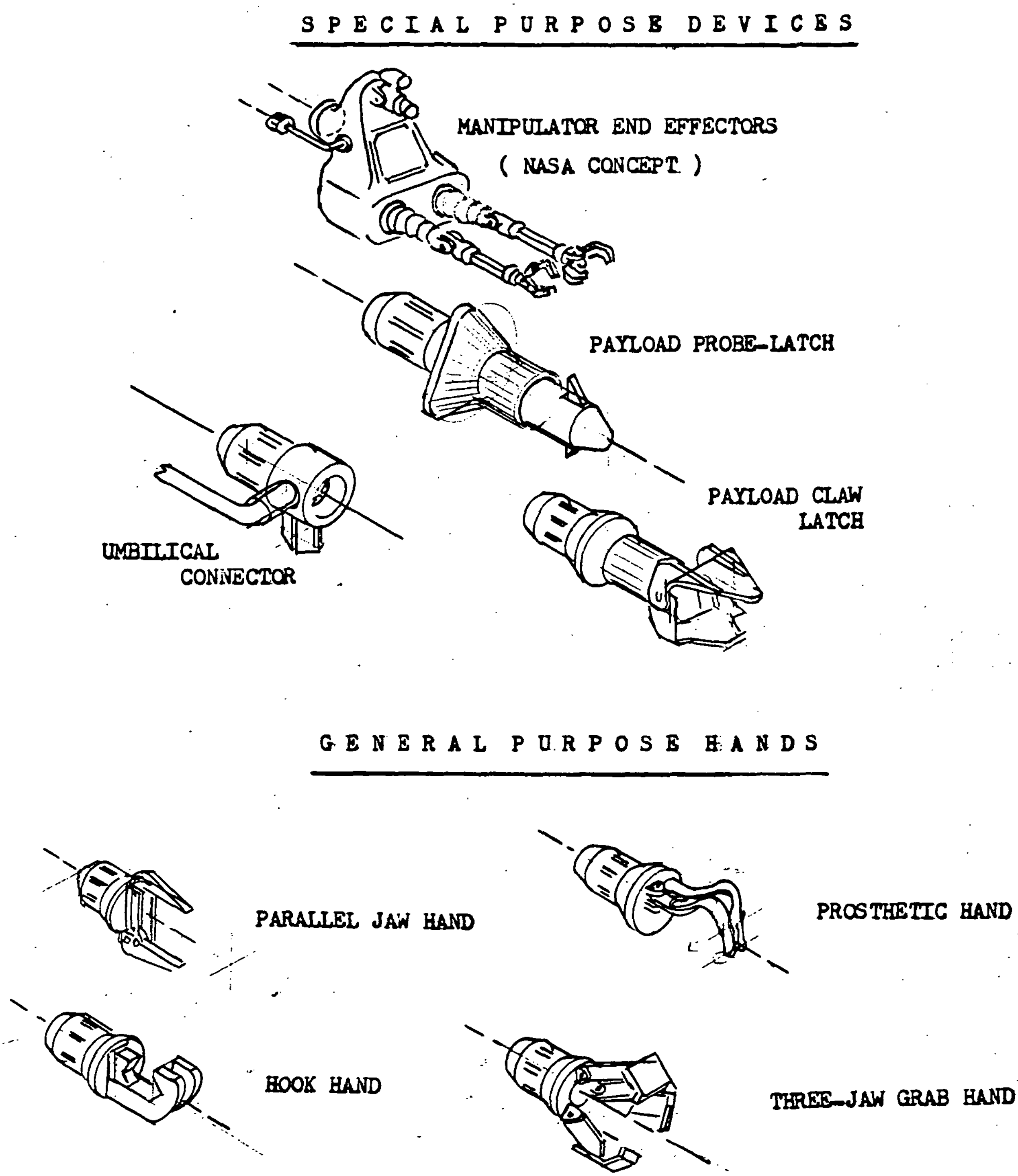


Figure 5-6. Classes of End Effectors

DEPLOYMENT TIME (MINUTES)

CENTER OF GRAVITY	PAYLOAD WEIGHT			
	65K LBS.	45K LBS.	25K LBS.	10K LBS.
A	5.2	4.3	3.2	2.5
B	7.0	5.8	4.3	3.4
C	9.7	8.0	6.0	5.0

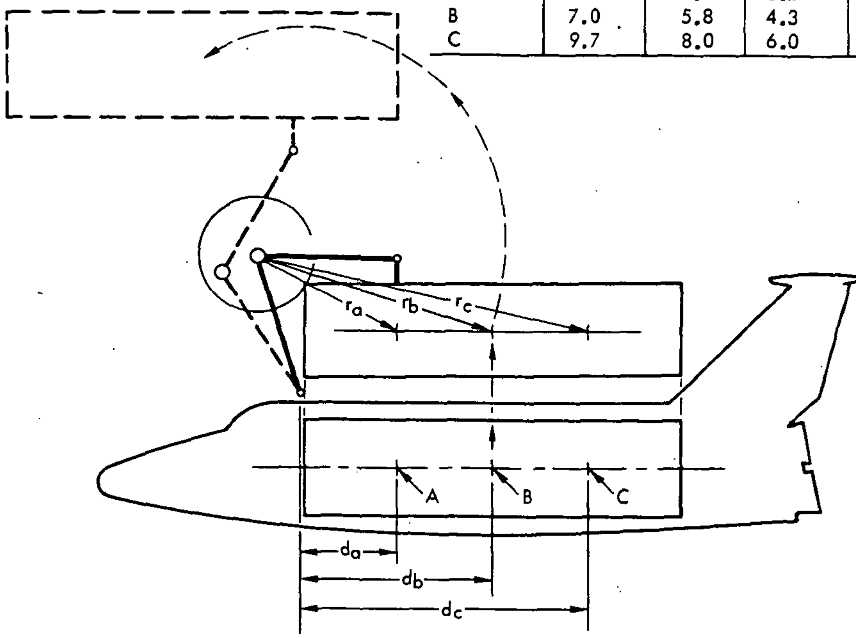


Figure 5-7. Manipulator Deployment Rates

Each arm is sized to individually deploy a 65,000-pound payload (15 feet in diameter by 60 feet) a distance of 600 inches vertically out of the cargo bay, and rotate it 90 degrees. This operation is completed in a maximum of 5.2 minutes (Figure 5-7).

RETENTION CONCEPTS

There are a wide variety of possible payload retention assemblies that would be used during stowage. The payload retention assembly accommodates payloads 15 feet in diameter by a length that can vary from payload to payload. Payloads that are smaller in diameter than 15 feet will be retained by standardized pallets. Retention includes payload center-of-gravity (e.g., control) as required by aerodynamic entry. Of the many potential candidates that exist, each is characterized by the number of retention/attach points, their location (side wall or bottom of the cargo bay) and whether each attach point utilizes latches or simply reacts loads in a slot or channel. Figure 5-8 describes the type defined by MSS and OOS studies and a three-point system that was under study for possible orbiter use. The figure also shows two options for the attach point at the bottom of the payload and two possible EOS/payload latching interfaces.

