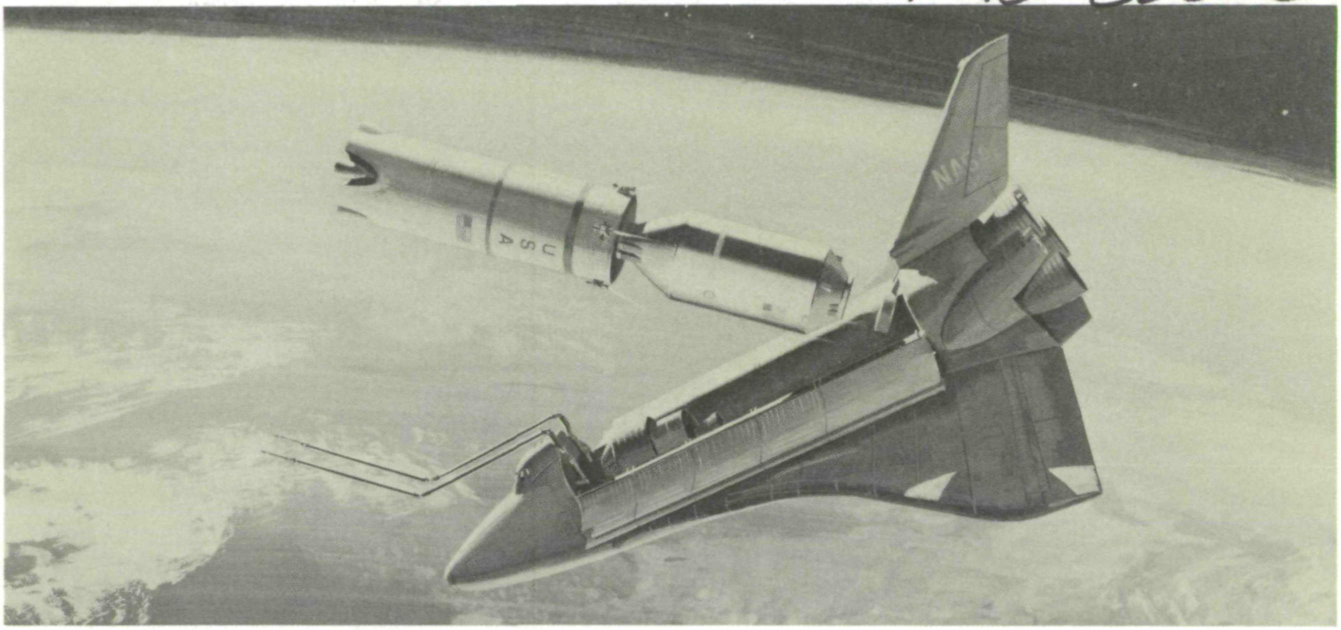
CONTRACT NAS8-27692
DR NO: MA-04

SD 72-SA-0053-4
JUNE 23, 1972

IN-SPACE PROPELLANT
LOGISTICS AND SAFETY

N72-30803



IN-SPACE PROPELLANT LOGISTICS

Volume IV

PROJECT PLANNING DATA

Space Division
North American Rockwell

12214 Lakewood Boulevard, Downey, California 90241

CONTRACT NAS8-27692
DR NO: MA-04

SD 72-SA-0053-4
JUNE 23, 1972

IN-SPACE PROPELLANT
LOGISTICS AND SAFETY

IN-SPACE PROPELLANT LOGISTICS

Volume IV

PROJECT PLANNING DATA

R E Sexton

R.E. Sexton, PROGRAM MANAGER

Space Division
North American Rockwell

12214 Lakewood Boulevard, Downey, California 90241

FOREWORD

This In-Space Propellant Logistics and Safety Study was performed by the Space Division of North American Rockwell Corporation for the National Aeronautics and Space Administration, Marshall Space Flight Center, under Contract NAS8-27672. The study was a twelve-month effort initiated on 25 June 1971 and completed on 23 June 1972.

The study was conducted as two separate but related projects. One project addressed the systems and operational problems associated with the transport, transfer and storage of cryogenic propellants in low earth orbits, while the other project addressed the safety problems connected with in-space propellant logistics operations. Correlation between the two projects was maintained by including safety considerations resulting from the Systems Safety Analysis, in the trade studies and evaluations of alternate operating concepts in the Systems/Operations Analysis.

Walter E. Whitacre of Marshall Space Flight Center, Advanced Systems Analysis Office, was the Contracting Officer's representative and provided technical direction to the overall contract and to the Systems/Operations Analysis project; Walter Stafford, of the same office provided technical direction to the Systems Safety Analysis project. The contractor effort was under the direction of Robert E. Sexton, Program Manager; the Systems/Operations Analysis effort was led by Robert L. Moore and the System Safety Analysis effort was led by William E. Plaisted.

This document is Volume IV of the following five volumes which contain the results of the Systems/Operations Analysis:

Volume I	Executive Summary	(SD72-SA-0053-1)
Volume II	Technical Report	(SD72-SA-0053-2)
Volume III	Trade Studies	(SD72-SA-0053-3)
Volume IV	Project Planning Data	(SD72-SA-0053-4)
Volume V	Cost Estimates	(SD72-SA-0053-5)

The results of the System Safety Analysis portion of the study are contained in the following three volumes:

Volume I	Executive Summary	(SD72-SA-0054-1)
Volume II	System Safety Guidelines and Requirements	(SD72-SA-0054-2)
Volume III	System Safety Analysis	(SD72-SA-0054-3)

This volume contains the project planning data in support of the selected configuration and operations.

Preceding Page Blank

ACKNOWLEDGMENTS

The contributors to Volume IV of this report include the following:

F. W. Rosenberg - Program Development

D. F. Gluck - Supporting Research and Technology

R. A. Pople - Operation Support

K. R. Granville - New Facilities and GSE Requirements

Preceding Page Blank

TABLE OF CONTENTS

Section		Page
1.0	INTRODUCTION AND SUMMARY	1
2.0	TEST REQUIREMENTS	5
2.1	DEVELOPMENT TESTING	6
2.1.1	Development Test Criteria	6
2.1.2	Subsystem Test Requirements	6
2.1.2.1	Propellant Module Structure	6
2.1.2.2	Thermal Control	7
2.1.2.3	Docking Subsystem	7
2.1.2.4	Propellant Transfer Subsystem	8
2.1.2.5	Settling Thruster Subsystem	9
2.2	GROUND TEST ARTICLE CONFIGURATION AND UTILIZATION	10
2.2.1	Structural Static Test Article	11
2.2.2	Structural/Dynamic Test Article	11
2.2.2.1	Structural/Dynamic Test Article	13
2.2.2.2	Thermal Dynamic Test Article	13
2.2.3	Propellant Transfer Test Article	14
2.2.4	Docking Subsystem Test Article	14
2.3	QUALIFICATION TESTING	16
2.4	ACCEPTANCE TESTING	16
2.4.1	Post Manufacturing Checkout	18
2.4.2	System Test	18
2.4.3	Logistics Module Environmental Tests	19
2.5	LAUNCH SITE OPERATIONS	19
2.5.1	Maintenance and Checkout Area	19
2.5.2	Shuttle Orbiter Loading Bay Area	20
2.5.3	Vehicle Assembly Building	20
2.5.4	Launch Pad Operations	21
2.6	FLIGHT TEST	21
3.0	SCHEDULES AND MILESTONES	23
4.0	NEW FACILITIES AND GROUND SUPPORT EQUIPMENT	27
4.1	FACILITY REQUIREMENTS	27
4.1.1	Propellant Manufacturing Capabilities	28

Preceding Page Blank

Section		Page
4.1.2	Propellant Logistics Loading Requirements	30
4.1.3	Additional and Modified Facilities	32
4.1.4	Facility Modification/Activation Schedule	41
4.2	GROUND SUPPORT EQUIPMENT	41
4.2.1	Equipment Identification	43
4.2.2	Ground Servicing Operations	43
4.2.3	Fabrication/Activation Schedule	51
5.0	SUPPORTING RESEARCH AND TECHNOLOGY	53
5.1	PROPELLANT TRANSFER	59
5.1.1	Transfer Propulsion System with Long Duration Firing Capability	59
5.1.2	Improved Data on Pull-Through Residuals for Various Tank Bulkheads and Baffles	60
5.1.3	Vehicle and Propellant Dynamics Interaction	62
5.1.4	Vortex Formation and Low Liquid Level Sloshing	64
5.1.5	Capillary Systems for Zero G Transfer	65
5.1.6	Quantity Gauging in Low Gravity Environment	67
5.1.7	Hydrogen Slush Manufacture, Storage & Transfer	69
5.2	STRUCTURES	71
5.2.1	Fracture Mechanics Material Properties	71
5.2.2	Advanced Composite Structure Material Properties	72
5.3	HIGH PERFORMANCE MULTI-LAYER INSULATIONS	73
5.3.1	Processing Parameters for Producing a Permanent Embossment Pattern in Plastic Film Used for Multi-Layer Insulation	73
5.3.2	Bonding of Polyimide (Kapton) Film to Itself	75
5.3.3	Calorimeter Test of Optimized Embossed Multiple Layer Insulation	
5.3.4	105 Inch Diameter Tank Insulation System Test	77
5.4	THERMODYNAMIC CONTROL	79
5.4.1	Thermodynamic Venting System (TVS)	79
5.4.2	Low Gravity Temperature Stratification and Pressure Rise	80
5.5	SYSTEMS	81
5.5.1	Logistics Module/Space Shuttle Interfaces	81
5.5.2	Docking and Line Mating Fixtures, Connects, and Disconnects	82
5.5.3	Comparison of Modular Versus Integral Propellant Tanks	84

Section		Page
6.0	PROJECT IMPLEMENTATION PLAN	87
	APPENDIX	
	List of Abbreviations and Definitions	89

ILLUSTRATIONS

Figure No.		Page
1.0-1	Propellant Module Inboard Profile	3
2.2-1	Summary of Subsystem Test Requirements	12
2.4-1	Flight Test Article Test Flow Sequence Acceptance	17
3.1-1	Preliminary Development Test Summary Schedule	24
4.1.1-1	LOX & LH_2 Manufacturing Requirements	29
4.1.2-1	Logistics Module Propellant Loading Sequence	31
4.1.2-2	Logistics Module Ground Propellant Line Sizes	33
4.1.2-3	Logistics Module Propellant Drain Time	34
4.1.3-1	Facility Propellant System Block Diagram	38
4.1.3-2	KSC Launch Pad Requirements	39
4.1.4-1	Facility Modification/Activation Schedule	42
4.2.2-1	Logistics Module Ground Operations Flow Path	45
4.2.2-2	Pre-Launch Operations	47
4.2.2-3	Post Landing Operations	50
4.2.3-1	GSE Fabrication/Activation Schedule	52
5.0-1	Supporting Research & Technology Schedule	54
6.0-1	Preliminary Master Propellant Module Development Schedule	88

Preceding Page Blank

TABLES

Table		Page
4.1.3-1	Additions and Modifications To KSC Propellant Facilities	36
4.2.1-1	Identification Listing of GSE	44
5.0-1	ISPLS Supporting and Research and Technology Costs	55

1.0 INTRODUCTION AND SUMMARY

Volume IV describes the pre-phase A conceptual project planning data as it pertains to the development of the selected logistics module configuration transported into earth orbit by the space shuttle orbiter. The data represents the test, implementation, and Supporting Research and Technology (SR&T) requirements for attaining the propellant transfer operational capability for early 1985. The test requirements and implementation plan are compatible with the space-based tug configuration development scheme. The plan is based on a propellant module designed to support the space-based tug with cryogenic oxygen-hydrogen propellants. Separate plans for CIS and RNS propellant modules were not developed because of the small differences between them and the space-based tug propellant module configuration. A logical sequence of activities that is required to define, design, develop, fabricate, test, launch, and flight test the propellant logistics module are described. Included are the new facility and ground support equipment requirements. The schedule of activities are based on the evolution and relationship between the SR&T, the development issues, and the resultant test program.

The project planning data presented in this document are divided into five principal categories:

a. Test Requirements
b. Test Schedules and Milestones
c. New Facilities and Ground Support Equipment
d. Supporting Research and Technology
e. Project Implementation Plan

The Test Requirements section describes the preliminary ground and orbital flight test program requirements for attaining an operational status of the propellant logistics module. Production plans for the operational logistics module subsequent to initial operational capability (IOC) are not a part of this report. Production quantities are determined in Volume II, Section 9.0. The program is predicated on the utilization of the following test articles:

a. Static Structural Test Article
b. Structural Dynamic/Thermal Test Article
c. Propellant Transfer Test Article
d. Docking Subsystem
e. Flight Test Article

The Schedules and Milestones section depicts the development and test evolution, phasing, operations, and milestones.

The New Facilities and GSE section identifies and describes in general terms the impact that the in-space propellant logistics program will have on the various Government facilities and the GSE conceptual equipment utilization and operational requirements.

The supporting Research and Technology section describes in detail those problem areas which require advanced technology to provide in-orbit refueling capabilities.

The Project Implementation Plan describes the major steps to be taken for establishing an orbital propellant logistics capability by early 1985. It includes the overall study results from Sections 2, 3, 4, and 5 of this volume.

The categories can be developed and defined during Phase A Conceptual and Phase B Definition studies. Figure 1-1 Propellant Module Inboard Module Profile depicts the selected configuration which is described in Volume II, Technical Report, and is the source from which the project planning data have been derived.

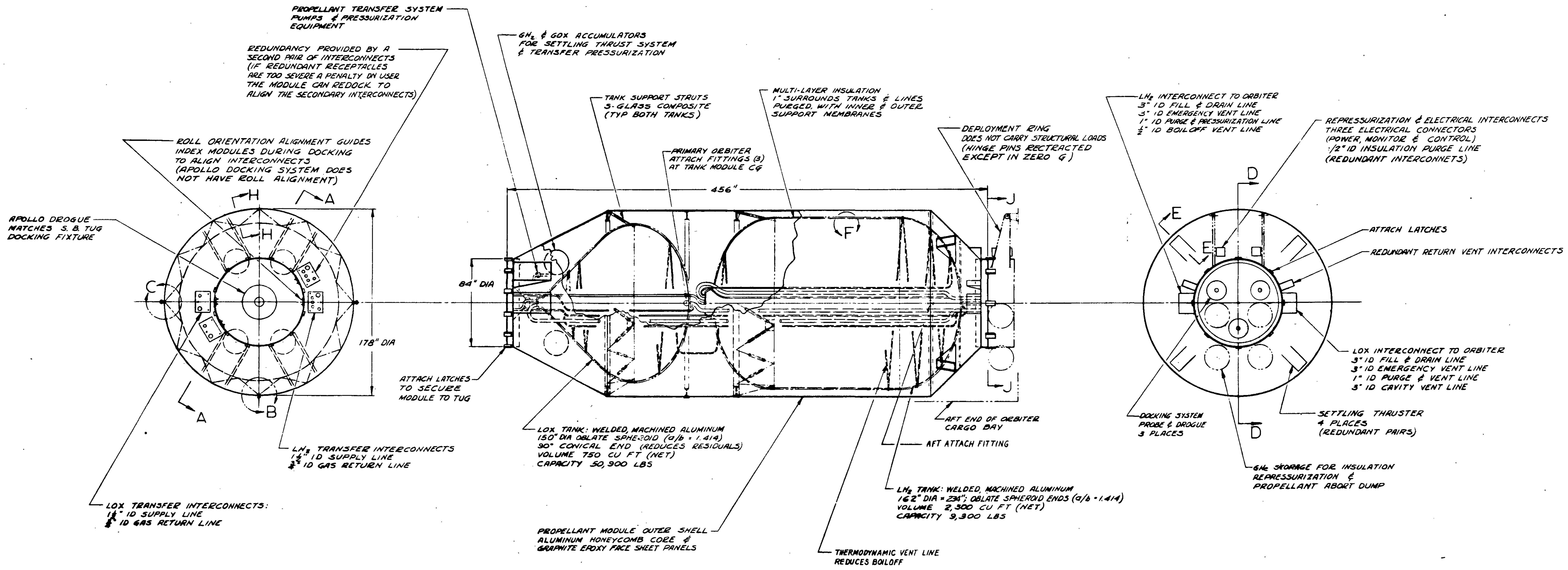


Figure 1.0-1. Propellant Module Inboard Profile
Selected Configuration

2.0 TEST REQUIREMENTS

This section describes the preliminary ground and orbital flight test program for attaining an operational capability to perform orbital propellant transfer operations by early 1985. This section is based on Program Level C as defined in Volume II. Development issues and test requirements are identified to provide the basis for developing a disciplined, cost-effective, integrated program consistent with reliability, safety, and schedule considerations.

The requirements provide the outline for the development, qualification, and acceptance test of the logistics module. These include the early laboratory material and components tests, subsystem tests, and the major ground test articles. These tests utilize the data derived from, and are a continuation of the supporting research and technology activities discussed in Section 5.

The major areas of concern with respect to the test requirements in support of the in-space propellant logistics program are: (1) development testing; (2) test article configuration and utilization; (3) qualification testing; (4) acceptance testing; (5) launch site operations; and (6) flight testing.