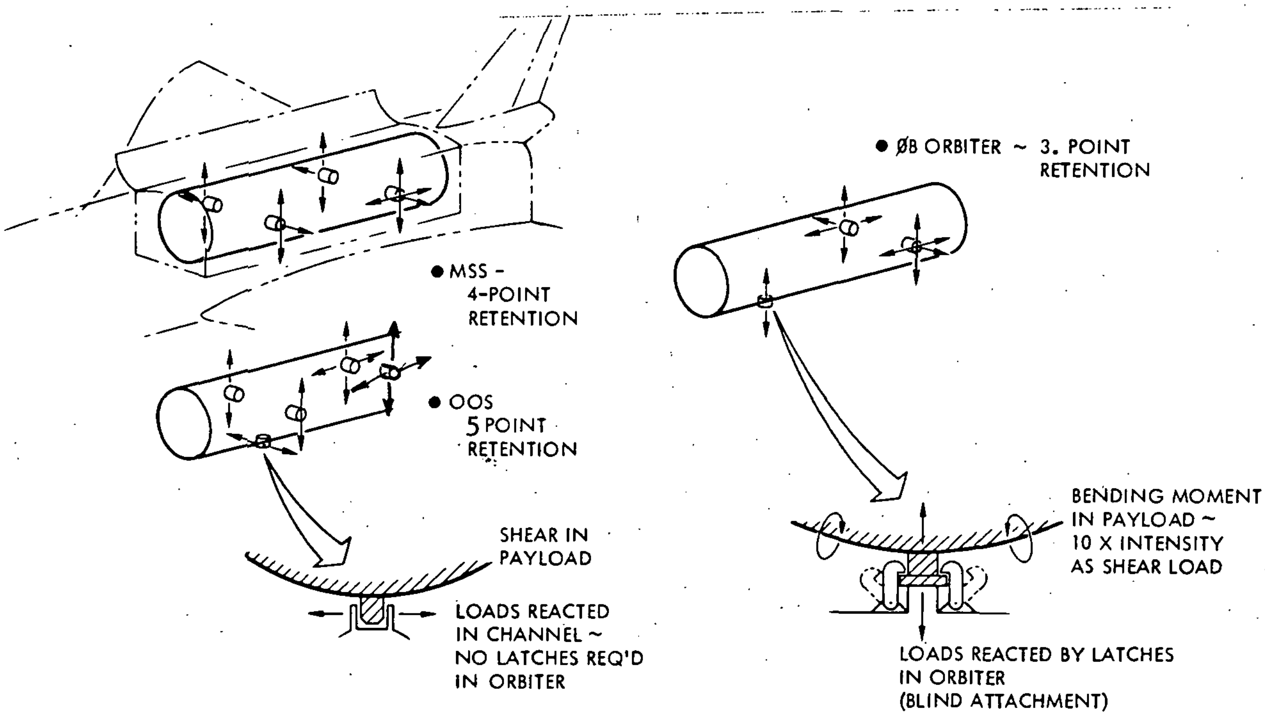


Figure 5-8. Payload Retention Systems

There are some large payloads that becuase of their particular design requirements cannot easily adapt to the retention concepts of the type shown in Figure 5-8, and as a result must utilize a large clamp or a cylinder hinge and rotating mechanisms (see Figures 5-9 and 5-10). Several of the tug concepts have selected either the large clamp or hinge approach. The applicability of these retention devices to the wide spectrum of payloads is obviously limited and a commonality analysis would eliminate them from consideration as a selected concept. They are discussed in more detail in the selected approach selection (5-7).