The basic ground rules established for this section shall include the following:

a. The logistics module development plan is predicated on a space-based tug IOC of January 1985.

b. The logistics module IOC is January 1985.

c. Production schedules for operational propellant modules are not included in the test plans.

d. The data developed in this volume also apply, in general, to propellant modules planned to support CIS and RNS via orbiter transport.

The test requirements section study results have served to identify the development issues and test phases pertaining to the propellant module subsystems and interfaces. Ground and orbital flight test requirements have been identified in which four ground test articles and one flight test article will be utilized. Facility requirements and locations for the conduct of the test program have been identified. There are no known state-of-the-art constraints in meeting the initial operational capability date. However, propellant transfer in near zero-g environment is a potential problem area. The SR&T activity identified and the development testing planned, including the ground and flight test program, should provide a high degree of assurance that an orbital propellant transfer capability will be operational by 1985.

2.1 DEVELOPMENT TESTING

Development tests are utilized by engineering to select and prove design concept feasibility by applying induced and natural environments and verifying hardware performance through the acquisition and evaluation of data. Informal test procedures are utilized which allow flexibility in the test conduct. Development test requirements are derived through a systemmatic approach by which the hardware usage is evaluated against parameters such as function, environment, failure problem areas, etc. As a result of the evaluation, development issues are identified and logic charts are prepared which provide visibility into the resolution of the issues and their relationships and constraints.

2.1.1 Development Test Criteria

Typical of the development test criteria to be generated and applied during the development phase are:

a. Development requirements will be satisfied by the maximum use of analysis, supported by development tests or a combination of both.

b. Dual usage of major test articles to minimize test hardware is a goal.

c. Test margins, where feasible, will be adequate to protect the test article from destruction. Off limit testing will be utilized at the completion of the development program.

d. The test will contribute to verifying the manufacturing process, operational techniques, procedures, and maintenance concepts.

2.1.2 Subsystem Test Requirements

Subsystems tests will be performed to verify the component, subassembly, and subsystem interfaces and performance. These tests will be performed at outside vendor facilities and at the contractor's laboratories. The following paragraphs identify subsystem test requirements.

2.1.2.1 Propellant Module Structure

The primary structure consists of the following major assemblies: a LOX tank, LH_2 tank, and outer shell (micrometeoroid shield). Testing of the primary structure will verify structural integrity for the various operating modes. A laboratory test program will precede the subsystem structural test program. Typical laboratory tests are:

a. Verification and selection of materials and processes

b. Evaluation of integrity of structural joints and related design approaches

c. Ability of outer shell coupon to withstand micrometeoroid impact

A static and dynamic structural test program will demonstrate and verify the structural integrity and design compliance. These requirements are for critical load and environmental conditions. Primary structural test requirements are listed below.

a. Demonstrate ability of the primary structure to withstand the shuttle boost and touchdown loads.

b. Verify ability of structure to withstand ground handling loads.

c. Demonstrate ability of structure to withstand loads for tug and orbiter docking.

d. Verify the analysis of tanker modes through a modal vibration test for the boost and orbital worst case conditions.

2.1.2.2 Thermal Control

The thermal control subsystem consists of the multi-layer insulation and related purge, pressurization, and the thermodynamic control systems, LH_2 and LOX tank coils and controls, heat exchanger, and overboard vent. Initially a laboratory test program will be required to evaluate materials, components, and subassemblies. Typical laboratory test requirements are:

a. Demonstrate and verify multi-layer insulation thermal efficiency and structural integrity.

b. Test, evaluate, and demonstrate component performance under simulated space operational environment.

c. Demonstrate and evaluate ability of heat exchanger assembly to deliver proper GH_2 volume at the proper temperature.

d. Evaluate and verify sensor and control performance.

The thermal control subsystem test requirements follow:

a. Verify the thermal efficiency and performance of the multi-layer insulation under simulated space environment including ability to vent during ascent and orbit.

b. Verify ability of LH_2 and LOX tank to vent properly and that no unnecessary venting of liquid or vapor occurs.

c. Evaluate and demonstrate ability of tank thermodynamic control LH_2 conditioning subsystem to allow delivery of propellant to receiver tank at proper temperature and quality.

d. Verify support equipment interface, checkout procedures, and techniques.

2.1.2.3 Docking Subsystem

The Docking subsystem consists of the Logistics Module interface structure which mates with the swingout fixture in the orbiter and the Logistics Module interface structure which mates with the tug. Both interfaces utilize probe and drogue type fixtures with latching capability. Included are the fluid and electrical line interconnections and redundancy.

Initially a laboratory test program will be required which will serve to evaluate and select materials and components. Typical laboratory test requirements are:

a. Verify seal, component, and subassembly operation under load, cryogenic, and vacuum environment.

b. Verify the ability of each fluid and electrical interconnection to function properly under simulated operating environment after repeated cycling.

The Docking subsystem tests are primarily tc evaluate the functional operation of the Logistics Module interfaces recognizing that the orbiter manipulator arms will guide and maneuver the logistics module into the orbiter swingout fixture and the tug into the Logistics Module Docking interface. The test requirements are:

a. Demonstrate the ability of the aft Logistics Module Docking interface to dock and functionally mate with the orbiter swingout fixture under ambient and environmental conditions.

b. Demonstrate the functional ability of the forward logistics module docking interface to dock with the tug docking interface.

c. Verify items (a) and (b) at outer limits for misaligned conditions.

d. Verify docking interface when the two halves are at different temperature extremes.

e. Verify ability of the docking interfaces to function properly after repeated cycling.

2.1.2.4 Propellant Transfer Subsystem

The Propellant Transfer subsystem consists of the following elements.

a. Propellant fill and drain

b. Emergency dump

c. LH_2 outlet baffle

d. Tank pressurization(NPSP control)

e. Propellant transfer (liquid expulsion)

f. Propellant gauging

Laboratory activities will consist of material, component and subassembly testing, and evaluation and selection. Typical laboratory test requirements follow.

a. Evaluate components under simulated operating environment.

b. Demonstrate and evaluate the propellant gauging subassembly performance at near zero-g conditions.

c. Demonstrate and evaluate the tank pressurization (NPSP) gas generator and pump assembly ability to convert liquid propellant to a gaseous state and control the delivery of the proper gas volume and pressure for pressurization of the Logistics Module tank ullage.

d. Demonstrate and evaluate liquid transfer pump performance characteristics under a space operating environment. Verify ability of pump to deliver proper propellant quantities within the specified NPSP requirements envelope.

The Propellant Transfer subsystem test requirements follow.

a. Demonstrate and evaluate the tank pressurization (NPSP) subsystem capability to provide proper tank ullage vapor pressure in conjunction with the gas generator with resultant subcooled propellants.

b. Demonstrate and evaluate the propellant transfer liquid expulsion subsystem for ability to deliver propellant to the receiver tank at the proper pressures and flow rates including throttled flow.

c. Verify ability of tank propellant gauging system to provide accurate propellant quantity indication for various tank propellant levels.

d. Evaluate failure mode effects on the subsystem.

e. Perform off-limit tests to ascertain operating effect on system performance and operating envelope.

f. Verify subsystem and related ground support equipment interface, operating procedure techniques, and safety considerations.

2.1.2.5 Settling Thruster Subsystem

The Settling Thruster subsystem converts liquid propellant to a gas through a heat exchanger. The gas is stored in an accumulator which supplies the settling thrusters. In addition, the subsystem contains various valves and controls. The subsystem is identical for the LOX and LH_2 propellants. Each consists of the following basic elements.

a. Propellant turbopump

b. Heat exchanger

c. Gas generator

d. Accumulator

e. Settling thrusters

f. Related valves and controls

Early laboratory tests will serve to verify the design of the various subsystem elements. Typical laboratory test requirements are:

a. Verify propellant turbopump performance characteristics.

b. Demonstrate ability of pump, heat exchanger, gas generator, and accumulator assembly to convert propellant into a gas at the proper flow rate and pressure.

c. Verify ability of thrusters to provide thrust for extended duration without performance degradation.

The Settling Thruster subsystem test requirements follow.

a. Demonstrate and verify the ability of the thruster subsystem to provide propellant from the Logistics Module tank through the turbopump and heat exchanger to the accumulator at proper flow rate and pressure.

b. Verify the ability of the thruster subsystem to provide GOX and GH_2 to the thruster from the accumulator at the proper flow rate and pressure.

c. Determine the settling thruster exhaust impingement pattern on the tanker aft body section and verify no detrimental effects on the logistics module external surface due to thruster extended duration operation.

d. Determine subsystem performance characteristics for off-limit considerations.

e. Verify subsystem ground support equipment interface, operating procedures techniques, and related safety consideration.

2.2 GROUND TEST ARTICLE CONFIGURATION AND UTILIZATION

The Logistics Module Development Test Program will require five test articles. This paragraph excludes the Flight Test Article (see paragraphs 2.5 and 2.6) and addresses itself to only the ground test program utilizing the following four test articles.

a. Structural static test article

b. Structural dynamic/thermal test article

c. Propellant transfer test article

d. Docking subsystem test article

These articles are exclusive of the early laboratory component/subsystem tests. The test objectives and description of each of the test article configurations are provided in the following paragraphs. Figure 2.2-1 provides a summary of the subsystem primary test requirements and the test article that will be utilized to satisfy those requirements. A goal in planning and scheduling of the test activity is the provision for multiple purpose usage of the test article. This testing versatility will provide a cost effective approach; however, high risk testing must be scheduled at the end of the test article activity to minimize the possibility of damage.

2.2.1 Structural Static Test Article

The prime objective of the Structural Static Test Article is to provide experimental verification of the Logistics Module structural integrity for the most critical load and environmental conditions.

The Structural Static Article is configured as follows.

a. LOX tank

b. LH_2 tank

c. Outer shell

d. Primary orbiter attach fittings (foward)

e. Aft attach fittings

f. Strain gage instrumentation

An alternate test configuration would be the utilization of propellant tanks with multi-layer insulation. This configuration would allow static structural testing under cryogenic environment utilizing LN_2. However, due to the increased weight of the LN_2 over LH_2, the Logistics Module LH_2 tank would require off loading. At the completion of structural testing this test article could also be used for early ground fit checks with the orbiter. The aft ring would be required on the test article in this case to allow mating with the swing-out ring. The static structural tests may be performed at the NR Seal Beach Structural Test Facility or at the NR Downey Laboratory and Test Facility in Building 450.

2.2.2 Structural Dynamic/Thermal Test Article

The structural dynamic/thermal test article activity has been planned to provide multiple purpose usage. The prime objective of the structural dynamic test article is to verify structural response and resonant frequency characteristics through a modal vibration test program. An option that requires investigation and possible further consideration is acoustic tests of selected logistics module sections in the boost configuration. At the conclusion of the dynamic test program the vibration instrumentation will be removed. These tests can be performed at NASA MSFC.

SUBSYSTEM	TEST REQUIREMENTS	TEST ARTICLES				
		STRUCT. TEST ARTICLE	DYNAMIC TEST ARTICLE	THERMAL TEST ARTICLE	PROP.TRANS.TEST ARTICLE	DOCKING SUBSYSTEM
STRUCTURE	1) DEMONSTRATE ABILITY OF THE PRIMARY STRUCTURE TO WITHSTAND THE SHUTTLE BOOST & TOUCHDOWN LOADS	X				
	2) VERIFY ABILITY OF STRUCTURE TO WITHSTAND GROUND HANDLING LOADS	X				
	3) DEMONSTRATE ABILITY OF STRUCTURE TO WITHSTAND LOADS FOR TUG & ORBITER DOCKING	X				
	4) VERIFY TANKER MODES DETERMINED BY ANALYSIS THRU A MODAL VIBRATION TEST FOR THE BOOST & ORBITAL CONDITIONS		X			
THERMAL CONTROL	1) VERIFY THE THERMAL EFFICIENCY & PERFORMANCE OF THE MULTI-LAYER INSULATION UNDER SIMULATED SPACE ENVIRONMENT INCLUDING ABILITY TO VENT UNDER ASCENT & ORBIT			X		
	2) VERIFY ABILITY OF LH_2 & LOX TANK TO VENT PROPERLY & THAT NO UNNECESSARY VENTING OF LIQUID OR VAPOR OCCURS			X		
	3) EVALUATE & DEMONSTRATE ABILITY OF TANK THERMODYNAMIC CONTROL LH_2 CONDITIONING SUBSYSTEM TO ALLOW DELIVERY OF PROPELLANTS TO RECEIVER TANK AT PROPER TEMPERATURE & QUALITY			X		
	4) VERIFY SUPPORT EQUIPMENT INTERFACE CHECKOUT PROCEDURES & TECHNIQUES			X		
DOCKING	1) DEMONSTRATE THE ABILITY OF THE AFT TANKER DOCKING INTERFACE TO DOCK & FUNCTIONALLY MATE WITH THE ORBITER SWING-OUT FIXTURE UNDER AMBIENT & ENVIRONMENTAL CONDITIONS				X	X
	2) DEMONSTRATE THE FUNCTIONAL ABILITY OF THE FORWARD TANKER DOCKING INTERFACE TO FUNCTIONALLY MATE WITH THE TUG DOCKING INTERFACE					X
	3) VERIFY ITEMS 1 & 2 ABOVE UNDER THE MAXIMUM SPECIFIED MISALIGNED CONDITION					X
	4) VERIFY TANKER/TUG DOCKING INTERFACE WHEN THE TWO HALVES ARE AT DIFFERENT TEMPERATURE EXTREMES				X	
	5) VERIFY ABILITY OF THE DOCKING INTERFACES TO FUNCTION PROPERLY AFTER REPEATED CYCLING					X
PROPELLANT TRANSFER	1) DEMONSTRATE & EVALUATE THE TANK PRESSURIZATION (NPSP) SUBSYSTEM TO PROVIDE PROPER TANK ULLAGE VAPOR PRESSURE IN CONJUNCTION WITH THE GAS GENERATOR WITH RESULTANT SUBCOOLED QUALITY PROPELLANTS				X	
	2) DEMONSTRATE & EVALUATE THE PROPELLANT TRANSFER LIQUID EXPULSION SUBSYSTEM (E.G., FAN) FOR ABILITY TO DELIVER PROPELLANT TO THE RECEIVER TANK AT THE PROPER PRESSURES & FLOW RATES INCLUDING THROTTLED FLOW				X	
	3) VERIFY ABILITY OF TANK PROPELLANT GAGING SYSTEM TO PROVIDE ACCURATE PROPELLANT QUANTITY INDICATION FOR VARIOUS TANK PROPELLANT LEVELS				X	
	4) EVALUATE FAILURE MODE EFFECT ON THE SUBSYSTEM				X	
	5) PERFORM OFF-LIMIT TESTS TO ASCERTAIN OPERATING EFFECT ON SYSTEM PERFORMANCE				X	
	6) VERIFY SUBSYSTEM GROUND SUPPORT EQUIPMENT INTERFACE OPERATING PROCEDURES, TECHNIQUES, AND RELATED SAFETY CONSIDERATIONS				X	
SETTLING THRUSTER	1) DEMONSTRATE & VERIFY THE ABILITY OF THE THRUSTER SUBSYSTEM TO PROVIDE PROPELLANT FROM THE VEHICLE TANKS THRU THE TURBOPUMP & HEAT EXCHANGER TO THE ACCUMULATOR AT THE PROPER FLOW RATE & PRESSURE		X	X		
	2) VERIFY THE ABILITY OF THE THRUSTER SUBSYSTEM TO PROVIDE GOX & GH_2 TO THE THRUSTER FROM THE ACCUMULATOR AT THE PROPER FLOW RATE & PRESSURE			X		
	3) DETERMINE THE SETTLING THRUSTER EXHAUST IMPINGEMENT PATTERN ON THE TANKER AFT BODY SECTION & VERIFY NO DETRIMENTAL EFFECTS ON TANKER EXTERNAL SURFACE DUE TO THRUSTER EXTENDED DURATION OPERATION			X		
	4) DETERMINE SUBSYSTEM PERFORMANCE CHARACTERISTICS FOR OFF-LIMIT CONDITIONS			X		
	5) VERIFY SUBSYSTEM GROUND SUPPORT EQUIPMENT INTERFACE OPERATIONS PROCEDURES, TECHNIQUES & RELATED SAFETY CONSIDERATIONS			X		

Figure 2.2-1 Summary of Subsystem Test Requirements

The prime objective of the Thermal Test Article is to evaluate and verify the performance of the thermodynamic control subsystem.

2.2.2.1 Structural Dynamic Test Article

The structural dynamic test article consists of the following elements.

a. LOX tank (with multi-layer insulation)

b. LH_2 tank (with multi-layer insulation)

c. Outer shell

d. Thermodynamic control subsystem

- o Valves and controls
- o Heat exchanger

e. Settling thruster subsystem

1. LO_2 and LH_2 heat exchangers (one each)
2. LO_2 and LH_2 gas generators (one each)
3. LO_2 and LH_2 accumulators (one each)
4. LO_2 and LH_2 turbopump (one each)

f. Test instrumentation accelerometers

g. Simulated masses for propellant transfer components

The structural dynamic tests can be performed at MSFC.

2.2.2.2 Thermal Test Article

The thermal test article configuration is the same as for the structural dynamic test article except that the structural dynamic test instrumentation will be removed and thermocouples added for the acquisition of thermal data. Simulated component masses will also be removed for the thermal tests. The thermal test can be performed at the NASA Mississippi Test Facility.

At the successful completion of the thermal tests the test article will be shipped to MSC to undergo thermal vacuum tests. The objectives of these tests are to verify the performance of the multi-layer insulation under simulated ascent, orbital, and descent environmental conditions. During these tests the ability of the system to vent during ascent and pressurize during descent will be verified. The propellant tanks will be pre-chilled and conditioned with cooled helium gas with the insulation purged and sampled for tank leaks.

2.2.3 Propellant Transfer Test Article

The prime objective of the propellant transfer test article is to demonstrate and evaluate the ability of the propellant transfer subsystem to deliver propellant to the receiver tanks at the required pressure and flow rates. The test article is an all-systems flight configured vehicle with simulated tug receiver propellant tank interface and propellant tanks for performing propellant transfer in a one-g environment.

The propellant transfer test article consists of the following elements.

a. LOX tank (with multi-layer insulation)

b. LH_2 tank (with multi-layer insulation)

c. Outer shell

d. Thermodynamic control subsystem

e. Forward and aft docking subsystem

f. Propellant transfer subsystem

g. Settling thruster subsystem

h. Simulated tug/logistics tank interface with insulated receiver propellant tanks

i. Propellant and electrical interconnects between tanker and orbiter

j. Pneumatic actuation, pressurization, and purge systems

Docking tests under cryogenic conditions will be performed utilizing the propellant transfer test article. The NASA Mississippi Test Facility or NR Santa Susana Propulsion Test Facility are candidate facilities that could support these test activities.

2.2.4 Docking Subsystem Test Article

The prime objective of the Docking subsystem is to evaluate and verify the docking subsystem operation at the maximum misalignment and temperature differential conditions.

The docking subsystem test article configuration consists of the following elements.

a. Forward drogue section including propellant and electrical interconnections

b. Aft docking system probe and drogue assembly including propellant and electrical interconnection

c. Simulated tug interface including propellant and electrical interface

For the docking tests under cryogenic conditions the propellant transfer test article will be utilized. Ambient testing could be performed at the NR Downey Facility. Testing under cryogenic conditions may be performed at the NR Santa Susana Propulsion Test or NASA Mississippli Test Facilities.

2.3 QUALIFICATION TESTING

Qualification tests are performed on flight-type hardware to demonstrate and verify that the hardware and related manufacturing processes meet design and specification requirements. The hardware is functionally operated while exposed to ambient and operational environmental conditions. These tests will serve to verify that design margins are adequate with hardware environmental exposures greater than experienced during logistics module ground and flight operations. Reliability evaluation and assessments provide analytical validation for verification of the test program phases consistent with confidence growth considering schedule, risk and safety. Test procedures are documented and conducted on a formal basis.

The qualification test phase is part of an overall integrated test program. The qualification requirements are derived during the design phase from an analysis of each equipment item's performance and environmental exposure during the mission, utilizing factors such as hardware criticality, past hardware history and test effectiveness. Subcontractor qualification test activities including test requirements and schedule are directly related to and managed through the contractor integrated test plan.

Typical criteria that will be generated and applied to the qualification test phase are:

a. Qualification requirements will be satisfied by analysis or test and may be a combination of both.

b. Qualification testing will be based on hardware functional criticality which would result in propellant module and/or shuttle loss.

c. Redundant path qualification testing is required when redundancy precludes a single point failure.

d. Hardware requalification is a requirement when a design or manufacturing process change has occurred.

2.4 ACCEPTANCE TESTING

Acceptance tests are conducted on deliverable flight and support equipment that will demonstrate and verify that the hardware conforms to specification requirements. Test environmental levels are in general no greater than will be experienced during ground and flight operations. These tests are performed at all hardware levels, i.e., materials, components, subassembly, subsystem and vehicle, as each item is ready for delivery to the next assembly or usage point. The tests involve supplier and contractor testing and continue through propellant module acceptance by the customer. All tests are performed to formal procedures and documentation. The operational logistic module flight operations are discussed under Volume II, Section 9.0. Ground operations are discussed under Volume II Section 9.0 and in Section 4.0 of this volume. The following paragraphs describe tests and procedures which are representative of the operational propellant module as well as the flight test article. Test requirements that are peculiar to the flight test article are identified. Figure 2.4-1 presents a block diagram of the flight test article test flow sequence from the contractor's facility to the launch site.

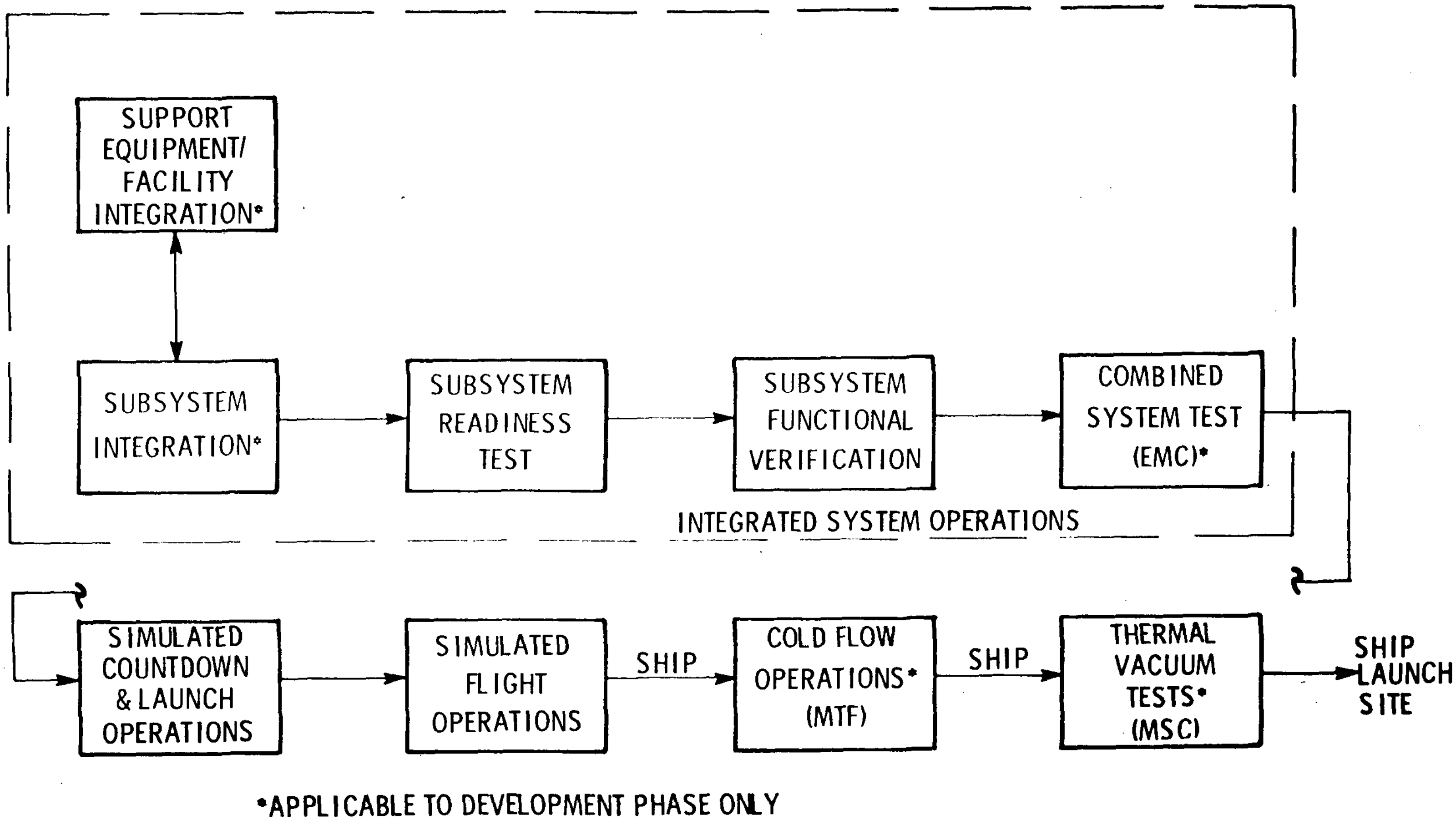


Figure 2.4-1 Flight Test Article Test Flow Sequence Acceptance

Typical of the acceptance test criteria to be generated and applied to the acceptance test phase are:

a. All deliverable end items will receive an acceptance test.

b. Parallel paths or alternate mode operations will be demonstrated.

c. Supplier subsystem acceptance testing procedures will be utilized at the contractor facility to the maximum extent feasible.

d. Whenever a subsystem module interface connection has been disrupted or a spare installed, reverification of the disrupted hardware is a requirement.

e. Logistics module post-manufacturing operations will be conducted under ambient conditions.

2.4.1 Post-Manufacturing Checkout

Post-manufacturing checkout operations are performed subsequent to the propellant module assembly and installation of the subsystems. The objective is to verify the compatibility of the subsystems and related support equipment. The support equipment and facilities will have been integrated and verified prior to interfacing with the module.

2.4.2 System Test

System test covers the operations performed on the logistics module at the contractor facility leading to acceptance. Each of the subsystems will undergo a readiness phase in preparation for subsystem functional verification. Subsystem readiness entails the servicing, calibration and verification that the subsystem is ready for the conduct of subsystem functional test. Functional verification tests provide for exercise of the subsystem through the operational modes including parallel path (backup). At the completion of subsystem verification the module is ready for combined system test. Combined system test provides verification that the module and related support equipment function satisfactorily as a composite system with in-depth performance verification monitoring through the support equipment. During combined systems operations the flight article only will undergo electromagnetic compatibility tests. The module will be instrumented and the command and response data recorded. The data will be reviewed to determine that no adverse effect exists from spurious and/or transient signals.

A simulated launch pad countdown operation will be performed next. The module/orbiter interface electrical connection will be utilized to stimulate the module and verify responses. This operation will serve to demonstrate and verify launch pad test procedures and verify the module/orbiter interface.

Simulated flight operations will be performed next. These operations, utilizing the orbiter and/or tug interface will serve to simulate the flight phases consisting of boost, ascent, and orbital operations. These operations involve shuttle/module and tug docking, propellant transfer from module to the tug, return and securing the module in the shuttle, descent and landing. At the conclusion of simulated flight operations the module is accepted.

2.4.3 Propellant Module Environmental Tests

The module will be shipped to the NASA MTF test site for the purpose of conducting propellant cold flow operations. These operations will verify the module's manufacturing process and system performance under a cryogenic environment. During the propellant fill and drain operations, valve performance will be verified, effect of cryogenic exposure on the multi-layer insulation ascertained and tank leakage checked. At the successful conclusion of the cold flow operations the module will be shipped to the MSC Space Environment Simulation Laboratory for thermal vacuum tests. These tests will verify that the module operates satisfactorily in a space-simulated environment and that the multi-layer insulation vents satisfactorily during ascent and can be pressurized during simulated descent. The module will next receive an integrated system test under ambient conditions to verify that no detrimental effects from environmental testing have occurred. The module will then be transported to the launch site. The environmental tests are not applicable to the operational propellant modules.

2.5 LAUNCH SITE OPERATIONS

The discussion in this section pertains to the peculiar propellant module flight test article launch site test and operations requirements for activation and launch preparation. Operational propellant module launch site operations are discussed in Volume II, and Section 4.0 of this volume. The prime objective of the flight test article launch site operations is to initially activate and verify the launch site facility/support equipment and propellant module/orbiter interface compatibility procedures and techniques, and provide training for operations personnel. The launch site locations are:

a. Propellant module maintenance and checkout area

b. Shuttle/orbiter loading bay area

c. Vehicle Assembly Building

d. Launch pad

2.5.1 Maintenance and Checkout Area

The logistics module maintenance and checkout area initial operations will provide for activation and verification of the compatibility of the ground support equipment, facility and propellant module. These operations are similar to the final logistics module acceptance operations performed at the contractor facility. Post-flight operations are also performed in this area and will serve to demonstrate the propellant module maintenance concept involving scheduled and unscheduled maintenance (i.e., parts removal and replacement, repair, and turnaround) techniques and procedures.

2.5.2 Shuttle Orbiter Loading Bay Area

The initial operations in the shuttle orbiter loading bay area will verify:

a. Procedures and techniques for handling, loading and unloading the module from the shuttle orbiter.

b. Module/orbiter physical, mechanical and electrical interface.

c. Checkout procedures and techniques.

d. Orbiter manipulator arm and swingout ring compatibility with the module.

Manipulator arm and swingout ring compatibility verification tests must recognize that these operations, from a structural integrity standpoint, are normally performed under zero-g orbital conditions. The test article will be instrumented with accelerometers and strain gauges for acquisition of load data for verification that the handling, loading and unloading operations do not exceed structural design requirements.

An alternate consideration is the utilization of the structural test article for early verification of the module/shuttle physical structure and mechanical interface compatibility as it pertains to items (a), (b), and (d) above. The test article would require retrofit with electrical and propellant interface connections.

2.5.3 Vehicle Assembly Building

The Vehicle Assembly Building operations entail (1) erection and mating of the shuttle orbiter (including module payload) with the booster on the launch umbilical tower; (2) non-hazardous type operations involving checkout of the module through the shuttle/launch umbilical tower/launch control center.

Initial operations will verify the effect on the module structure due to the handling and erection of the orbiter. During these operations strain gage and accelerometer data will be acquired for evaluation and verification that structural design limits are not exceeded.

Early module checkout operations will verify the facility/shuttle and orbiter/module electrical interfaces. These operations entail the checkout of the module through the launch control center during which test procedures and techniques will be evaluated and verified.

If early structural and mechanical physical fit checks with the orbiter are required, the structural test article could be utilized for this purpose.

2.5.4 Launch Pad Operations

The prime objectives of the propellant module flight test article launch pad operations are to: (1) verify the module/shuttle/facility interfaces, countdown procedures and techniques; (2) demonstrate compatibility of the module/shuttle under cryogenic conditions; (3) provide launch crew training; and (4) demonstrate and verify that the operations and procedures for the operational logistics module are satisfactory.

The launch pad operations provide the first opportunity for demonstrating the compatibility of the module/shuttle/launch pad and control center compatibility. Initially, continuity tests will verify wiring interfaces, EMI tests will be conducted to verify that no induced interference exists between module shuttle, and facility. Propellant fill and drain tests will demonstrate the adequacy of the system to transfer propellant from the facility into the module through the shuttle interface. In demonstrating countdown abort operations, the ability to transfer the propellant from the module to the ground facility, and the purge, vent, safing and securing operations will be verified. Finally, the flight test article countdown and launch will demonstrate and verify the production module and launch pad operations and procedures. An alternate consideration if earlier launch pad propellant transfer operations with the orbiter and module is required, is the utilization of the thermal test article as a propellant module simulator.

2.6 FLIGHT TEST

The prime objective of the flight test program is to demonstrate and verify the logistics module design and operational concept for the boost, ascent, orbit, descent, landing, and turnaround conditions. One flight test article will be utilized for conducting a series of flight tests which will lead to the demonstration and certification of a man-rated propellant module. Four flights as a minimum have been specified. Preflight, flight, and post-flight operations for the operational module are described in Volume II and Section 4.0 of this volume. The flight test article will be instrumented to acquire additional data for evaluation of the logistics module subsystem performance. The instrumentation package could be interfaced with the tug for RF data transmission to the orbiter or ground station. During the module/orbiter operations, additional data pertaining to the logistics module subsystem performance could be acquired by recorders in the cargo compartment.

The initial logistics module flight would be accomplished using LN_2 in place of LOX and LH_2 propellants in order to minimize hazards. The logistics module LH_2 tank would be off-loaded since LN_2 is heavier than LH_2. This flight test will demonstrate and verify module deployment and tug/module docking and hookup including pre-transfer module checkout. Additional objectives are to separate the logistics module from the shuttle and demonstrate a partial propellant emergency dump and then return and demonstrate manipulator arm capture and module docking with the shuttle. Once the module is in the shuttle cargo bay, an emergency propellant dump of the remaining propellant will be demonstrated. This operation will determine the effect, if any, of propellant dump on the orbiter with regard to propellant pattern, impingement and window fogging. Further, flight test #1 objectives are to evaluate and verify descent and touchdown loads, safing procedures, maintenance, and turnaround operations.

Flight Test #2 objectives are to demonstrate and evaluate the module-tug orbital propellant transfer operations under 10^{-3} to 10^{-4}-g acceleration. During these operations the performance of the docking thermal control and propellant transfer subsystems will be evaluated. This operation will demonstrate a single tug/module propellant transfer. The module with residual propellant, if any, will be returned to the orbiter and undergo propellant dump.

Flight Test #3 objectives are to evaluate module operations for two propellant transfer demonstrations. During these operations the tug would dock with the module separate from the orbiter and undergo propellant transfer operations and return the module to the orbiter. These operations would then be repeated. The second propellant transfer operation would be evaluated for module propellant separation and vortexing characteristics and performance.

Flight Test #4 objectives would consist of demonstrating and verifying two additional tug propellant transfer operations. The satisfactory completion of these operations and their verification through data evaluation will provide propellant module man-rated certification which will coincide with initial operational capability.