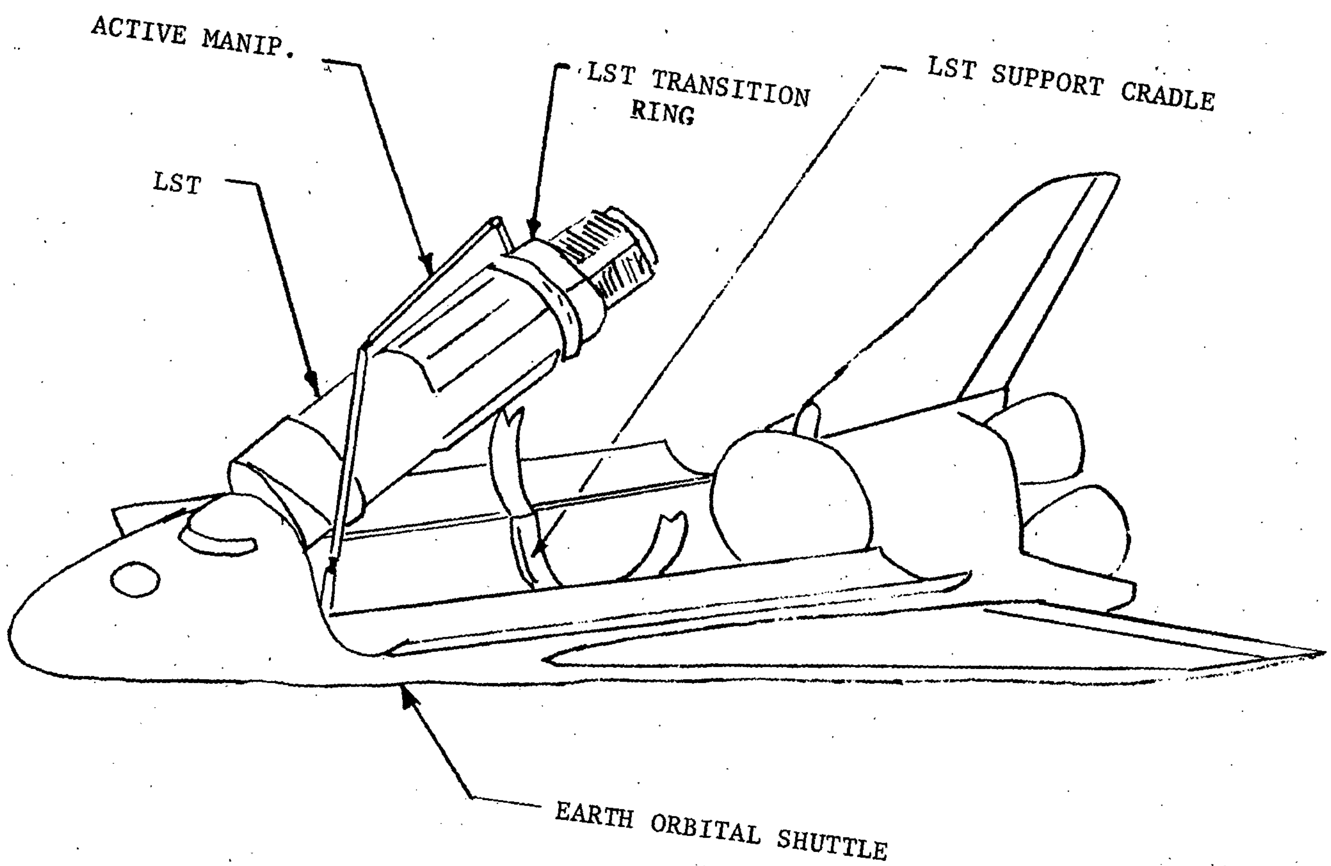


Figure 5-9 . Clamp Retension Concept

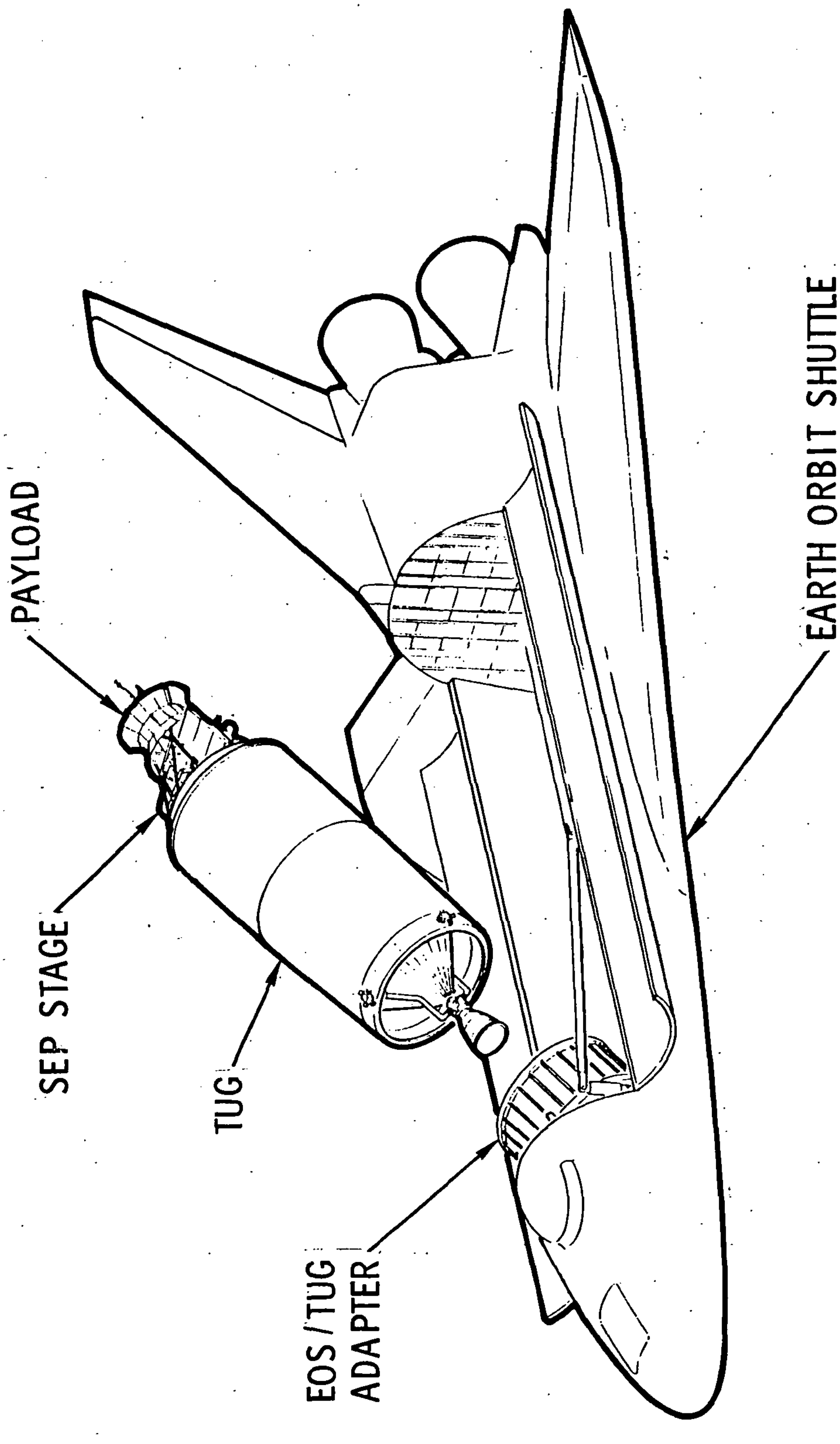


Figure 5-10. Rotating Hinge Retention Concept

Figure 5-12 shows the selected retention concept. The advantages of this selected concept are: (1) it employs a simple latch design, (2) no orbiter loads are transmitted to the payload, (3) the payload is not affected by the flexibility of the orbiter, (4) the side load in the keel saves 500 pounds in orbiter structure, and (5) the lower fitting is a passive mechanism (slot).

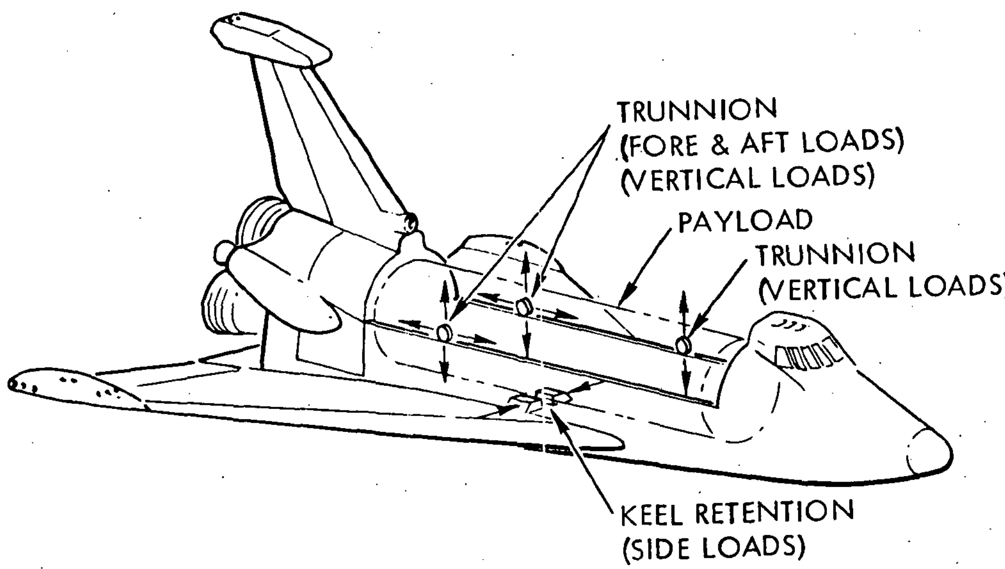
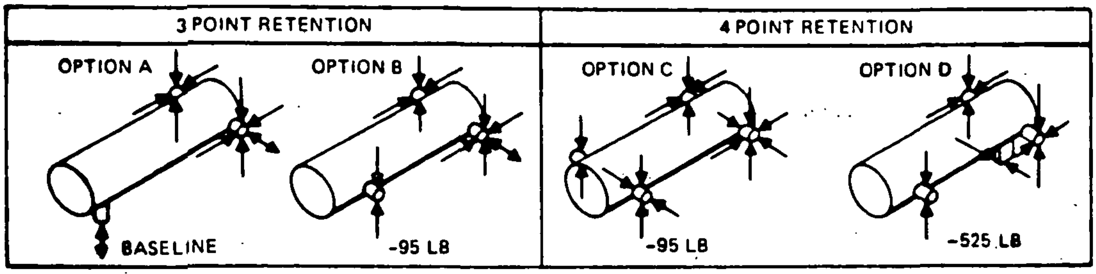
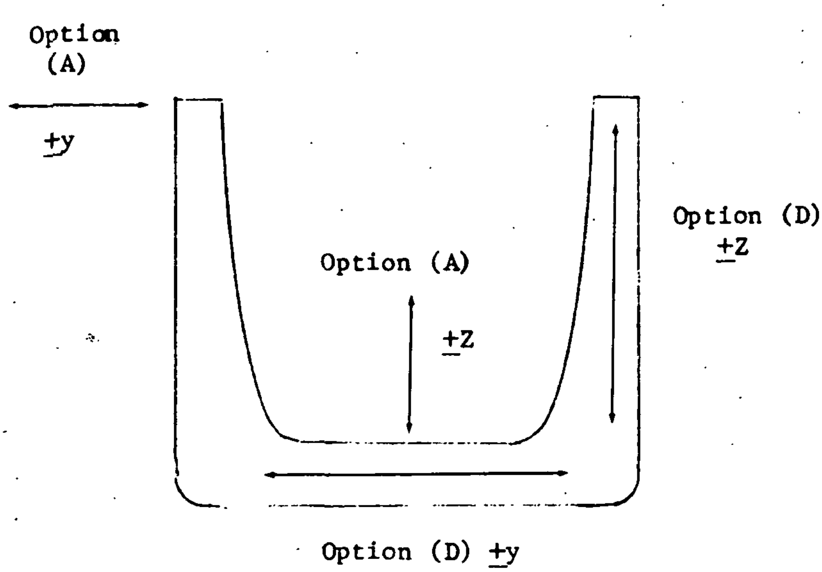


Figure 5-11 Selected Payload Retention Concept

The sketch below illustrates the weight savings the selected concept had over the baseline and other alternatives.



One contractor's initial retention concept corresponded to Option A which was acceptable if only a singular payload location was provided. Alternate concepts B, C, and D were evaluated in order to accommodate multiple retention location in the cargo bay. If it is assumed that (5) five retention locations are required, then Option D is approximately 500 pounds lighter than Option A. In Option A the vertical loads were reacted on the lower centerline of the bay (see sketch below) resulting in an inefficient load path. This concept would have required additional stiffening of beam members. By moving the retention point location to the side of the bay the loads were then taken out by the side walls in shear, which is an inherent load path. The other significant comparison was the method in which the side loads were taken out. In Option A these loads were introduced normal to the side walls which resulted in bending moments in the frames. Option D moved this load path to the bottom of the bay and reacted them by a keel through the frames (in shear).



PIVOT MECHANISM

This system for the retraction and stowage of payloads is shown in Figures 5-12 and 5-13. The model used had redundant actuators and drive mechanisms. It also contained a flexible passenger transfer tunnel. All retraction mechanisms have a manual override capability that the crew can actuate from the crew compartment. The actuators are located inside the airlock providing accessibility for possible in-orbit maintenance or emergency manual operation, (IVA). Torque shafts and adjustable push rod systems are routed through the airlock wall to latching and actuation points. All actuations have lock/unlock indicators and are inspectable by line-of-sight systems from the airlock aft viewing port. Crew transfer (shirtsleeve) is provided into the payload bay at the centerline by a flexible tunnel. This tunnel allows pressurized transfer into habitable payloads in either the extended or stowed position. Hardwire power, communications, and monitoring interface connectors, and other fluids/gases interfaces are located inside the connecting tunnel/hatch area (see item I, Docking Port and Hatch Locations) and are accessible (IVA) for payloads that provide a matching seal. Payload retraction is a simple 90-degree rotation into the cargo bay.