3.0 SCHEDULES AND MILESTONES

This section contains the preliminary test schedule and milestones that are a result of satisfying the test requirements discussed in Section 2.0 of this volume. The schedule pertaining to new facility and ground support equipment is discussed under Section 4.0 of this volume. The Supporting Research and Technology schedule and related discussion is covered under Section 5.0 of this volume. A preliminary master propellant module implementation development schedule that incorporates the study results of this volume is presented in Section 6.0. The schedule depicts the major steps to be taken for establishing module propellant logistics orbital capability by early 1985.

Figure 3.1-1, Preliminary Development Test Summary Schedule, provides the milestones, events, and activities to accomplish the manufacturing and test operations to satisfy the program development, qualification, and acceptance test requirements. The ground test schedule allows for flight test article modification if problems arise during development testing.

The test schedule activities cover a duration of approximately eight years, starting with test planning and culminating with the last flight of the test article and an IOC date of January, 1985, which coincides with the IOC of the tug. Test planning activities begin in the last quarter of 1976, concurrent with the start of Phase C design of the selected configuration. During this activity, test requirements will be established and documented in a test program plan. Phase C activities culminate in January, 1979, and Phase D development/operations begin and are performed for a duration of six years. During this phase the development test plan will be updated and requirements will be implemented. Early testing will consist of laboratory material selection and component testing, followed by the subsystem test phase culminating in the second quarter of 1982.

Five major test articles will be manufactured, assembled and tested during the development test program. Manufacturing, assembly, and acceptance test operations of the test articles at the contractor's facility will cover a duration of approximately three and one-half years, culminating in the first quarter of 1983. These operations will commence with the structural static test article, mid-1979, and conclude with the shipment of the flight test article to MSFC for cold flow tests.

The development ground test program covers a period of approximately three and one-quarter years beginning in the last quarter of 1980 at the start of the structural static test program and culminating with the propellant transfer test article operations in the last quarter of 1983. The structural static test article operations will be performed for a duration of nine months ending in the third quarter of 1981. The structural dynamic/thermal test article covers a duration of approximately two and one-quarter years, beginning in the first quarter of 1981, and culminating in the first quarter of 1983. During this period, structural dynamic tests will be performed at MSFC. Cold flow tests will be performed at MTF culminating with thermal vacuum tests at MSC.

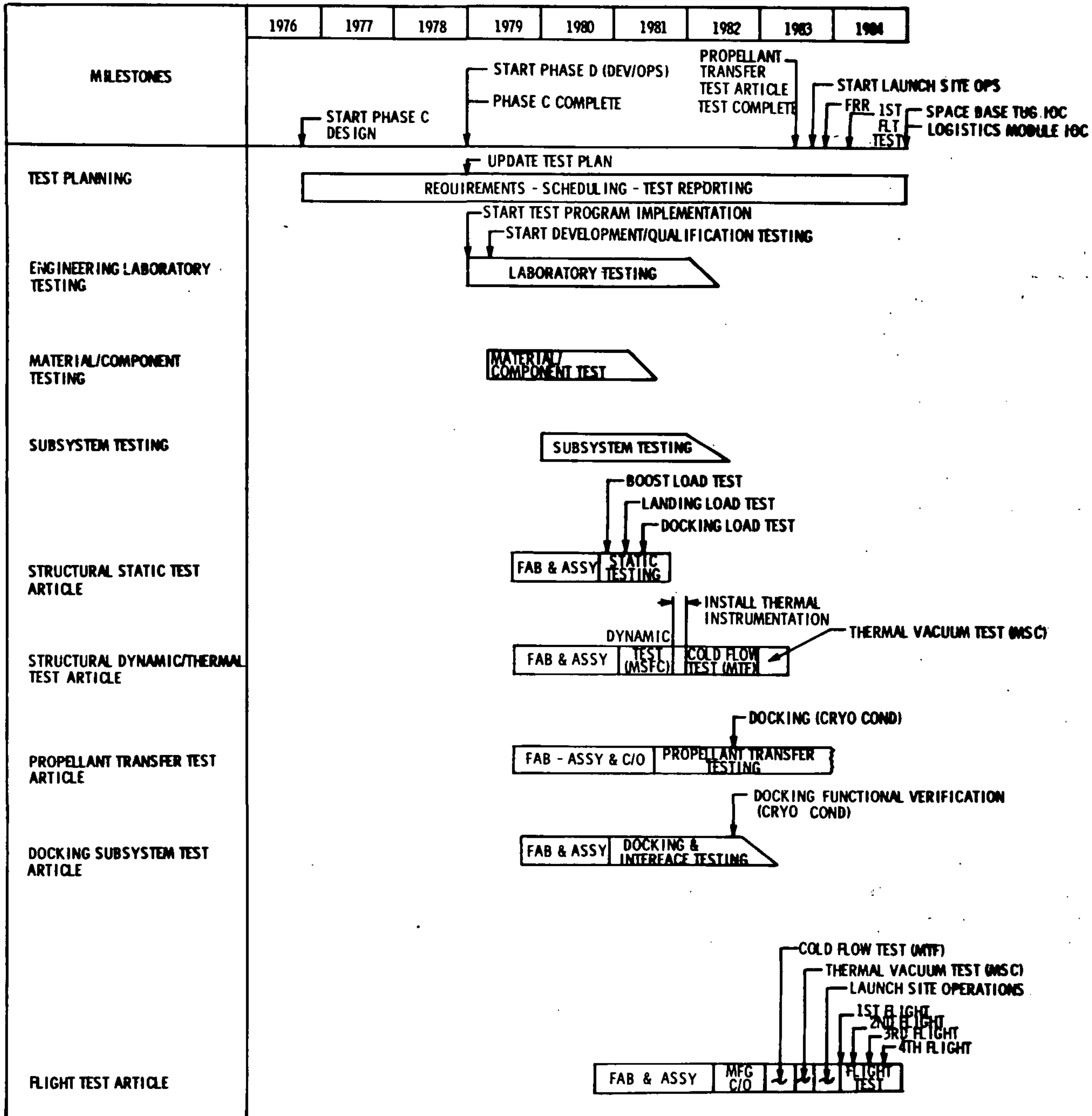


Figure 3.1-1 Preliminary Development Test Summary Schedule

The propellant transfer test article operations are conducted for a duration of two and one-half years beginning in mid 1982 and are completed at the end of 1983. The docking subsystem test article operations begin in 1981 and are conducted for a duration of approximately 21 months. Interface with the propellant transfer test article for docking tests under cryogenic conditions will occur in the third quarter of 1982.

The flight test article initial launch site ground operations begin in the last quarter of 1983 and continue for four months culminating in the first launch and flight. Three additional flights will cover a duration of 10 months and terminate with an IOC of January, 1985.

4.0 NEW FACILITIES AND GROUND SUPPORT EQUIPMENT

4.1 FACILITY REQUIREMENTS

The objective of this portion of the study has been to identify and describe the impact that the In-Space Propellant Logistics program will have on the various Government facilities and equipment. The criteria used to evaluate this impact were based upon the utilization of the drop tank shuttle orbiter/liquid propellant booster configuration baseline, the utilization of a logistics module (59,000 pounds maximum propellant capacity), located in the cargo bay of the shuttle, the utilization of the five space traffic program level concepts A, B, C, D, and E, and the maintainability of the maximum level of safety for facility equipment, ground support equipment, flight vehicle equipment, ground personnel, and flight crew personnel.

The major areas of concern with respect to facility requirements in support of in-space propellant logistics systems have been developed into four categories of effort, consisting of: (1) the determination of liquid oxygen and hydrogen manufacturing and delivery capabilities for each of the various space traffic program levels; (2) the determination of the propellant logistics module loading timelines, with respect to propellant flow rates, transfer line sizes, and loading controls and sequences; (3) the determination of additional and modified facilities and equipment in support of the logistics module flight and test articles, from design tests and post-manufacturing checkout to post-flight safing and checking operations; and (4) the development of timeline schedules, for effort required to modify those facilities.

Although this portion of the study effort was limited in scope, sufficient information has been developed to bring into proper perspective, the effect of those additional requirements imposed on the Government facilities in order to support the In-Space Propellant Logistics program. The conclusions established herein are based upon optimum technical feasibility, operational compatibility, safety considerations, and cost minimization, and can be summarized as follows:

a. Modification of existing liquid oxygen manufacturer's facilities will be required to support space traffic program levels D and E for CIS and RNS.

b. The existing (Saturn V) liquid hydrogen manufacturer's facility capacity is capable of supporting all of the space traffic program levels.

c. The liquid oxygen and hydrogen utilization impact due to the propellant logistics requirements is minimal compared to the total shuttle propellant requirements.

d. Liquid oxygen and hydrogen series loading of the logistics module was selected because of the lower hazard risks involved.

e. Independent ground control for loading the logistics module was selected because various potential hazards would be reduced.

Preceding Page Blank

f. Small propellant transfer lines (two-inch nominal diameter) are adequate to provide the maximum flow rates for the logistics module, within the shuttle loading timelines, and safe emergency drain time.

g. Minimal modifications and additions are anticipated for the KSC launch facilities.

h. Relatively extensive modifications are anticipated at the other facilities (new and modified platforms, tie-down structure, fluid and cable distribution systems, etc.).

i. In-space traffic program levels A, B, and C can be supported utilizing one launch pad, and as many as four launch pads may be required to support the highest traffic level E (CIS).

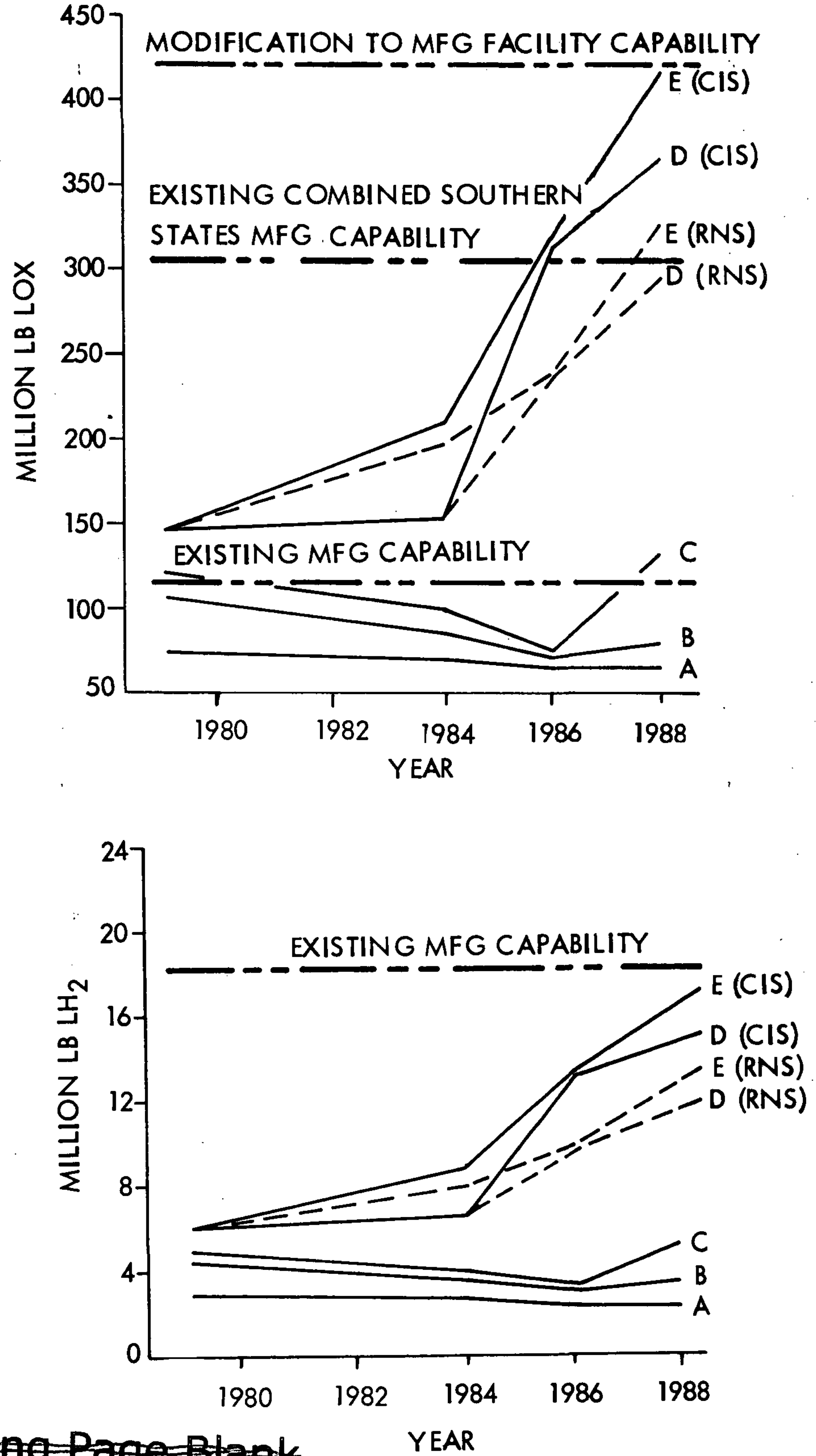
j. The facility modification and activation implementation schedules are supportive to the in-space logistics programmed initial operational capability of January, 1985.

4.1.1 Propellant Manufacturing Capabilities

The manufacturing and delivery capability of numerous liquid oxygen and liquid hydrogen producers in the southern United States was researched. This research was required to determine what effect the various space traffic program levels would have on the present and future liquid oxygen and hydrogen production capability. The research consisted primarily of defining the various manufacturers' production output, present capabilities above the existing production output, and the potential growth capabilities. These findings were compared with the propellants anticipated to be launched from earth during the peak years of the space traffic program levels. Figure 4.1.1-1 depicts the yearly consumption of liquid oxygen and hydrogen for each of the in-space traffic program levels versus the manufacturer's production and delivery capabilities.

The data shown apply to all shuttle launches during a given year, and include the propellants utilized for the orbiter, booster, and logistics module. Propellant losses during ground transit and storage have been taken into account, and the same have been deducted from the manufacturer's on-site delivery capability.

The manufacturer that presently supplies liquid oxygen for the Saturn V launch vehicle is capable of supporting space traffic program levels A, B, and most of C without requiring modifications to the existing facilities. The major liquid oxygen manufacturers in the southern states combined are capable of supporting most of program levels D and E without requiring modifications to the existing facilities. This capability does not include their present production output, but does include the existing potential above the present production capability.



~~Preceding Page Blank~~

Figure 4.1.1-1 LOX and LH_2 Manufacturing Requirements

In order to support program levels D and E for CIS and RNS during the peak years, it would require modification to the manufacturer's existing facilities. Various liquid oxygen manufacturers indicated that to meet these increased production requirements, modifications to their present facilities or the installation of new facilities could be accomplished expeditiously with no foreseeable problems. The liquid oxygen utilization impact due to the in-space propellant logistics requirements (i.e., that propellant transported in the logistics module) is considered minor compared to the total shuttle propellant requirements. The logistics module usage is approximately one percent of the total liquid oxygen requirements.

The manufacturer that presently supplies liquid hydrogen for the Saturn V launch vehicle is capable of supporting all of the space traffic program levels without requiring modifications to the existing facilities. The liquid hydrogen utilization impact due to propellant logistics requirements is considered minor compared to the total shuttle propellant requirements. The logistics module usage is approximately 5 percent of the total liquid hydrogen requirements.

4.1.2 Propellant Logistics Module Loading Requirements

The propellant loading of the logistics module will be accomplished with the module installed in the cargo bay of the orbiter, while the orbiter is in the vertical position on the launch pad. This is considered to be the safest mode of operation because of the hazards related to handling the orbiter and/or the logistics module while the logistics module is prefilled with propellants. The shuttle orbiter and booster propellants will be loaded in parallel (i.e., the liquid oxygen and hydrogen tank of both vehicles will be loaded simultaneously in a two-hour time period). The logistics module propellants will be loaded in series (i.e., the liquid oxygen tank will be loaded first, then the liquid hydrogen tank will be loaded; both, in the same two-hour time span as the shuttle). Figure 4.1.2-1 presents the timeline comparison of the shuttle and the logistics module propellant loading sequence.

Series loading for the logistics module has been selected because of the lower hazard risks associated with the fact that the tank, lines, and disconnects are located in close proximity within the enclosed cargo bay of the shuttle. In this particular environment, where a leak could develop during liquid oxygen prechill or fast-fill operations, there would be no hydrogen on board to support an explosive atmosphere; whereas, in a parallel loading mode there would. The logistics module will be loaded with propellants independent of the orbiter systems, through flow control units located on the launch tower. The flow control units will be capable of modulating at low-flow rates for prechill and topping modes, and at high flow rates for the main filling mode. Independent control is considered advantageous to the total propellant loading concept because various potential hazards would be reduced. These hazards are related to the utilization of common (shuttle and logistics module) lines for filling and draining operations, and the independent use of these lines during emergency offloading operations when an emergency situation occurs within either the shuttle or logistics tank systems. Since the baseline shuttle orbiter does not provide interfaces for propellant loading of

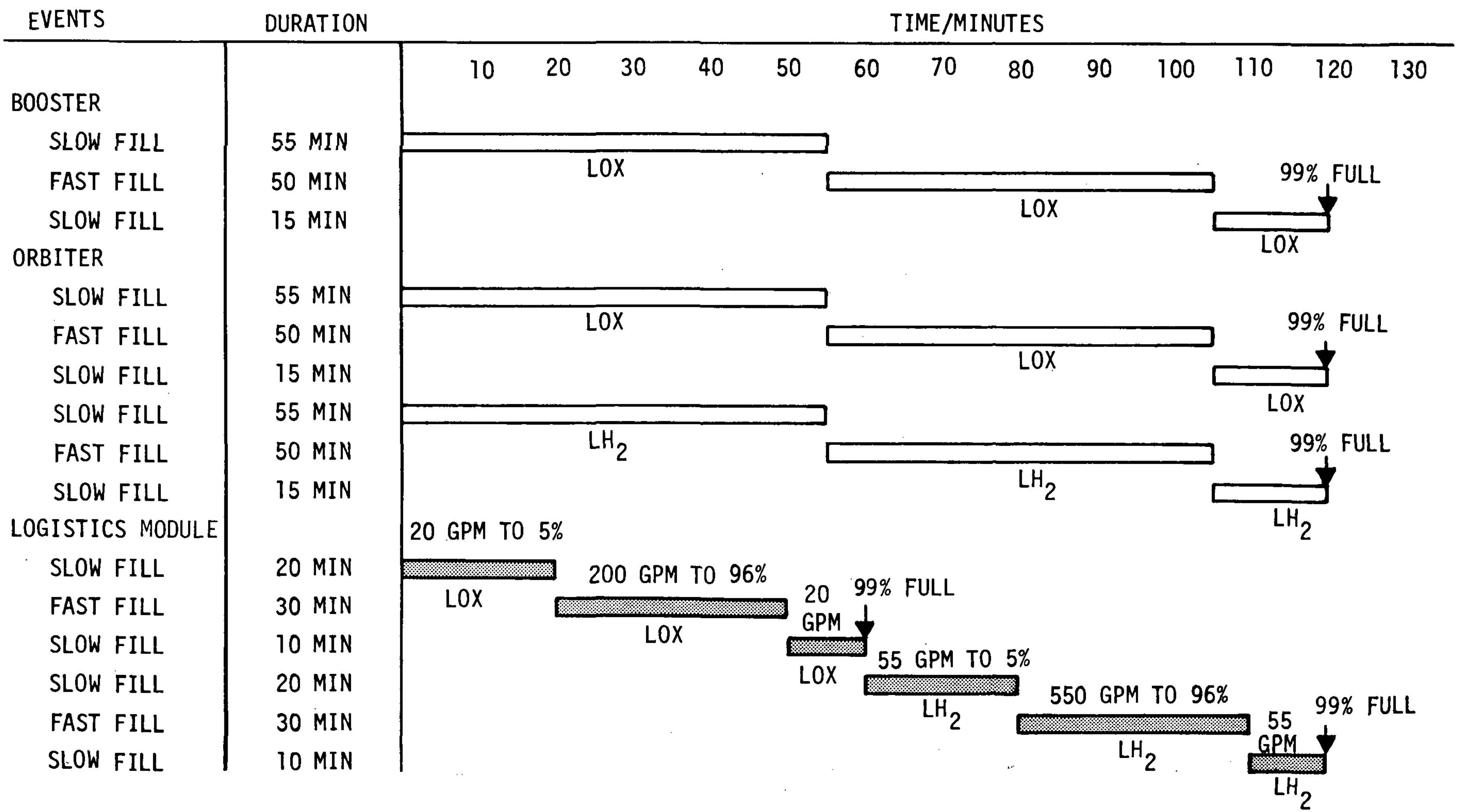


Figure 4.1.2-1 Logistics Module Propellant Loading Sequence

of the logistics module, it is also considered imperative from a safe operations standpoint, that the liquid oxygen and hydrogen fill and drain lines interfaces be separated, and located such as to prevent potential vapor mixing hazards.

The timelines shown for the logistics module were developed utilizing Saturn S-II propellant loading comparisons. The flow rates were determined by these timelines and the requirement for the serial loading concept. A two-inch nominal pipe diameter is of sufficient size to provide the selected flow rates for both the liquid oxygen and hydrogen systems. Figure 4.1.2-2 depicts various liquid oxygen and hydrogen flow rates in comparison with calculated system pressure drops for three given line sizes.

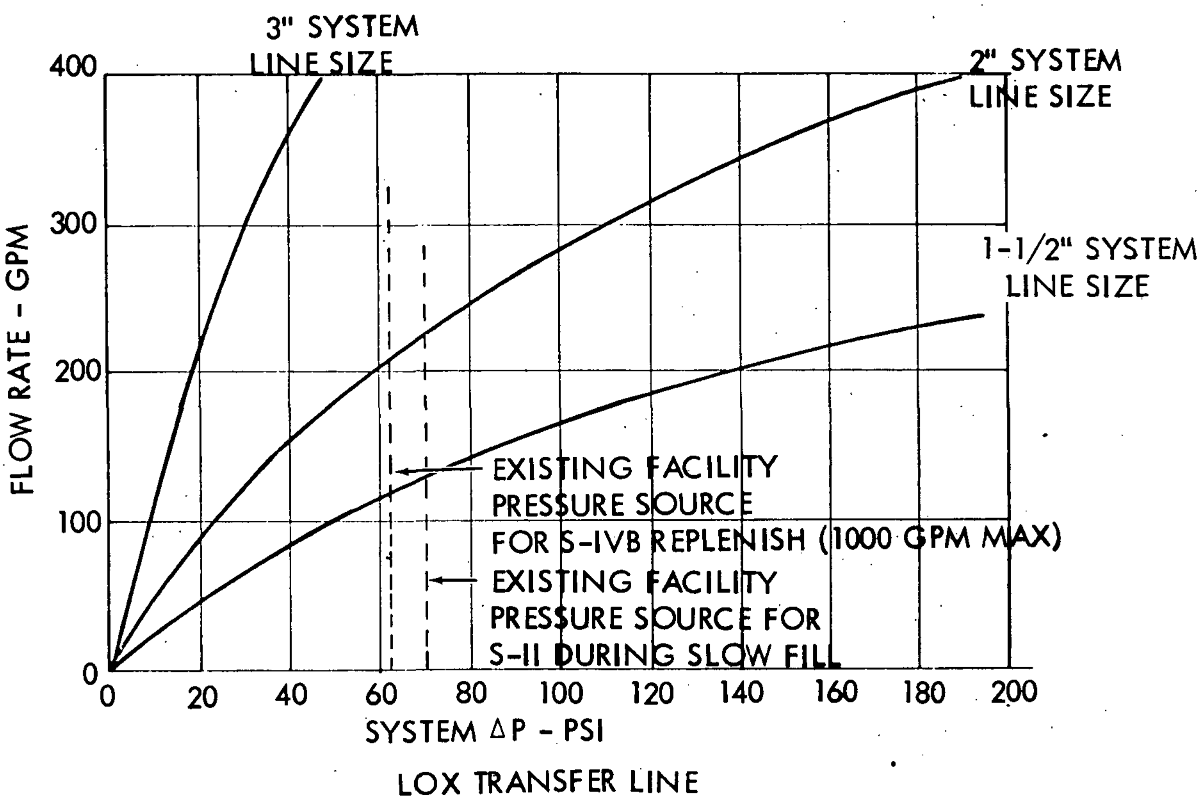
The data show that for the liquid oxygen system at the existing facility transfer line interface for either the Saturn S-II main fill line or the Saturn S-IVB replenish line, the pressure is adequate to provide the 200 gpm flow rate with a two-inch nominal diameter system line size. For the liquid hydrogen system at the existing facility transfer line interface for the Saturn main fill line, the pressure is adequate to provide the 550 gpm flow rate with a two-inch nominal diameter system line size. A critical factor also considered in determining the line size was in limiting the tank drain time under emergency conditions to a safe level. The selected two-inch line size is capable of draining the logistics tank in a time period comparable with the shuttle orbiter and booster drain times under emergency conditions either by pressure feed or gravity feed. Figure 4.1.2-3 depicts the drain time for three given line sizes under various ullage pressure conditions in the liquid oxygen or hydrogen tanks.

The data show that the drain time required for the LOX tank, utilizing the two-inch line, would be approximately 31 minutes with a 4-psig ullage pressure feed and 50 minutes with a gravity feed. The drain time required for the LH_2 tank, utilizing the two-inch line, would be approximately 29 minutes with a 4-psig ullage pressure feed, and 170 minutes with a gravity feed. These drain times are comparable with the present Saturn S-II and shuttle emergency drain times.

The use of hydrogen slush as a propellant for the In-Space Propellant Logistics program is discussed in detail under Trade Studies, Volume III, Section 2.10. The results of this trade study indicate that the use of hydrogen slush cannot be recommended at this time due to insufficient experimental data on its handling and operation. Therefore, hydrogen slush will not be considered for use in the facility and GSE systems.

4.1.3 Additional and Modified Facilities

Various additions and modifications to Government facilities will have to be accomplished in order to support the In-Space Propellant Logistics program. The facility additions and modifications defined herein are described in general terms, and are intended to be a guide into a more detailed and extensive study effort. The government facilities under consideration for usage in the In-Space Propellant Logistics program have not been exactly definitized, but the following is a list of those facilities that can be modified to support each phase of the program.



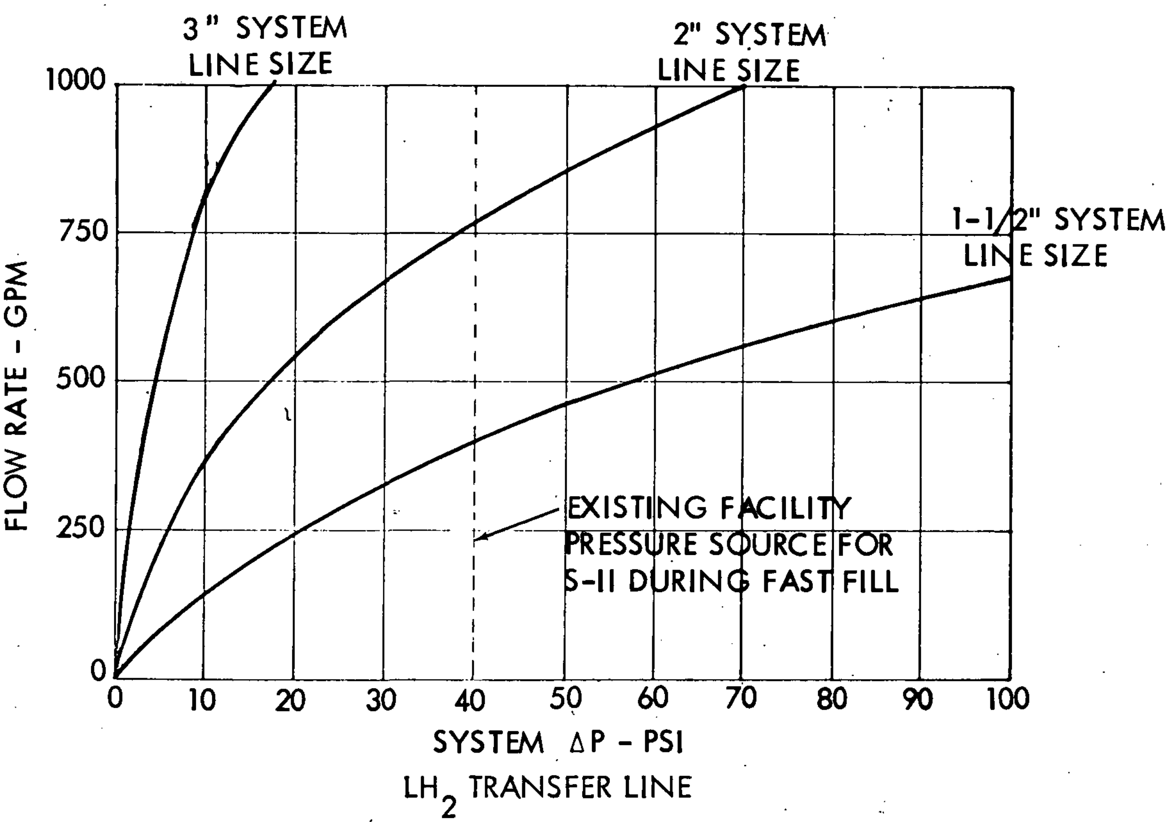
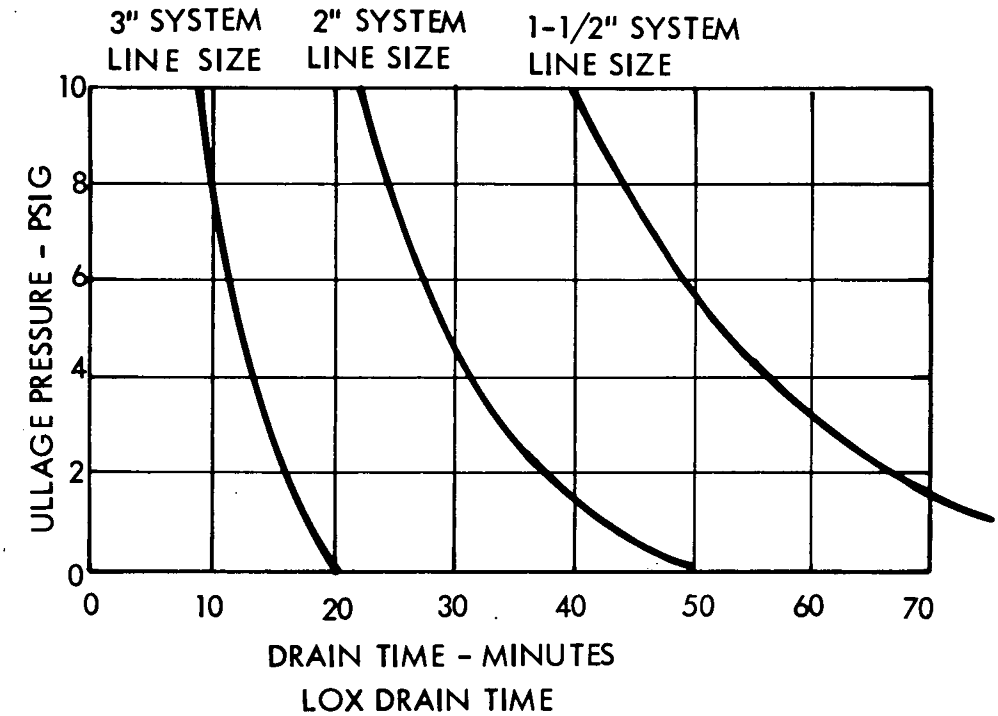


Figure 4.1.2-2 Logistics Module Ground Propellant Line Sizes



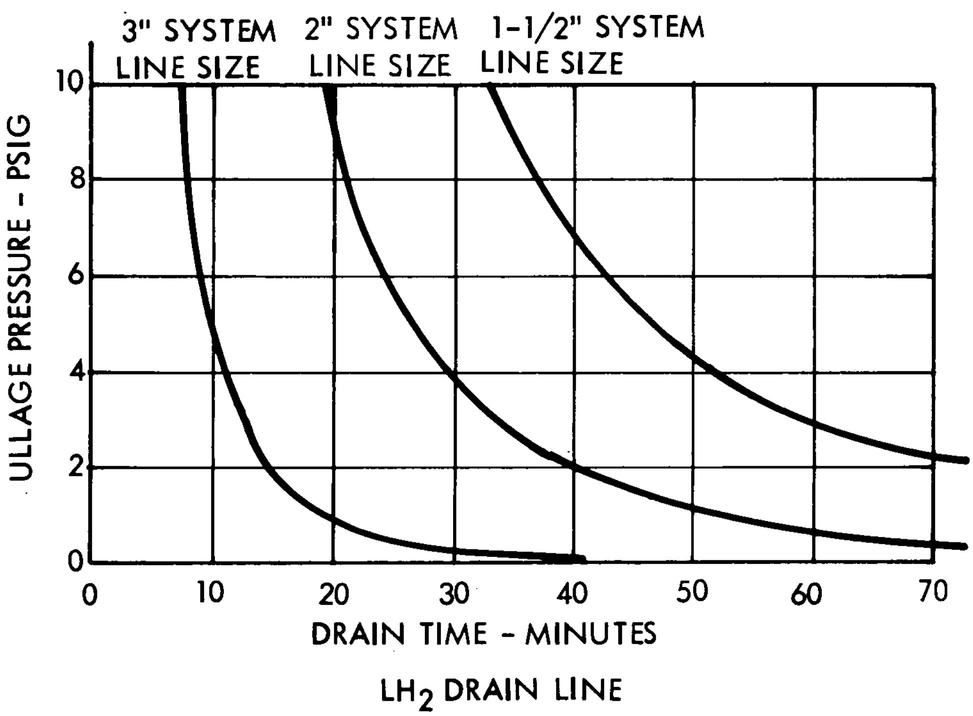


Figure 4.1.2-3 Logistics Module Propellant Drain Time

a. KSC Saturn V Launch Complex

(To be utilized for installation, checkout, and propellant loading of the logistics module flight article and flight test article)

b. NASA Seal Beach, California Checkout Buildings

(To be utilized for post-manufacturing checkout of the logistics module flight article, flight test article, and propellant transfer test article)

c. Mississippi S-II Static Firing Stand or Santa Susana Propellant Transfer Test Stand

(To be utilized for design and functional verification of the propellant, pneumatic, and electrical systems of the logistics module flight test article and the propellant transfer test article)

d. Houston Vacuum Chamber Complex and Huntsville Dynamic Test Stand

(To be utilized for thermal testing of the logistics module insulation, and dynamic structural testing of the module structure for the dynamic/thermal test article)

e. Seal Beach or Huntsville Static Structural Test Facility

(To be utilized for hydrostatic structural testing of the logistics tank structural test article)

f. Landing and Safing Facility

(To be utilized for post-launch safing, checkout, and refurbishment of the logistics module flight article and flight test article)

The main study emphasis has been directed at the KSC facilities and equipment utilized to support propellant storage and transfer operations, while still reviewing to a lesser degree, that equipment and facilities utilized to receive, check out, handle, service, launch, safe, and refurbish the logistics module flight article, and to test the various logistics module test articles. Table 4.1.3-1 compares the existing KSC launch facility storage capacity, refill rates, and transfer rates with the propellant utilization requirements. The table also includes the anticipated additions and modifications required to meet the propellant requirements.