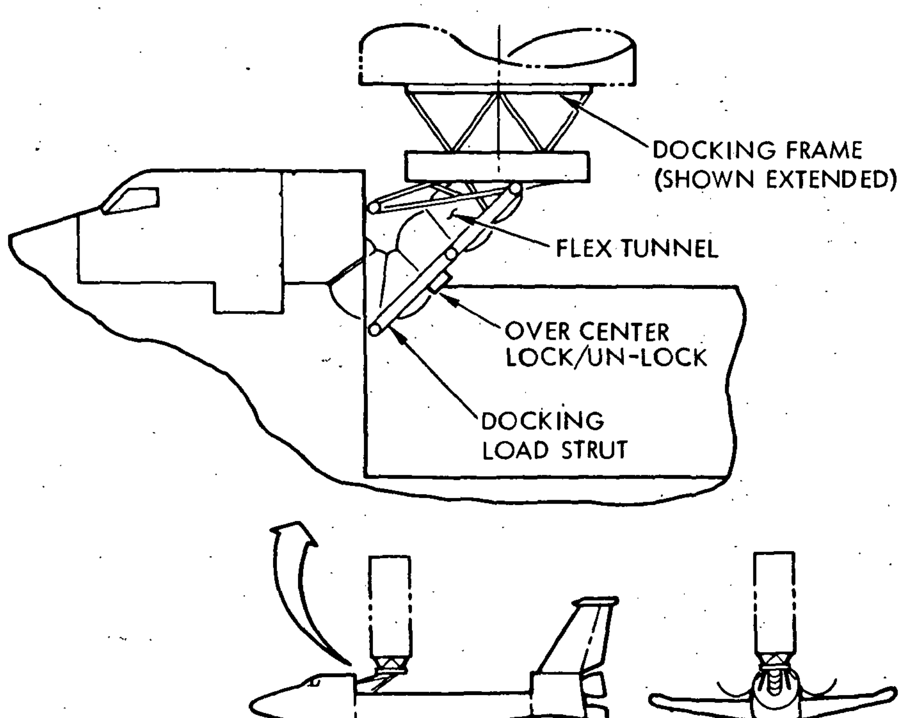


Figure 5-12. Pivot Mechanism

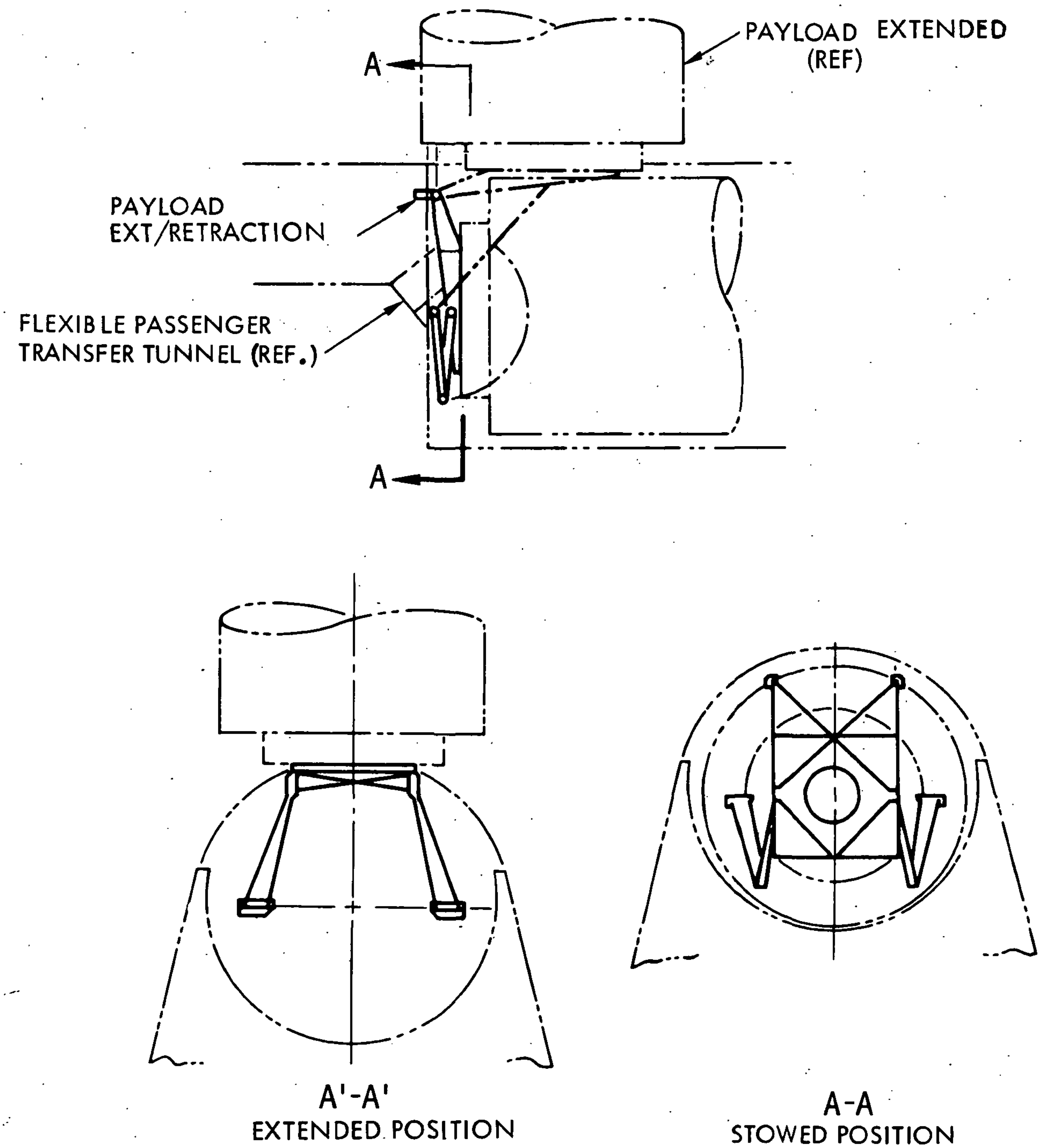


Figure 5-13. Payload Retraction Mechanism

5.5 OPERATIONAL PROCEDURES

Two operational procedures were developed for EOS payload retraction and stowage, one for each of the conceptual approaches. Procedure number 8-1 applies to the EOS equipped with a manipulator. Procedure number 8-2 is applicable to the EOS with a pivoting mechanism in the cargo bay. Both procedural approaches have operations that potentially involve other interfacing activities (mating, attached element operations, and separation). These interfaces were handled by reference only. The following paragraphs are descriptions of each procedure.

Details of the assumptions, initial and final conditions are included with each of the operational procedures and are contained in Appendix B.

PROCEDURE 8-1 (MANIPULATOR APPROACH)

This procedure contains 35 operations. Options are included in the procedure that are utilized if the mission does not require manning of the payload. Also referenced were two interfacing activities (Attached Element Operations and Separation). The Attached Element Operations were referenced for those operations that would be utilized if crew ingress of a payload is required. The Separation procedure is referenced to cover the operations involved with the removal of an adapter located on the cockpit airlock. The remarks/rationale for each operation of the procedure are described in Appendix B.

PROCEDURE 8-2 (PIVOT MECHANISM APPROACH)

The pivot mechanism approach was developed in essentially the same manner as the manipulator approach. The operations begin with readying the EOS and the payload for retraction, and then effecting the retraction/stowage. It also covers the possible operations associated with crew ingress if servicing and maintenance are required prior to positioning the payload in the EOS cargo bay. The flow diagram also contains a by-pass that is used if no crew ingress is required by the mission. A description of the rationale/remarks for each of the 14 operations of the logic flow are contained in Appendix B.

PROCEDURE APPLICABILITY

Since the majority of EOS flights might involve both deployment and retraction on the same mission, a commonality evaluation of EOS payload deployment and EOS payload retraction was performed. A combined deployment/retraction and stowage procedure was developed and used for this task (see Appendix A, trade A-2). The combined procedure has five operational options.

1. Deploy payload only
2. Retract and stow payload only
3. Deploy one payload, then retract and stow a second payload
4. Retract and stow one payload, then deploy a second payload
5. Retract a payload (service), then redeploy same payload

5.6 FUNCTIONAL REQUIREMENTS

The factors considered in establishing functional requirements for EOS payload retraction and stowage are 1) the type of payloads to be handled, 2) the operations involved in moving and attaching the payload within the orbiter cargo bay, and 3) safety. The following functional requirements are applicable to the approach indicated.

The function requirements for this activity and for deployment are unique, when compared to the other activities, in that the majority of these functional requirements apply only to one element, the EOS.

The column on the right-hand side of the requirement identifies the operational procedure to which the requirement is applicable; 8-1 and 8-2 are the manipulator and pivot mechanism approaches, respectively.

Item	Manipulator 8-1	Pivot Mech. 8-2
1. Retrieve Multiple Payloads	X	X
2. Payload Positioning	X	
3. Manage Contamination	*	*

1. Retrieve Multiple Payloads - The EOS shall be capable of retrieving up to three separate payloads during a single mission.