As can be seen from the table, there are no modifications anticipated for the propellant storage facility. The liquid oxygen storage capacity is 8.6 million pounds per launch pad, with a maximum refill rate of 1.2 million pounds per day. The liquid oxygen utilization for one launch will be approximately 4.3 million pounds. This would allow for more than adequate reserve for each launch, and with the present refill rate, could load the storage tank to the full condition in a 3-1/2-day period. (This exceeds other constraints mentioned later, which limit the requirement to one launch every seven days from one launch pad.) The liquid hydrogen storage capability is .51 million pounds per launch pad, with a maximum refill rate of .08 million pounds per day. The liquid hydrogen utilization for one launch will be approximately .18 million pounds. This would allow for more than adequate reserve for each launch, and with the present refill rate, could load the storage tank to the full condition in a 2-1/2-day period. Thus, a vehicle could be launched from one pad every 2-1/2 days.

Table 4.1.3-1

Additions and Modifications to KSC Propellant Facilities

Equipment	Existing Capabilities	New Propellant Usage	Additions/ Modifications
LOX storage	8.6 mil lb/pad 1.2 mil lb refill/day	4.3 mil lb/launch	None
LH_2 storage	.51 mil lb/pad .08 mil lb/refill/day	.18 mil lb/launch	None
LOX transfer	10,000 gpm	1700 gpm	Add flow control complex, transfer lines, and interfaces. Adjust pump governors to provide lower flow rate
LH_2 transfer	10,000 gpm	10,550 gpm	Add flow control complex, transfer lines, and interfaces. Increase storage tank pressure from 60 psig to 65/70 psig.

The anticipated additions and modifications to the propellant transfer system are not considered to be extensive. The liquid oxygen transfer system existing maximum flow rate capability is 10,000 gpm. The fast fill flow rate required for the logistics module will be 200 gpm. This will occur during the orbiter/booster slow fill 1500 gpm mode. Thus, the only modifications to the existing liquid oxygen pumping systems will be to adjust the pump governers to provide a low flow rate of 1700 gpm. The liquid hydrogen transfer system existing maximum flow rate capability is 10,000 gpm. The fast fill flow rate required for the logistics module will be 550 gpm. To obtain the total flow rate of 10,550 gpm during the combined fast fill sequence, the liquid hydrogen storage tank ullage pressure will have to be increased from the present 60 psig value to approximately 65-70 psig. (This value is within the design and relief setting parameters of the storage tank.) To provide independent control of the liquid oxygen and hydrogen prechill, main fill, topping, and drain functions for the logistics module, a flow control unit for each system will be required. These two units will be similar to the orbiter/booster control units in regard to system concept (i.e., system configuration, valving, and operational function), but will be smaller in overall size (two-inch nominal line size). Propellant interfaces for the flow control units will have to be provided in the main transfer lines upstream of the orbiter/booster control units on the launch tower. Figure 4.1.3-1 depicts in block diagram form, the propellant transfer configuration from the storage tank to the orbiter/booster interface on the launch tower.

Other KSC facility modifications and additions to be considered are in the transfer aisle, low bay, high bay, and launch control center areas. Some of the functions of the transfer aisle area will be to provide receiving, unpackaging, pre-installation inspection, installation, and interface verification capabilities for the logistics module. One of the functions of the low bay area will be to provide premate checkout capabilities for the logistics module. Some of the functions of the high bay area will be to provide stacking, prelaunch checkout, and launch readiness capabilities for the logistics module. Additional facility equipment required in these three areas will consist mainly of personnel access platforms, console support platforms, transfer dolly center support structure, and fluid and electrical distribution system interfaces. The existing hoisting equipment is adequate for all logistics module lifting functions. Modifications in the launch control center will be required to provide pneumatic and electrical control for the various logistics module servicing, propellant loading, and launch countdown functions. This will entail additions and/or modifications to various control console equipment (e.g., indications, communications, switch controls, etc.).

The requirement for the number of launch pads necessary to support the various space traffic program levels, is considered to be of significant importance. The number of launch pads required to support any space program will depend to a large degree on the number of launches per month for that program, the launch pad turnaround time, the shuttle turnaround time, the shuttle fleet size, and various other constraints. For the purpose of this study, only the number of launches per month and the shuttle and launch pad turnaround times will be considered. Figure 4.1.3-2 reflects the number of launch pads required versus various efficiency levels for the number of launches per month for each space traffic program level.

As can be seen from the graph, program levels A, B, and C can be supported by one launch pad, program level D (RNS) can be supported by two launch pads, program level E (RNS) can be supported by two or three launch pads depending on the efficiency level, program level D (CIS) can be supported by three launch pads, and program level E (CIS) can be supported by three or four launch pads depending on the level of efficiency. The 100-percent efficiency line was based upon a shuttle and launch pad turnaround of seven days. The launches per month for program levels A, B, and C were determined by taking the flight schedule for the peak usage years and distributing those flights evenly over the entire year. The launches per month for progrm levels D and E were determined by compacting the total CIS/RNS lunar flights into two 80-day refill periods, and distributing the rest of the flights (also during peak usage years) evenly over the entire year. Only non-polar orbital

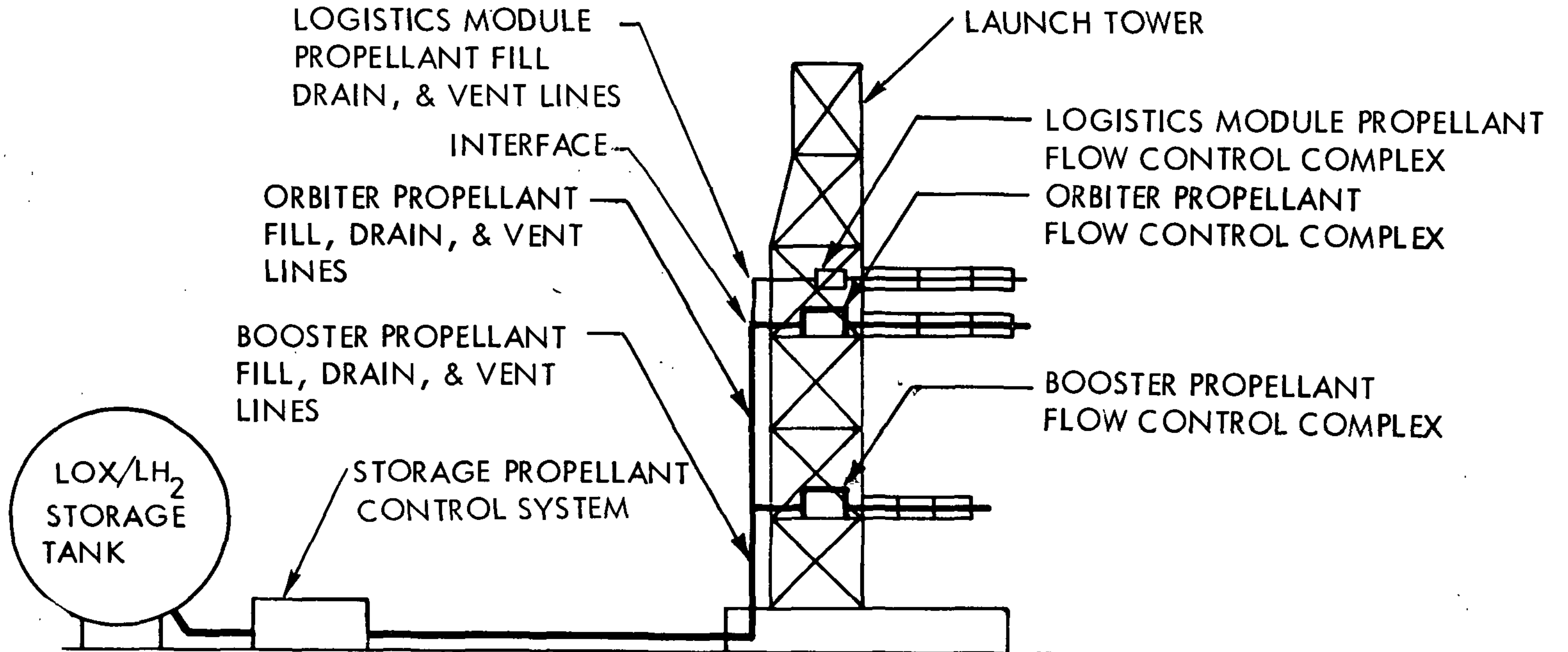


Figure 4.1.3-1 Facility Propellant System Block Diagram

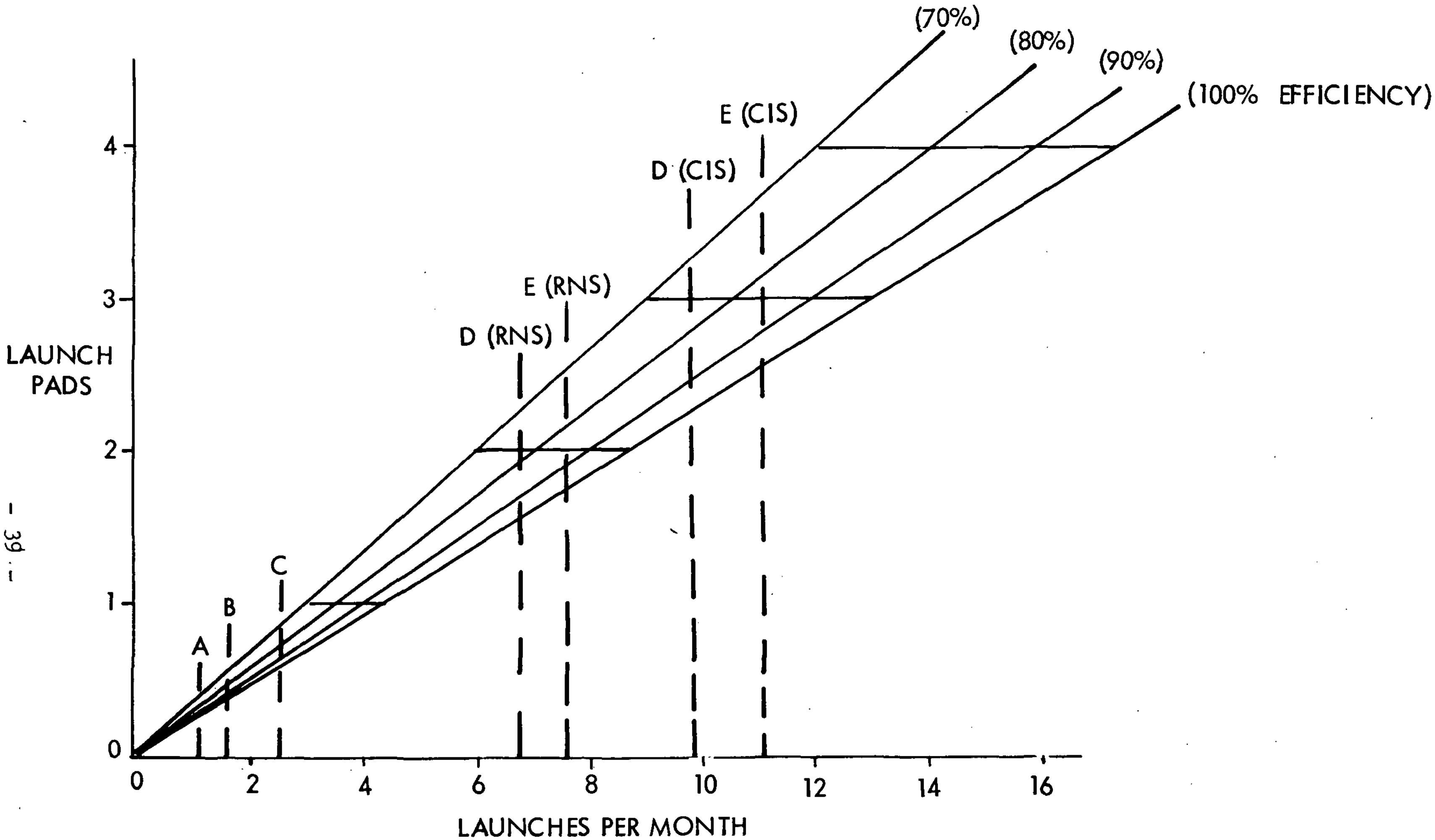


Figure 4.1.3-2 KSC Launch Pad Requirements

missions (eastern launch range) were utilized for these data. Also, it was assumed that two CIS/RNS vehicles would be available in orbit during the peak years (one for lunar missions and one for planetary missions).

Modifications and additions to other than KSC facilities will consist primarily of configuration fit-up revisions to existing equipment (e.g., platforms, fluid systems, cable systems, etc.) in order to accept the logistics module in the respective test fixtures. These modifications and additions, as described in general terms, should consist of the following:

a. Seal Beach Post-Manufacturing C/O Building (Flight Article, Flight Test Article and Propellant Transfer Article Testing)

   Rework of existing personnel and equipment access platforms, logistics module tie-down structure, and umbilical interface panels to accommodate the smaller logistics module configuration. Also, the fluid and electrical distribution systems will require modifications in terms of rerouting, adding, and deleting lines, cables, trays, and supports.

b. Mississippi S-II Static Firing Test Stand or Santa Susana All-Systems Test Stand (Propellant Transfer Test Article, Dynamic/Thermal Test Article and Flight Test Article Testing)

   Rework of existing personnel and equipment access platforms, test article tie-down strucutre, and umbilical interface panels to accommodate the smaller logistics module configuration. The fluid and electrical distribution systems will require modifications in terms of rerouting, adding, and deleting lines, cables, trays, and supports. Also, the propellant transfer system will require minor modifications to reduce the flow rates and pressures during prechill and fast-fill operations; and, the associated pneumatic and electrical console equipment will require some system and component modifications.

c. Houston Vacuum Chamber Complex (Dynamic/Thermal Test Article and Flight Test Article Testing) and Huntsville Dynamic Test Stand (Dynamic/Thermal Test Article Testing)

   Rework of the existing personnel and equipment access platforms, test article tie-down structure, and other miscellaneous instrumentation, electrical and mechanical instrumentation, electrical and mechanical devices.

d. Seal Beach Static Structural Test Facility (Structural Test Article Testing)

   Rework of existing personnel and equipment platforms, test article tie-down structure, and umbilical interface panels to accommodate the smaller logistics module configuration.

e. Landing and Safing Facility (Flight Article and Flight Test Article Safing and Testing)

Addition of various personnel access platforms, console support platforms, and fluid and electrical distribution systems.

4.1.4 Facility Modification/Activation Schedule

The schedule of activities pertinent to the implementation of the facility modifications and additions described herein are based upon meeting the various logistics module flight and test article milestones. Figure 4.1.4-1 presents the facility modification and activation schedules and the applicable flight and test article milestones.

The milestones shown have been derived from an in-space logistics program initial operational capability of January, 1985, as delineated in Section 6.0, Project Implementation Plan, of this volume. The implementation start dates and completion dates of each of the noted facilities are supportive to the Phase C implementation date and the flight and test article milestones.

The effort involved will consist primarily of the basic engineering design of the predetermined modifications and additions (and also a continuing engineering effort through the test period), the procurement of necessary materials, components, and subsystems as applicable, and the fabrication, installation, and acceptance testing of the hardware needed to update the facilities to the logistics module flight and test article configuration.

4.2 GROUND SUPPORT EQUIPMENT REQUIREMENTS

The objective of this portion of the study has been to identify and describe, in general terms, the ground support equipment (GSE) conceptual hardware and utilization required to perform handling, transportation, checkout, and servicing functions for the logistics module operational flight article in support of the propellant logistics program.

The major areas of concern with respect to the GSE requirements have been developed into three categories of effort consisting of: (1) the identification of all GSE required at each of the specific operational and test areas, (2) the determination of the logistics module ground servicing operations flow path, and (3) the development of timeline schedules for effort required to design, develop, fabricate, and test the GSE equipment.