   Maximum weight: 65,000 pounds (including cargo bay provisions)

   Maximum size: 15 ft. diameter by 58 ft. length (including retention/stowage mechanisms)

   The requirement for multiple payload retrieval is derived from (1) economy of operations and (2) space station flights that require a D'RAM to be retrieved and delivered to the station in conjunction with a cargo module exchange.

2. Payload Positioning - The EOS shall provide a mating port for crew egress to condition payloads for retraction and stowage.

   An external service/checkout port is required for selected payloads that have external appendages (antenna booms, solar arrays) that prohibit attachment in the cargo bay. Manned ingress may be required into one payload while another is in the cargo bay. External appendages and equipment items may require manual retraction and deactivation prior to the payload transfer to the cargo bay. Selected scientific sensors may require protective packaging to service the entry and landing loads.

   Illumination of the cargo bay for selected steps in the retrieval operation may require shuttle maneuvers as a backup to floodlights.

3. Manage Contamination - The EOS shall be capable of selectively inhibiting the firing of attitude control engines and the venting of cabin effluents.

   Certain subsystem and scientific equipment are extremely sensitive to engine impingement and contamination. Solar arrays, antennas, and optical sensors should be exposed to a minimum of contamination.

*EOS Only

Item	Manipulator 8-1	Pivot Mech. 8-2
4	X	
5	X	X
6	X	
7	X	X
8	X	X

4. Release of Manipulator Attachment - The EOS shall provide an alternate means of physical separation from the payload if the manipulator effector end fails to release.

5. Physical Retention/Stowage - Retention/stowage mechanisms shall be capable of payload capture subsequent to physical mating. Redundant attachment points shall be provided by both the payload and the retention/stowage mechanism.

6. Payload Separation - The EOS shall provide a separate and independent means for separating the payload from physical attachment to an external service port.

   A payload that cannot be separated from an external port represents a catastrophic mission failure preventing Earth return.

7. Provide Electrical Power - The EOS shall provide electrical power and grounding to the payload while in the cargo bay or connected to an external port.

   Electrical power may be required to condition subsystem and scientific equipment during the retraction operations. EOS supplied power may also be required to pacify subsystems and provide health and safety monitoring.

   Specifically, the EOS shall provide the following electrical power interfaces to the payloads:

8. Provide Venting - The EOS shall provide payload service panels for in-flight fluid venting and dumping. Many payloads will contain hazardous liquids and gases such as:

   - UDMH
   - IRFNA
   - Hydrazine
   - Hydrogen Peroxide
   - Liquid Hydrogen
   - Liquid Oxygen
   - Liquid Helium
   - Freon
   - Gaseous Nitrogen
   - Gaseous Helium

9. Atmosphere Management. The EOS shall provide the necessary interfaces to dump, purge, and fill the payload atmosphere.

The preferred service and checkout mode is shirtsleeve. However, various payloads are not pressurized while on orbit. In addition, cryogenic liquids used to cool scientific sensors and other trace gases may result in a hostile atmosphere.

10. Hardwire Communication and Data - The EOS and payload shall collectively provide the capability to monitor the health and safety status of the payload. A data bus tie for commands and responses shall be provided. Two-way voice shall be provided to support all manned operations.

Payloads contain propellant liquids and gases that can result in potential safety hazards requiring rapid venting and or redeployment of the payload. Conditioning signals may be required to activate or pacify subsystem equipment. Voice and alarm status is a mandatory crew safety requirement for all activities requiring ingress into a payload.

11. RF Data and Command - The EOS shall be capable of establishing a RF link and transmitting command signals to condition the payloads for retrieval.

Selected payloads will require single or multiple RF commands to initiate the following response:

1. Removal of spin, nutation, or tumble
2. Inhibit and/or change attitude control modes
3. Retract external appendages (solar arrays, antennas)
4. Inhibit orientation of sensors
5. Activate protective doors and shutters
6. Dump/vent fluids and gases

Item	Manipulator 8-1	Pivot Mech. 8-2
9	X	X
10	X	X
11	X	X

Requirement	Manipulator 8-1	Pivot. Mech. 8-2
12. <u>Visual Monitoring</u> - A Means shall be provided for monitoring the various steps in the retraction sequence (e.g., attachment of wiring and plumbing, stability of payload, and either direct or television viewing of the operations). The information obtained from this monitoring must be available to the operator and/or controller of the retraction mechanism. The orbiter shall provide the following monitoring capability via the payload information management interface: a. Payload total pressure b. Payload oxygen partial pressure c. Pressure of payload pressure vessels and temperature and pressure of cryogenic vessels d. Payload internal temperatures e. Monitor for explosive atmosphere for pressurized payloads f. Monitor for toxic atmosphere for pressurized payloads g. Provide fire detection and control of pressurized payloads	X	X
13. <u>Stability</u> - The retraction mechanism must hold the payload stable until it is physically retracted into the orbiter. There are two reasons for maintaining stability of the payload during retraction. First, stabilization is a safety measure which can prevent bumping of the payload and orbiter structure. Second, some payloads will be mated to other elements before release and stabilization is required for effective operations during mating.	X	X

Requirement	Manipulator 8-1	Pivot Mech. 8-2
14. Separation - Separation of plumbing and wiring connections shall leave them in a state such that, if needed, they can be reconnected to and function with either the retrieved payload or another payload retrieval on the same mission. Some missions require retrieval of the same payload as deployed on that mission (e.g., ground based tug missions). In these cases, hardware communication links and propellant purge and vent lines woulc be reconnected.	X	X
15. Structural and Mechanical		
a. C.G. Excursions. The EOS orbiter has requirements that its design places on payloads that require retraction. Figure 5-15 shows the limits of the allowable c.g. travel versus payload weight.	X	X

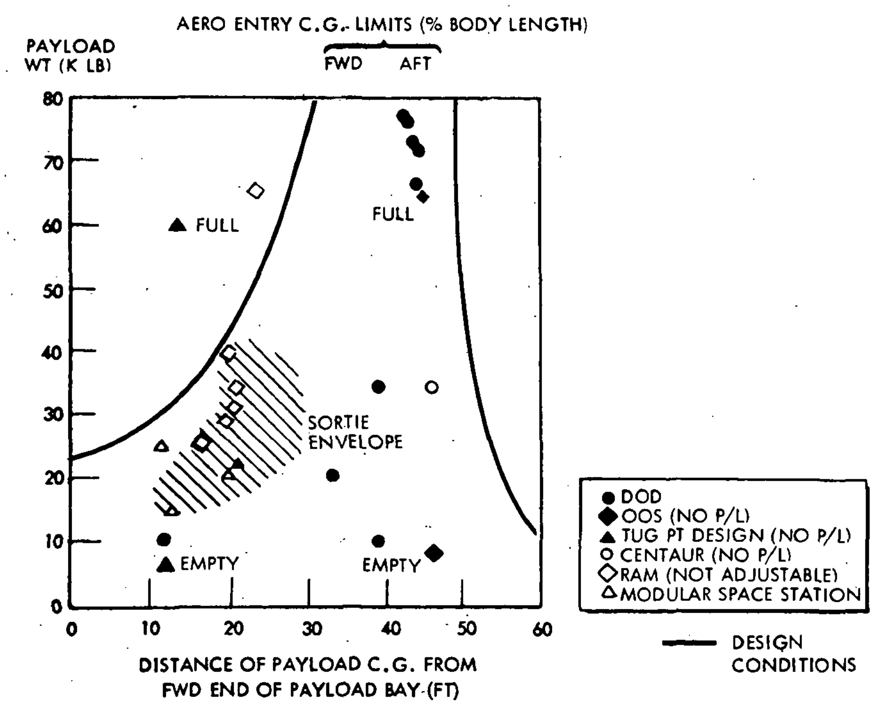


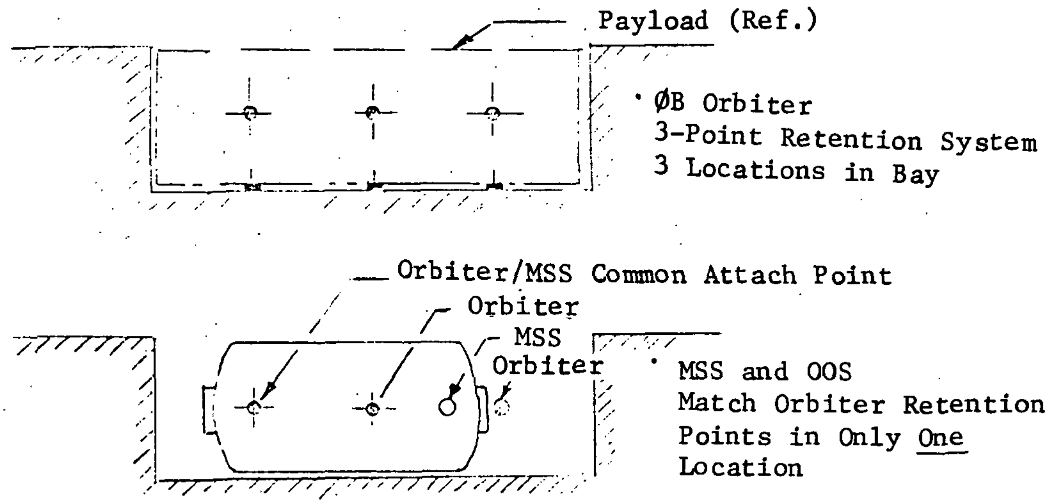
Figure 5-14. Payload Longitudinal C.G. Constraints