The in-space propellant logistics GSE requirements have been expressed without going into specific details, with the results being developed for general systems/equipment definition. Sufficient data have been developed to provide a meaningful broad-scope view of the GSE requirements, ground operations, and servicing timelines. The conclusions established herein are formulated utilizing criteria based on the similarity of configuration and utilization of Saturn S-II GSE, and the unique basic requirements imposed by the logistics module, and can be summarized as follows:

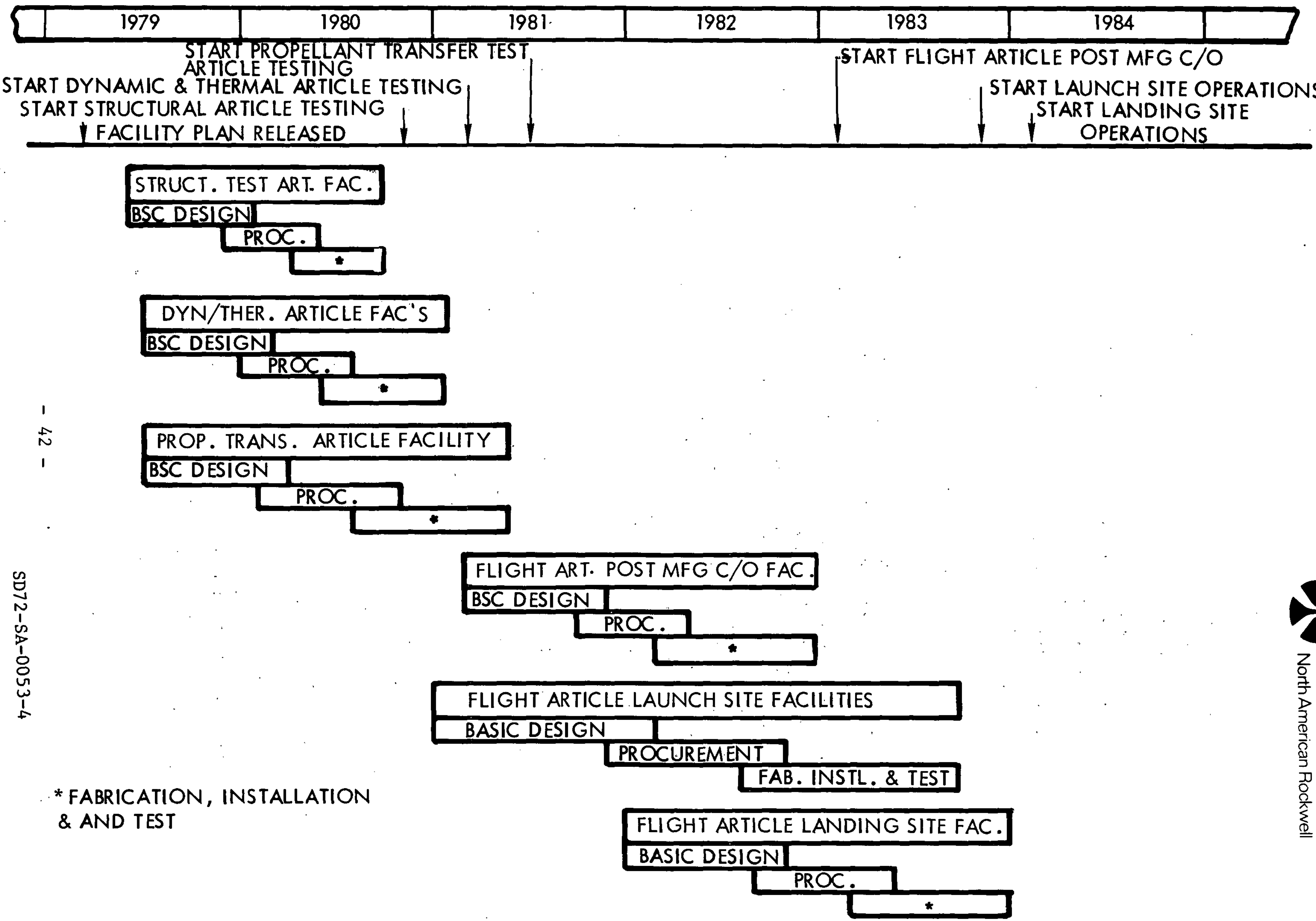


Figure 4.1.4-1 Facility Modification/Activation Schedule

a. The GSE requirements have been definitized in general terms, and the equipment and systems can be designed within the present state-of-the-art knowledge and experience.

b. The ground operations flow and prelaunch/post-landing timelines have been developed, and they meet the overall shuttle program requirements with no foreseeable problems.

c. The GSE fabrication and activation implementation schedules are supportive to the in-space logistics programmed initial operational capability of January, 1985.

4.2.1 Equipment Identification

The mechanical and electrical GSE identified herein will be utilized to support the ground operation functions for the propellant logistics module in the following operational and test areas: (1) post-manufacturing checkout and acceptance testing; (2) transportation operations; (3) premate checkout operations; (4) installation and mating verification; (5) prelaunch systems readiness operations; (6) launch preparation and launch operations; and (7) post-flight safing and maintenance operations. The GSE will be designed to satisfy the specific operational and test area requirements for the propellant logistics module. Table 4.2.1-1 presents the conceptual identification (in generalized groupings) of the necessary GSE required to support the various ground operational functions for the logistics module at the specific test area.

The equipment is categorized into four classes of GSE: (1) checkout (verifies flight article systems, provides controls, distributes electrical and fluid signals, and supplies electrical power); (2) auciliary (performs special functions and fulfills special operational requirements); (3) servicing (supplies, distributes, conditions, and disposes fluids for the flight article systems; and (4) handling (supports and handles the flight article, its assemblies, subassemblies and components).

The determination of whether existing Saturn, Apollo, or Government GSE could be utilized to perform some of the operational functions, has not been achieved in this study because the logistics module performance capabilities and interfaces have not been defined in sufficient detail. Therefore, only the requirement for a particular GSE item or system of items has been identified.

4.2.2 Ground Servicing Operations

The ground servicing operations required to support the propellant logistics module flight article shall include the flow path, from the time of delivery from manufacturing at the start of its operational life, through post-landing operations and recycling. Figure 4.2.2-1 depicts the representative logistics module flight article flow path, and the figurative GSE requirements.

Table 4.2.1-1. Identification Listing of GSE

GSE NOMENCLATURE	POST MFG CHECKOUT	TRANSPORTATION OPERATIONS	UNPACKAGING & INSTALLATION PREPS.	PREMATE & INTERFACE C/O	LAUNCH OPERATIONS	POST FLIGHT SAFING & C/O
CHECKOUT						
PNEU/ELECT. CHECKOUT CONSOLE	X			X		X
MISC. C/O EQUIPMENT SET (FLOWMETERS, BLANKING PLATES, ETC.)	X			X		X
LEAK DETECTION EQUIPMENT	X			X		X
FLUID/ELEC DISTRIBUTION SYSTEMS	X			X		X
AUXILIARY						
IN TANK ENTRY EQUIPMENT	X			X		X
ACCESS PLATFORM EQUIPMENT	X		X	X		X
UMBILICALS AND DISCONNECTS	X			X	X	X
TANK WEIGHING EQUIPMENT			X			
ENVIRONMENTAL CONTROL UNIT	X			X		X
SERVICING						
PNEU. SERVICING UNIT					X	
PORTABLE VACUUM UNIT	X			X	X	X
PURGE CONTROL UNIT						X
TANK DESICCANT/PRESS. UNIT		X				
FLUID/ELEC. DISTRIBUTION SYSTEMS					X	
HANDLING						
TRANSPORTATION DOLLY		X				
PROTECTIVE FRAMES & COVERS		X				
LIFTING RINGS, SLINGS, & MISC. HOISTING EQUIPMENT	X		X	X		X
MISC. COMPONENT HANDLING EQUIP.	X			X	X	X
FWD & AFT PROTECTIVE SKIRTS	X	X	X			

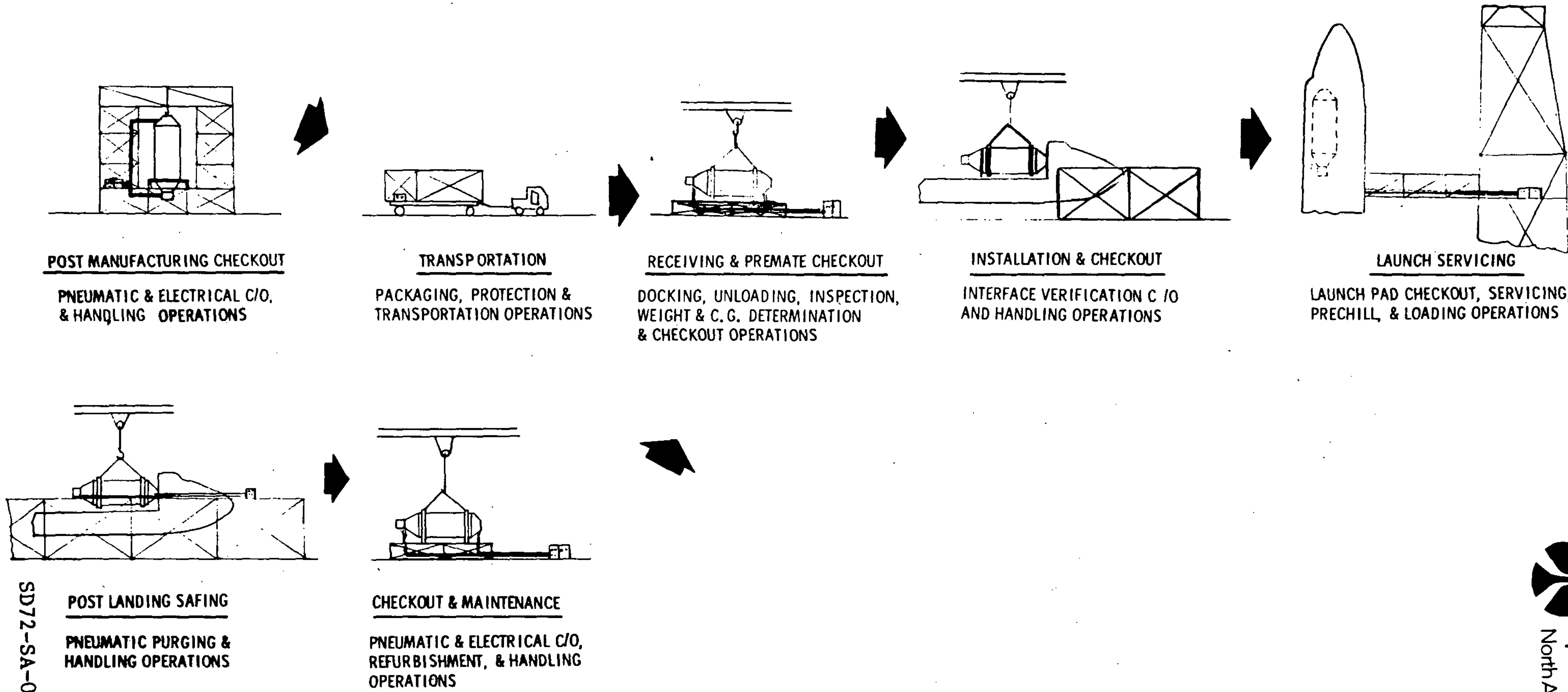


Figure 4.2.2-1 Logistics Module Ground Operations Flow Path

The post-manufacturing acceptance checkout operations will be accomplished in a vertical position on a facility base mount fixture. The logistics module will be positioned into the checkout station on the mount fixture, utilizing facility cranes and GSE hoisting and handling equipment. Access will be provided by facility work platforms and GSE supplemental access platforms. Pneumatic and electrical checkout GSE will perform the acceptance checkout functions. Following post manufacturing checkout, the logistics module will be positioned on the GSE transportation dolly via the same lifting equipment, and made ready for transport to KSC by sea or air. The liquid oxygen and hydrogen tanks will be maintained in a clean condition and protected by means of a portable desiccant or pressurization unit. The entire logistics module will be protected with appropriate packaging, and GSE frame and cover transportation equipment.

Upon delivery to KSC, the logistics module will be transported to the Vertical Assembly Building (VAB) transfer aisle area for unpackaging, inspection, weight/c.g. determination, and preparation for premate checkout and installation into the orbiter cargo bay. The logistics module will be positioned into the low bay checkout cell. Access will be provided by facility work platforms and GSE supplemental access platforms. Pneumatic and electrical checkout GSE will conduct various integrated systems checkout tests. Upon completion of premate checkout the logistics module will be removed to the transfer aisle area and positioned into the orbiter cargo bay, utilizing facility cranes and GSE hoisting and handling equipment, and then mated to the orbiter interfaces. The logistics module-to-orbiter interface verification tests will be performed in preparation for launch. Subsequent to these prelaunch checkout operations, the orbiter will be stacked and positioned on the launch pad. The logistics module GSE servicing pneumatic equipment will then be activated to supply, distribute, condition, and dispose fluids for the logistics module systems, in support of launch propellant loading and servicing countdown operations.

Upon completion of orbiter landing and cooldown, the logistics module will be inerted and safed, utilizing a GSE pneumatic purge unit. The module will then be removed from the orbiter cargo bay and transferred to the maintenance/refurbishment area and installed in the checkout stand. GSE (common to other checkout sites) will be provided at the maintenance area, to provide for logistics module subsystem functional diagnostic checkout, flight analysis, maintenance, handling, transportation, and complete visual inspection functions. Periodic programmed maintenance tasks will include removal replacement, repair, calibration, adjustment, checkout, test, and inspection to the subassembly or detail part level. Upon completion of post-landing operations, the logistics module will be recycled back to launch operations.

In addition to the aforementioned GSE, equipment will be provided for special logistics module field operations, such as tank entry and storage functions. Tank entry will require GSE internal access stands, hoisting equipment, work platforms, ladders, environmental enclosures and tank air conditioning equipment.

The logistics module and shuttle preflight operations, in accordance with the Figure 4.2.2-2 activity timeline phasing, will primarily consist of the following:

EVENT SEQUENCE AND TIME LINE

SEQUENCE OF EVENTS	DURATION
a. ORBITER, LOGISTICS MODULE, AND PAYLOAD PREMATE CHECKOUT	(8 HR)
b. LOGISTICS MODULE AND PAYLOAD INSTALLATION AND INTERFACE VERIFICATION	(12 HR)
c. BOOSTER PREMATE CHECKOUT	(4 HR)
d. MATE BOOSTER TO LUT, MATE ORBITER TO BOOSTER, AND ERECT	(28 HR)
e. ORDNANCE INSTALLATION AND UMBILICAL HOOKUP	(11 HR)
f. ROLLOUT AND ARRIVAL AT PAD	(9 HR)
g. LUT / PAD INTERFACE HOOKUP AND LAUNCH READINESS CHECKOUT	(14 HR)
h. TANK PURGE AND ORDNANCE HOOKUP	(5 HR)
i. COUNTDOWN	(5 HR)
j. PROPELLANT LOADING (ALL TANKS)	(2 HR)
k. REACTANT TANK LOADING AND PRESSURIZATION	(1 HR:30 MIN)
l. PROPELLANT REPLENISHING	(40 MIN)
m. CREW TRAVEL AND INGRESS	(30 MIN)
n. TERMINAL COUNT	(15 MIN)
o. AUTOMATIC SEQUENCE	(10 MIN)
P. LIFTOFF	

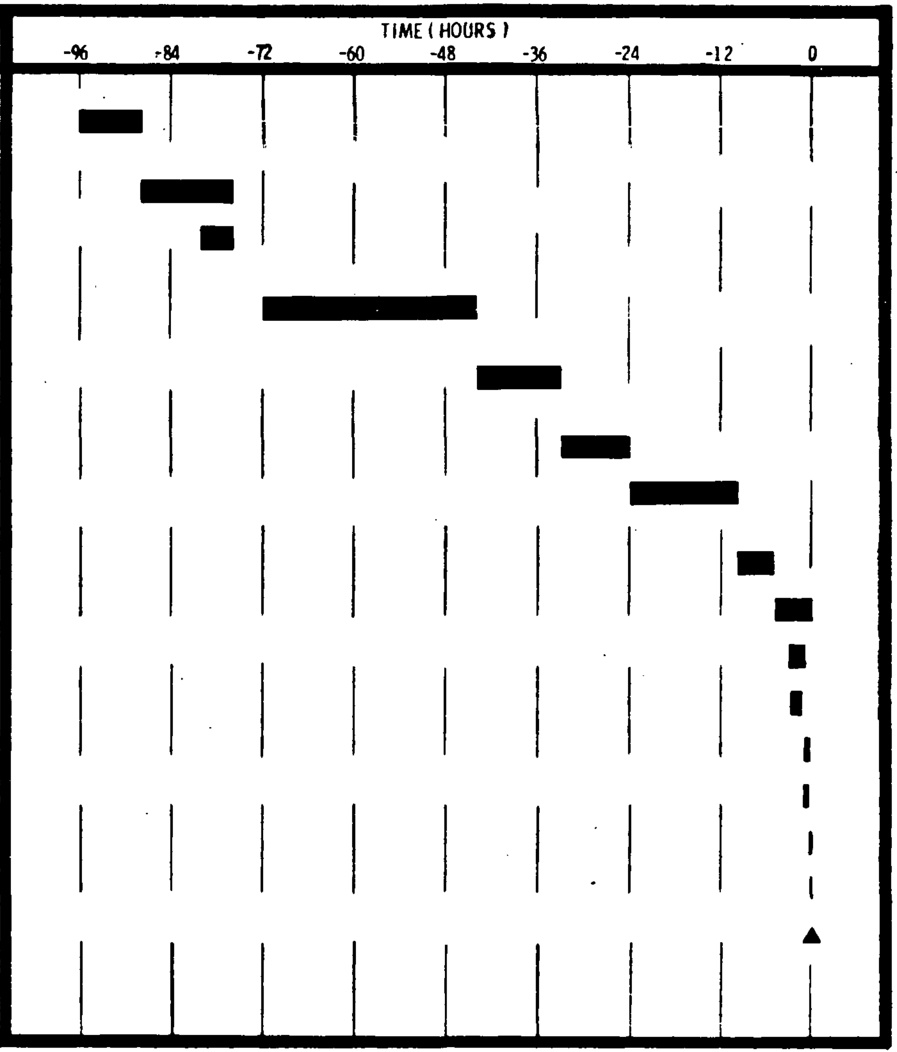


Figure 4.2.2-2 Pre-Launch Operations

Space Division
North American Rockwell

a. Orbiter, Logistics Module, and Payload Premate Checkout - Checkout performed during the premate period provides the basic confidence that the orbiter and logistics module subsystems have withstood the previous flight and are capable of supporting another mission.