	Manipulator	Pivot Mech.
	8-1	8-2
b. Payload Retention	X	X

b. Payload Retention. The basic problem associated with payload retention is characterized by Figure 5-16. There is a requirement that the EOS have multiple retention point locations. It is further desirable that these retention points be either numerous (18-inch by 24-inch O.C.) or variable. The requirement for a retention mechanism influences the ability to provide extension tunnels and adapters. The center-of-gravity geometry of a specific module might require that it be retained at the aft end of the cargo bay. This arrangement would make manned entry an additional weight and volume penalty.

The number of retention points should be a minimum of four for Space Station Modules, Cargo Modules, Experiment Modules, and RAM Support Modules. Other payloads may require a slightly different arrangement due to their structural arrangements and physical characteristics; i.e., location of solar panels, sensors, antennas, etc.

Multiple retention point locations along the length of the bay will be necessary to accommodate a variety of payloads for several reasons: (1) payloads approaching 60 feet in length may have their structural provisions only at the extreme forward end, such as an astronomy telescope; (2) short payloads could presumably be moved fore or aft to accommodate one retention location, but would require additional unwanted structural provisions to pick up the other retention points if widely spaced; (3) the physical arrangement of some payloads will preclude their ability to match their structural hardpoints with only a few widely spaced attachments in the payload bay; (4) the center-of-gravity, coupled with structural arrangement and overall length of payloads will also dictate the need for multiple locations of retention points to stay within the required payload c.g. envelope.



• Requirement

- Orbiter Needs Multiple Retention Point Locations 18 in. - 24 in. O.C. to Accommodate a Wide Variety of Payload Characteristics
  - Length/C.G. Relationship
  - Structural Features
  - Solar Arrays, Sensors, etc.
  - Manned Entry Requirements (Tunnels and Adapters)

Figure 5-15. Retention-Point Locations

Manipulator	Pivot. Mech.
8-1	8-2
X	X

16. Payload Shirtsleeve Access - Shirtsleeve access is required from the EOS passenger compartment to pressurized payloads in the cargo bay. This access might be necessary to perform servicing prior to redeployment.
Access to all payloads shall be on the payload module centerline to allow use of the berthing port hatches for crew access. The passageway or tunnel shall be sized to allow transfer of a suited crewman wearing a portable life support system (PLSS), excluding utility runs, lighting, and crew mobility aids. Additional volume could be considered for the rescue of a disabled crewman from the payload module. The requirement to preclude the intrusion of the tunnel or passageway into the 15 x 60-foot clear volume of the cargo bay implies

Manipulator	Pivot Mech.
8-1	8-2

that part of the tunnel may be flexible to accommodate payload modules attached at different cargo bay locations (see Figure 5-17). This is a potential trade area - payload access accommodation with a single flexible tunnel vs. detachable non-flexible adaptors of various lengths. Capability to dump or pump-down the tunnel atmosphere shall be provided to accommodate IVA crew access to an unpressurized payload.

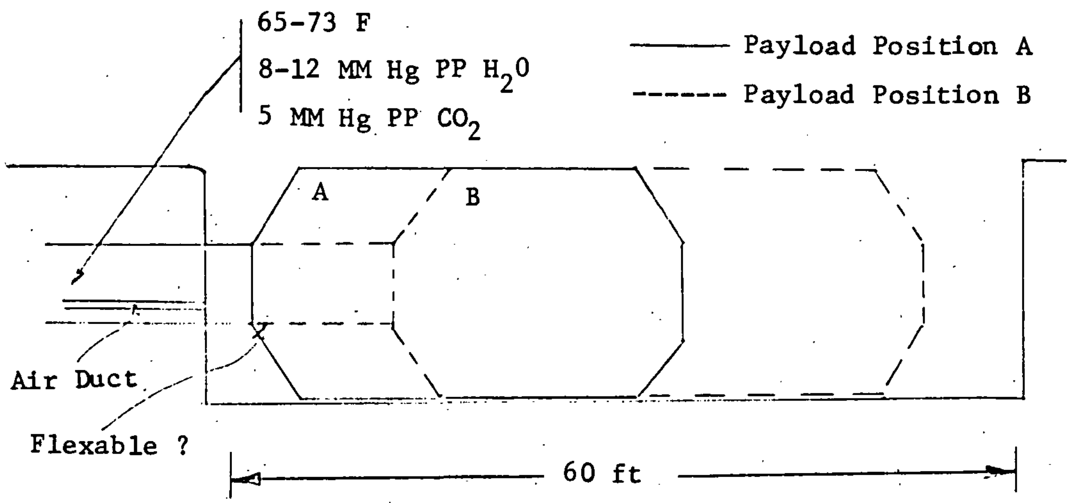


Figure 5-16. Payload Shirtsleeve Access

Manipulator	Pivot Mech.
8-1	8-2
X	X

17. <u>Attachment Integrity Verification</u> - The manipulator shall be capable of verifying the integrity of the payload-retntion interface by applying and sensing forces prior to release of the paylod.

	Manipulator	Pivot Mech.
	8-1	8-2
18. <u>Payload Retraction</u> - The retraction mechanism must be capable of handling any pallet, shield, or supporting structure that must be retracted along with the payload. In some cases, the operational payload (e.g., an experiment module) is permanently attached to a pallet that provides the handling points for the retraction mechanism. Only one payload shall be moved at a time during any one sequence of operations. If two payloads were handled independently of each other at the same time, there would be inherent danger of collision. An envelope prescribing the allowable movement of the retraction mechanism and/or the payload shall be established. Again, safety is the overriding consideration. The envelope shall take into account such possibilities as payload plume impingement on the orbiter and collision between the payload and the orbiter. The retraction mechanism must hold the payload stable prior to retraction. Stabilization is a safety measure than can prevent bumping of the payload the the orbiter structure.	X	X

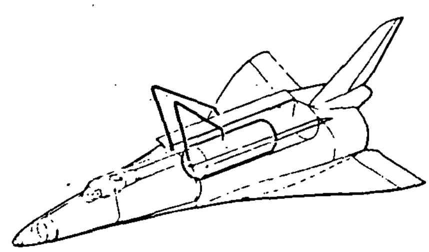
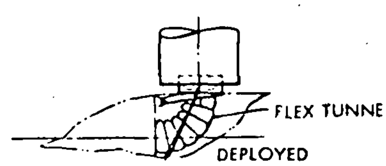
The functional requirements for EOS Payload Retraction/Stowage are unique in the respect that they relate almost exclusively to the orbiter. The majority of the requirements are independent of the approach taken to accomplish the retraction and stowage. In the other interfacing activities there were hardware choices that could be made as a function of distinct element paris. Thus, the requirements could then be developed by element. Since the EOS was selected as the active element of this activity all functional requirements became primarily an EOS model that all payloads, requiring use of the shuttle for retraction, would be required to be compatible with. For these reasons no separate functional requirement choices were made by element pair.

5.7 DESIGN INFLUENCES & PREFERRED APPROACH SELECTION

In order to properly select the preferred approach for EOS payload retention and stowage it was necessary to go beyond this interfacing activity and include the requirements of EOS payload deployment. The two activities are so closely related that an attempt was made to see if the same hardware could accomplish both functions. Therefore in the analysis that was made the functional requirements were expanded and analyzed along with consideration of, Mating (Section 1.0), Orbital Assembly (Section 2.0), and EOS Payload Deployment (Section 4.0).

PRIMARY ALTERNATIVES

Five alternates were identified as potential candidates to handle the retraction of payloads into the EOS cargo bay. The two choices selected for further study were the pivot mechanism and on-board manipulation. Paragraph 5.3 (Alternative Approaches) contains a description of each the five alternatives and the rationale used to select the two approaches that were evaluated further. The two approaches are:

MANIPULATOR	PIVOTING MECHANISM
	

Operation models of both approaches were constructed and evaluated using the functional requirements established for the activity and evaluating factors of reliability, safety, cost, etc. Added to the comparison of requirements against approach models was an assessment of the additional benefits that each of the alternatives might have. Areas where one or both alternates would have synergistic benefits were examined.

An additional step of this evaluation/selection process was an assessment of each approach and how it was effected by the operational procedures of paragraph 5.5. This comparison of approach to procedure also included the combined deployment/retraction and stowage procedure. This last comparison was made because the procedural applicability efforts conducted for this study showed that there would be a high probability that deployment/retraction and stowage operations would both be required on many shuttle flights. Thus, it was impossible to eliminate considerations of both interfacing activities. Table 5.3 (Approach Selection) contains a summary of how each approach meets

Table 5-1. Approach Selection

Functional Requirement	Manipulator	Pivot Mechanism	Remarks
o Retrieve multiple payloads	Excellent	Good	Flexibility of manipulator greater for capture and stowage.
o Provide cargo bay illumination	Excellent	Good	Manipulator can move light source easily
o Stow payload	Good	Good	
o Provide utilities	Good	Excellent	Pivot mechanism is capable of providing continuous utilities from the extended thru the stowed position.
o Maintain payload stability	Good	Excellent	Pivot has a more controlled motion path.
Evaluation Factor			
o Technology	Slightly beyond the state of the art	State of the art	
o Operational complexity	Least	Slightly higher	
o Reliability	Good	Best	
o Commonality	Best	Poor	Pivot requires special adapters for many payloads
o Relative cost	Higher	Lowest	
o Crew interface complexity	Highest	Lowest	Manipulator requires special training and high levels of crew involvement
o Center of gravity control	Best	Poor	Attach point on pivot mechanism limited to end of cargo bay.

the functional requirements of retraction and stowage and how they compare for the eight additional evaluation factors considered.

Retrieve Multiple Payloads - There will be some missions of the EOS that will require the retrieval of more than one payload on a single mission. As was pointed out in the Deployment interfacing activity a pivot mechanism can be designed to handle this requirement and would perform the functions adequately. A concept is illustrated in Figure 5-18 . It would, however, require additional weight and volume and thereby reduce the dynamic clearance envelope in the cargo bay from the 15-ft diameter that is presently available to payloads. However, the flexibility of the manipulator to handle this function is excellent. It can be accomplished without any additional design complexity being added to the manipulator design for single payload retrieval.

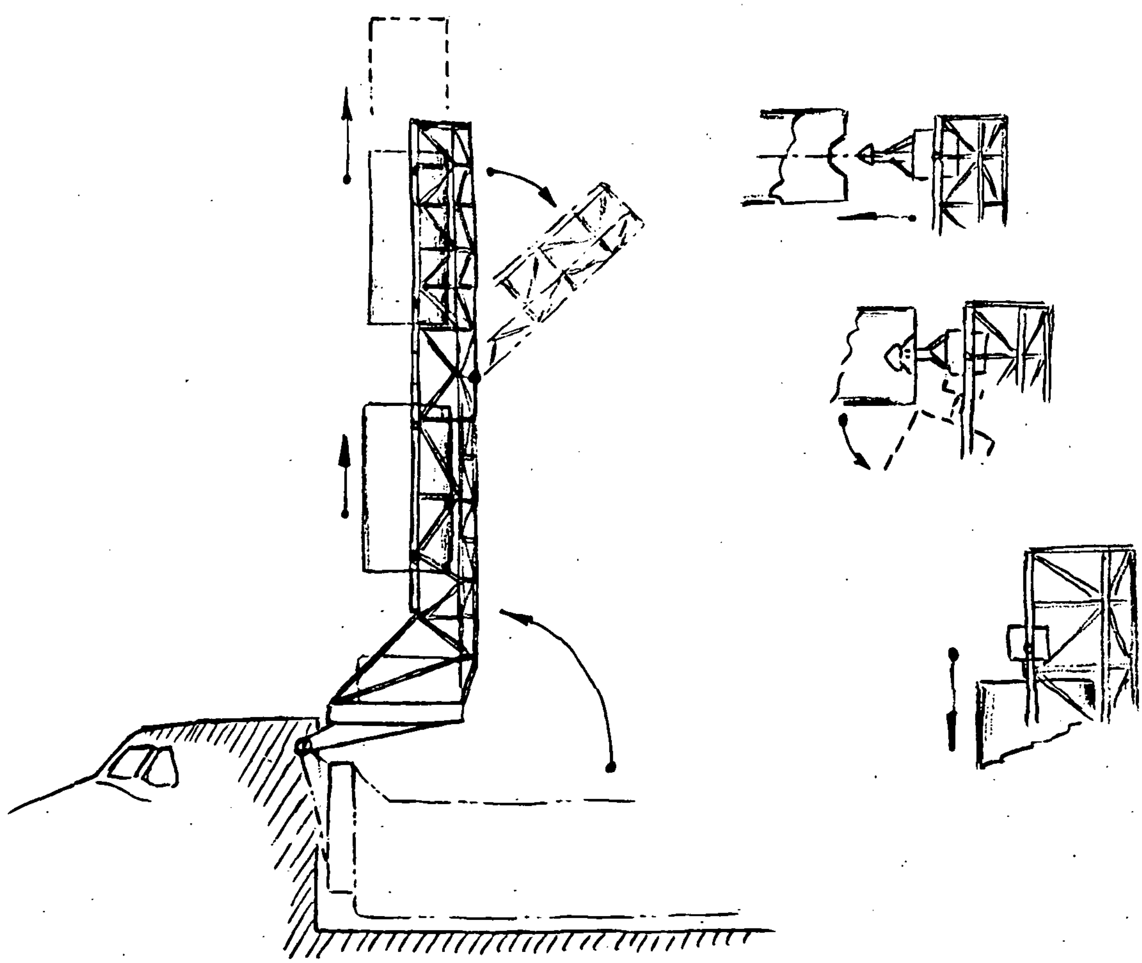


Figure 5-17. Multiple Payload Handling Concept

Deploy Tug Payloads

The ability to use a universal retention concept is highly unlikely. Some payloads designs will be such that structural penetrations to react loads will either be impractical or prohibitive from a weight standpoint. These payloads (TUG for example) will require a clamp device or rotating hinge mechanism to provide the load distribution path between the payload and the EOS attachment points.

The selection of either (1) rotating hinge or (2) clamp for Tug retention in the EOS cargo bay is greatly influenced by the main propulsion LOX tank location as follows:

LOX Tank Location	Retention Concept	
	Clamp	Hinge
Aft	(1) X	(2) Preferred
Forward	(3) Preferred	(4) X

(1) Aft LOX Tank and Clamp Mechanism. Not selected due to unfavorable dynamic response created by large c.g. to retention location moment arm

(2) Aft LOX Tank and Hinge Mechanism. Preferred because the rotating hinge mechanism is located close to combined Tug/Payload c.g., thereby reacting the principal $\pm X$ axis loads. The $\pm Y$ and $\pm Z$ axis loads can be reacted using the universal retentions.

(3) Forward LOX Tank and Clamp Mechanism. Minimizes the dynamic response by locating the retention device on the LOX tank support. The resultant loads are reacted near the c.g. and using an existing structural member.

(4) Forward LOX Tank and Hinge Mechanism. Not selected primarily due to the large separation between retention device and Tug/Payload c.g.

The selections between items (2) and (3) will be determined in the current DOD Upper Stage/Shuttle System study.

Selection of the rotary hinge concept would eliminate the need for the manipulator since the rotating hinge can perform the same functions as the pivot mechanism. The selection of the large clamp will favor use of the manipulator.

Provide Cargo Bay Illumination - This requirement must be satisfied prior to the initiation of the retraction sequence. The manipulator has the advantage over the pivot mechanism in that the second arm can be used to position floodlights in any number of locations making the illumination portable and flexible. This portability can be extended not only to the payload attach points, but also to the verification that external appendages (i.e., solar arrays, antennas, windows, lens covers) have not been damaged and/or were retracted correctly.

Stow Payload - The EOS shall provide a separate and independent means for separating the payload from physical attachments external to the cargo bay. The manipulator and the pivot mechanism can both equally meet this requirement. The pivot mechanism can have manual backup release mechanisms in the IVA tunnel near the mating interface. The manipulator can use either mechanical means to effect the backup for stowage, or the second manipulator arm.

Provide Utilities - Both approaches can provide an equal quantity and type of utilities. There is an advantage for the pivot mechanism in that it is potentially capable of maintaining these utilities throughout the retraction phase and, if necessary, redeployment of the payload.

Maintain Payload Stability - The retraction mechanism must hold the payload stable until it is physically retracted into the orbiter. Primarily it will avoid possible bumping between the orbiter bay and the P/L. The pivot mechanism has an advantage over the manipulator in that it provides a much more rigid retraction device that will move a payload over a more controlled, predictable motion path than a manipulator. (See the manipulator and pivot mechanism models for system capabilities.)

Release Payload - Both approaches can equally meet the requirement of separate and independent means of releasing a payload. They can also both maintain the plumbing and wiring connections in a state such that, if need be, they can be reconnected.

NOTE: This factor was considered because of the potential of having to deploy a payload after it has been retracted and serviced.

Provide Manned Entry to Payload - While the payload is in the stowed position in the bay both approaches will utilize the same concept to provide manned access to the payload, a flexible tunnel. The pivot mechanism has the specific advantage of being capable of connecting the tunnel to the frame of the mating/retraction structure. Thus this manned entry capability can be continuous in both the extended and stowed positions. In the manipulator case if shirtsleeve access is required for a stowed payload then the utilities connections and the monitoring of the habitable condition of the P/L will be broken when the payload is erected. The effect of the operational complexity will be most evident during the attached EOS - RAM missions requiring extension of a payload beyond the orbiter moldline.

Technology - The technology status of the two approaches is slightly different. In the pivot mechanism the mechanical devices and actuator drive assemblies are well within the state of the art even though a prototype has yet to be completed. With the manipulator the same status (within the state of the art) exists for the mechanical portions (drive motors, clutches, actuators, basic arm design) of the concept. There is still some development work required in areas of stiffness, and force feedbacks for the anticipated wide range of payload masses.

Maintenance - The pivot mechanism has a potential design advantage over the manipulator. Its actuator can be located inside the crew tunnel where they would be accessible for on-orbit maintenance or emergency manual operation. The torque shaft and adjustable push rod systems could be routed through the pressure wall to latching and actuation points. Maintenance on some of the components of the pivot mechanism and the manipulator could require IVA/EVA operations. However, neither concept has identified on orbit maintenance requirements. All normal maintenance would be performed upon return of the EOS to ground.

Safety - Basically both approaches can be made safe. The question resolves itself then to what potential hazards exist with each alternative. The pivot mechanism with its more controlled motion paths would be the easiest of the two options to make safe. It represents a simple concept with fewer potential hazard than the manipulator. The major safety problem with the pivot would be a failure of the activation system with a payload partially deployed. This could be handled with redundant drive motors backed-up with a manual override capability.

The manipulator has four potential hazards that would create significant safety problems, namely: (1) once motion of the payload has been initiated failure to the control, and/or brake mechanisms could result in damage to either the orbiter, payload or manipulator, (2) there is the potential problem of having a manipulator failure cause the arm to "hang-up such that it cannot retract a payload from the bay", (3) the manipulator end effector could become engaged in a receptacle and fail to release; thus the cargo bay doors could not be closed until the release was affected, (4) the final potential major problem is one in which during the final motions prior to engagement of the end effector and the receptacle either a mechanical failure (to the manipulator and/or the attitude control system of either vehicle) or an operator error could cause an inadvertent movement of the end effector or arm, damaging the payload or its appendages.

While these potential failure modes are significant all of them can be compensated for by adding redundancy in design and force feedback capability. Therefore since both approaches can be made safe, safety did not drive the decision between the two approaches. It did however establish a bias toward the pivot mechanism since it appears to be the easiest of the two to make safe.

Operational Complexity - There are operational activities where the complexity of the pivot mechanism is greater than that of a manipulator. An example that can serve to illustrate this is the exchange of a space station cargo module including crew transfer. This example will include both deployment as well as retraction and stowage considerations. The basic differences between the two approaches are summarized below:

Step	Pivot Mechanism	Step	Manipulator
1.	Hard dock EOS to station (through payload)	1.	Berth EOS to station
2.	Transfer crew to station	2.	Transfer crew to station through EOS mating port
3.	Undock EOS from cargo module	3.	Utilizing manipulator effect exchange of cargo modules
4.	Redock EOS to cargo module that is to be returned.		

The use of the manipulator approach to affect the exchange of modules at a orbital facility involves only one berthing as opposed to the pivot mechanism mode of a docking followed by a near proximity maneuvering, stationkeeping, and redock (at an estimated propellant penalty of 350 pounds per redock).

The use of manipulators for payload retraction and stowage has the potential for additional operational simplicity in that it can minimize the complexity of operations concerned with the preparation of a payload for final checkout prior to stowage. The manipulator can assist in the retraction of appendages, and with TV cameras it can perform a visual inspection of the payload.

Although these operations can be adequately performed with the pivot mechanism concept a manipulator is favored for delivery and exchange of modules at a facility and the retrieval of satellites and unmanned payloads.

Reliability - Inherent in the two approaches is the basic simplicity of the pivot mechanism approach as compared to the manipulator. It will require more cost to bring the level of reliability of the manipulator to that of the pivot. Although there are problems in designing the manipulator approach, there are no elements that cannot be made as reliable as required.

Commonality - Use of the manipulator approach can be carried across many elements of the space vehicle inventory. The manipulator end effector receptacles (see the design models 5.4) are simple and can be adapted for use on any payload. The manipulator can also be used as an aid in other interfacing activities (mating, orbital assembly, cargo/crew transfer, propellant transfer).

<u>Relative Cost</u> - Cost studies of comparable manipulator and pivot mechanism approaches that have evaluated not only the weight estimates of both mechanisms but also included the costs of enlarging or shrinking the shuttle to maintain constant payload weight have concluded that the manipulator approach is more expensive than the pivot mechanism approach.

<u>Bias</u> - The near-term bias favors the pivot mechanism assembly because of its less complex design utilizing docking techniques that have been developed on previous space programs. Thus the pivot mechanism could be used during the first few years of the EOS program. At this time in the program there would not be any orbital depots or other module assemblies in orbit. The need to use the EOS for module revisits or replacements would be at a low level of activity. Thus development of the manipulator could lag the orbiter. When the complexity of the missions increases the manipulator could be added to the EOS as a delayed development.

<u>Payload CG Control</u> - In the area of controlling the allowable CG travel versus payload weight the pivot mechanism does not have the flexibility of the manipulator. It attaches to the payload at the forward end of the payload bay. If the payload CG falls outside of the acceptable range, then the pivot mechanism must have adapters to move the payload to the right location in the bay.

CONCLUSIONS

Based upon the analyses and evaluation the selection of a singular approach for EOS payload retraction and stowage is not warranted. If only singular payloads were considered a preference for the pivotal concept is evidenced. It is less complex, lighter, less costly, and facilitates manned access to the payload. However, when consideration of the synergistic benefits that can be achieved by the use of the manipulator in assembly of the station, handling of multiple payloads, and potential on-orbit maintenance operations is included the manipulator is a highly desirable concept.

In addition to the added margin of safety inherent in the use of the manipulator for station cargo module and RAM exchange operations (more positive control of modules in close proximity) the manipulator can be used for attaching and replacing modular packages such as an airlock laboratory or antenna package. Handling multiple payloads can be readily accomplished with the manipulator. The sequence of operations is not restricted and free-flying close proximity operations can be avoided.

The principal advantages of the pivotal mechanism concept are:

1. It consists of a simple system that can be readily used for single payload deployment and retrieval operations (adapter required for some satellites).

2. It provides a conventional and common on axis docking capability for mating with the orbiter or payloads with other elements.

3. It provides the potential for continuous shirtsleeve access to habitable payloads during cargo bay storage and deployed payload operations without interruption of EOS-payload interface.

4. It provides the potential for shirtsleeve access (if necessary) to the deployment/retraction actuation and the interface connections.

5. It provides a more positive control of the payload during erection and retraction operations.

Thus each approach has highly desirable features. Also each approach can be adapted to meet all the operational requirements identified. For example, the pivotal mechanism concept could include a "rack" as illustrated in Figure 5-18, which would permit the handling of multiple payloads.

It is recommended that both the pivotal mechanism and the manipulator concept be developed. EOS programmatic considerations - cost, schedule, payload traffic models - rather than operational activities should determine the selection of the baseline concept. Development options include 1) selection of one as a baseline and kit installation of the other, 2) provisions for kit installation of both concepts, or 3) if the EOS traffic model permits, a sequential development of concepts on successive orbiters.