b. Logistics Module and Payload Installation and Interface Verification - The orbiter will be moved to the mating area and the cargo bay set up for receipt of the propellant module and payload modules. Holding equipment will then be utilized to install these modules in the cargo bay. Next, interfaces will be connected and verified by performing continuity and pressure tests.

c. Booster Premate Checkout - Similar to Item "a".

d. Mate Booster to LUT, Mate Orbiter to Booster and Stack - The booster will be moved to the mating area and all separation and mating mechanisms and surfaces are inspected and readied for mating. The booster will then be lifted to the vertical position and lowered onto the mobile launcher, and hold-down mechanisms attached and secured. All booster electrical, hydraulic, pneumatic and cryogenic launcher interfaces are connected and verified. Next, the orbiter will be lifted to a vertical position and mated to the booster. All orbiter electrical, hydraulic, pneumatic, and cryogenic launcher interfaces are connected and verified.

e. Ordnance Installation and Umbilical Hookup - All ordnance will be installed and verified and umbilicals connected and verified.

f. Rollout and Arrival at Pad - The space shuttle mobile launcher will be transported by the transporter from the VAB to the launch pad. The pad will have been previously prepared for the arrival of the shuttle system.

g. LUT/Pad Interface Hookup and Launch Readiness Checkout - The pad-to-mobile launcher electrical and fluid interfaces will be connected and verified. Warning and monitoring systems interfaces will be verified by condition simulations.

h. Tank Purge and Ordnance Hookup - After the connection of ordnance connectors, liquid hydrogen tanks and lines will be conditioned to a hydrogen atmosphere. Rigid pad and vehicle access controls are now in effect.

i. Countdown - Start of five-hour countdown will be initiated.

j. Propellant Loading (All Tanks) - Childown of all transfer lines and tankage, venting, transfer, replenishment, and termination are accomplished by an automated system. After childown, simultaneous loading of all liquid oxygen and hydrogen into the booster, orbiter, and payload (if required) will begin. The logistics module loading will be initiated at the same time; however, liquid oxygen loading will precede liquid hydrogen loading in a serial loading mode.

k. Reactant Tank Loading and Pressurization - Next, the reactant tanks will be loaded and pressurized.

l. Propellant Replenishing - The topping mode (flow rate) of the propellant loading control system will be used to replenish propellants lost in boil-off.

m. Crew Travel and Ingress - The launch pad facility will have a rapid-lift elevator within the service tower to transport four crew members, two load masters, ten passengers, and the closeout crew to the boarding platform access arms.

n. Terminal Count - Next, the terminal countdown which includes a verification that all systems are configured for launch will be performed.

o. Automatic Sequence - During the final ten minutes prior to launch, the countdown will progress automatically.

p. Liftoff - The space shuttle will achieve a free liftoff and rise from the pad.

The logistics module and orbiter post-landing operations, in accordance with the Figure 4.2.2-3 activity timeline phasing, will primarily consist of the following:

a. Landing Complete (T = 0) - The orbiter completes its mission and returns to the launch landing site and lands. The flight crew immediately initiates on-board safing, securing, and shutdown procedures.

b. Tow Orbiter to Safing Area - The orbiter will be towed (or taxied) to the safing area.

c. Secure Orbiter and Remove Flight Personnel and Flight Data - Upon reaching the safing area, ground servicing system hookup and installation will begin concurrently with flight crew and passenger egress. At the same time, the pilot log and recorded flight data will be obtained and post-flight data analysis initiated.

d. Perform Post-Flight Safing - During post-flight safing, orbiter and logistics module liquid propellant residuals will be drained and propellant and reactant tanks will be vented and inerted. The vehicle interstitial spaces will be purged to remove heat from the structure; and all ordnance will be safed or removed.

e. Tow Orbiter to Hangar Area - When the safing and cooldown requirements have been met, the vehicle will be towed to the maintenance area for hangar operations.

f. Prepare for Hangar Operations - Upon arrival at the maintenance hangar, the orbiter will be positioned, secured, placed on jacks, raised and leveled. Normal servicing will then commence as well as additional data analysis on mission anomalies.

EVENT SEQUENCE AND TIME LINE

SEQUENCE OF EVENTS	DURATION
a. LANDING COMPLETE (T = 0)	
b. TOW ORBITER TO SAFING AREA	(1 HR)
c. SECURE ORBITER & REMOVE FLIGHT PERSONNEL & FLIGHT DATA	(3 HR)
d. PERFORM POST-FLIGHT SAFING	(7 HR)
e. TOW ORBITER TO HANGAR AREA	(2 HR)
f. PREPARE FOR HANGAR OPERATIONS	(1 HR)
g. UNLOAD LOGISTICS MODULE (CARGO)	(24 HR)
1. OPEN CARGO ACCESS DOORS	(30 MIN)
2. INSTALL CARGO HOISTING MECHANISM	(30 MIN)
3. DISCONNECT LM/ORBITER INTERFACES	(1 HR)
4. REMOVE LOGISTICS MODULE	(2 HR)
5. RETURN LM TO RECEIVING AREA	(1 HR)
6. PERFORM LOGISTICS MODULE INSPECTION	(1 HR)
7. PERFORM LM POST-FLIGHT CHECKOUT	(2 HR)
8. PERFORM LOGISTICS MODULE SERVICING, REPAIR, & MODIFICATION	(12 HR)
9. PREPARE LM FOR NEXT FLIGHT	(4 HR)
h. PERFORM ORBITER INSPECTION, POST-FLIGHT CHECKOUT, SERVICING, REPAIR, & MODS	(24 HR)
i. SECURE ORBITER FROM HANGAR OPERATIONS	(4 HR)
j. PREPARE ORBITER FOR NEXT FLIGHT	

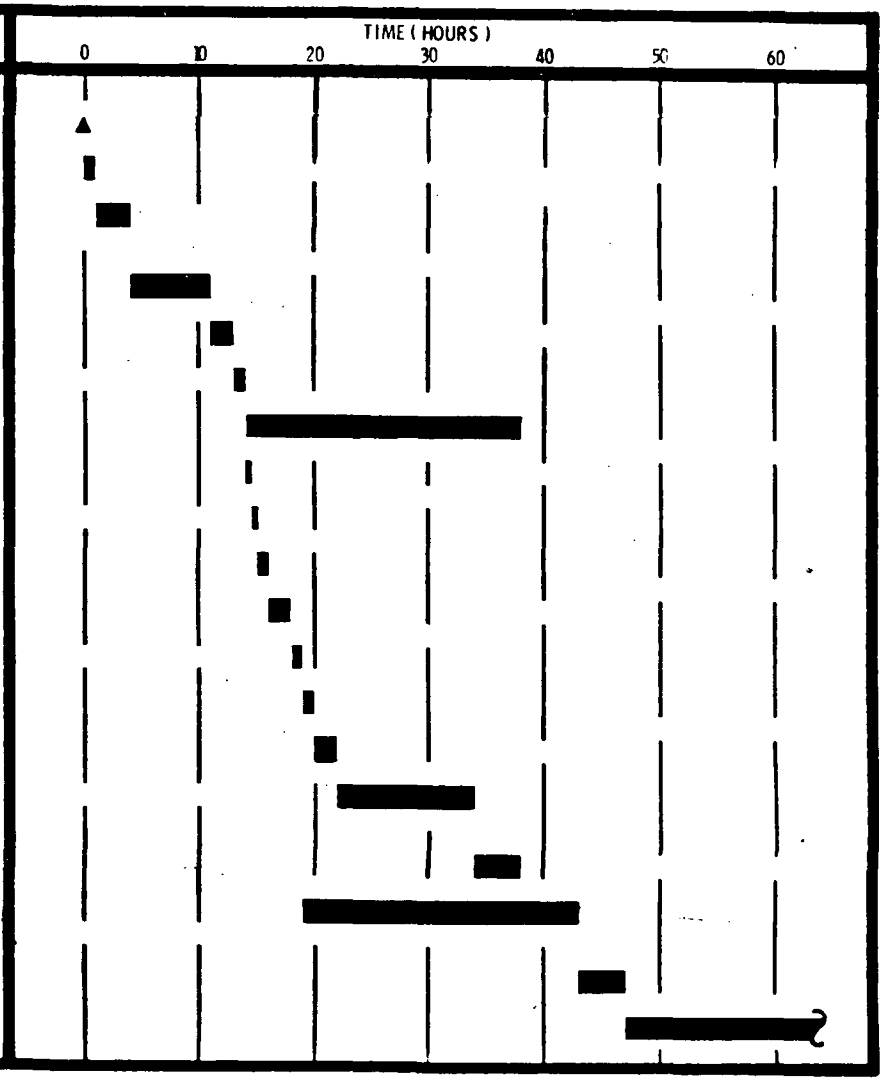


Figure 4.2.2-3 Post-Landing Operations

g. Unload Logistics Module (Cargo) - The orbiter will then be prepared for logistics module removal. First, the cargo bay doors will be opened and the cargo hoisting mechanism moved into place. Next, all logistics module/orbiter interfaces will be disconnected and the logistics module removed from the cargo bay. The logistics module is then returned to the receiving area where a comprehensive inspection will be performed. Next, the logistics module will undergo a checkout in order to verify the post-flight integrity of all systems. Following checkout, the logistics module will undergo normal servicing, maintenance, repair, and modifications prior to recycling for the next flight.

h. Perform Orbiter Inspect, Post-Flight Checkout, Servicing, Repair, and Modifications - Similar to the logistics module, the orbiter will undergo inspection, post-flight checkout, servicing and repair to eliminate all noted discrepancies and possible impending failures. Modifications required prior to the next flight will be installed during this time period.

i. Secure Orbiter from Hangar Operations - Following the above operations, the orbiter will be secured from hangar operations in preparation for the next flight or possibly storage.

j. Prepare Orbiter for Next Flight - Finally, the orbiter is prepared for assembly and launch for the next mission.

4.2.3 GSE Fabrication/Activation Schedule

The schedule of activities pertinent to the implementation of the GSE, described herein, is based upon meeting the various logistics module flight article milestones. Figure 4.2.3-1 depicts the GSE implementation schedules and the applicable flight article milestones.

The milestones shown have been derived from an in-space logistics initial operational capability of January, 1985, as delineated in Section 6.0, Project Implementation Plan, of this volume. The implementation start dates and completion dates of each of the noted GSE activities are supportive to the Phase C implementation date and the flight article milestones.

The effort involved will consist primarily of the basic engineering design of the various GSE end items (and also a continuing engineering effort through the test period), the procurement of necessary materials, components, and subsystems as applicable, the development testing of critical GSE, and the fabrication, installation, and acceptance testing of the components, subassemblies, assemblies, and end items of GSE.

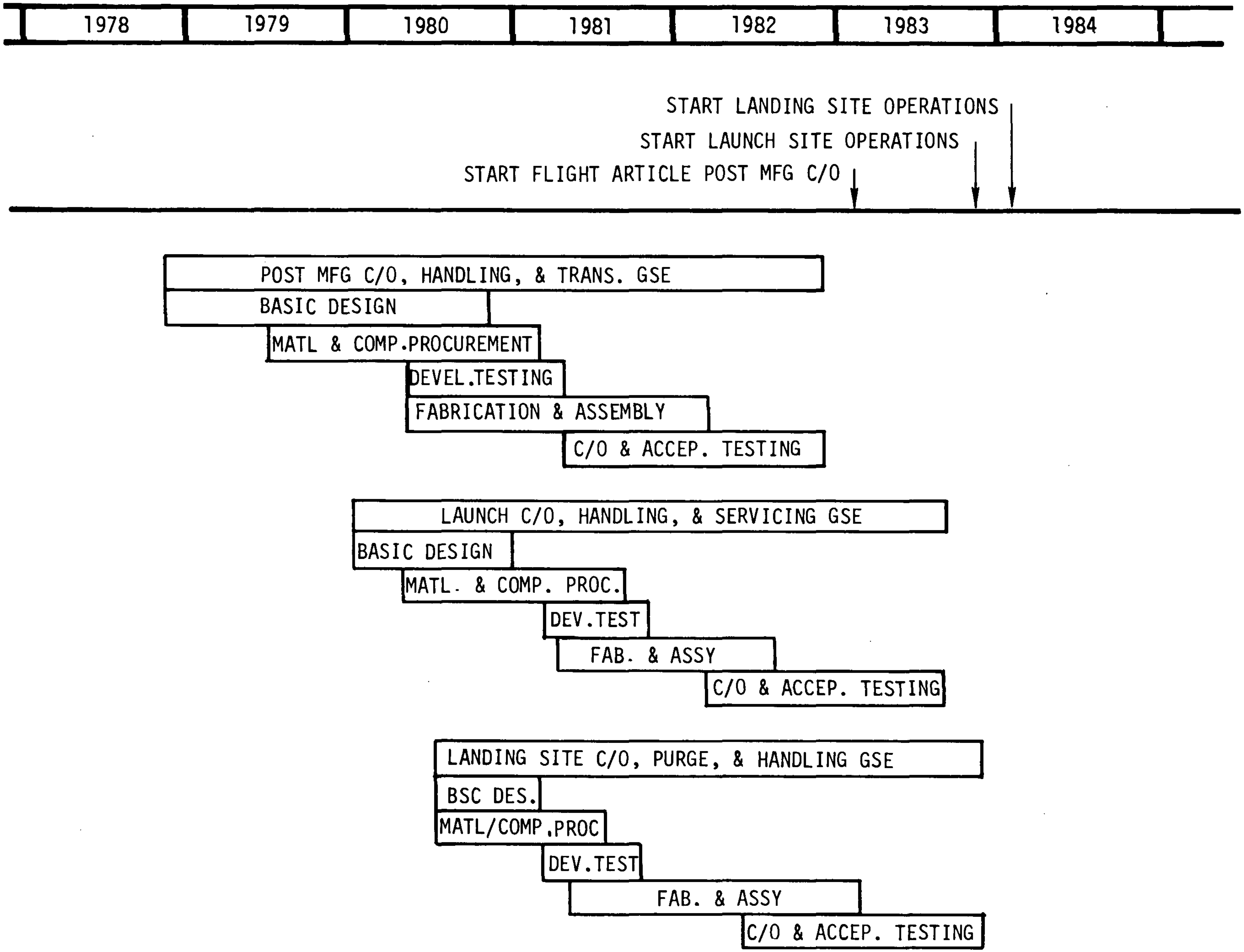


Figure 4.2.3-1 GSE Fabrication/Activation Schedule

5.0 SUPPORTING RESEARCH AND TECHNOLOGY

This section describes in detail those problem areas which require supporting research and technology (SR&T) to provide in-orbit refueling capabilities for the tug, the chemical interorbital shuttle, and the reusable nuclear stage. Many of the problems are peculiar to orbital transfer of propellant, although some of the problems are of general interest and the work would be applicable to several elements of the space program. However, the effort required, schedules, and manpower and cost estimates are based upon satisfying orbital transfer technology requirements alone. It is tacitly assumed that presently funded technology programs in directly related areas, such as multilayer insulation and thermodynamic venting systems, and in complementing areas, such as avionics and rendezvous techniques, will continue to be supported at current levels.

Required SR&T has been categorized under five task headings as follows:

a. Propellant Transfer

b. Structures

c. High Performance Multilayer Insulation

d. Thermodynamic Control

e. Systems

These tasks are divided into a number of sub-tasks. Sub-task titles and schedules are given in Figure 5.0-1. Manpower requirements and costs to complete the SR&T program are presented for each sub-task in Table 5.0-1. Costs are broken down into two categories: material/equipment and facilities. In addition, manpower requirement and costs are presented on a year-by-year basis from CFY '73 through CFY '77 in Table 5.0-1. Results of this table can be readily summarized if a cost figure is assigned to the manpower requirements. Assuming manpower costs to be $20/man-hour, then the total SR&T costs (manpower, materials and facilities) are given below:

CFY 73	$2,777,000
CFY 74	4,765,000
CFY 75	4,095,000
CFY 76	1,667,000
CFY 77	410,000

The emphasis in the SR&T tasks is on experimental data. This emphasis is warranted in the light of the number of unknowns involved in the orbital transfer of cryogenic propellant. Tests are proposed wherever possible with non-cryogenic fluids under one "g" conditions; for example, this is possible

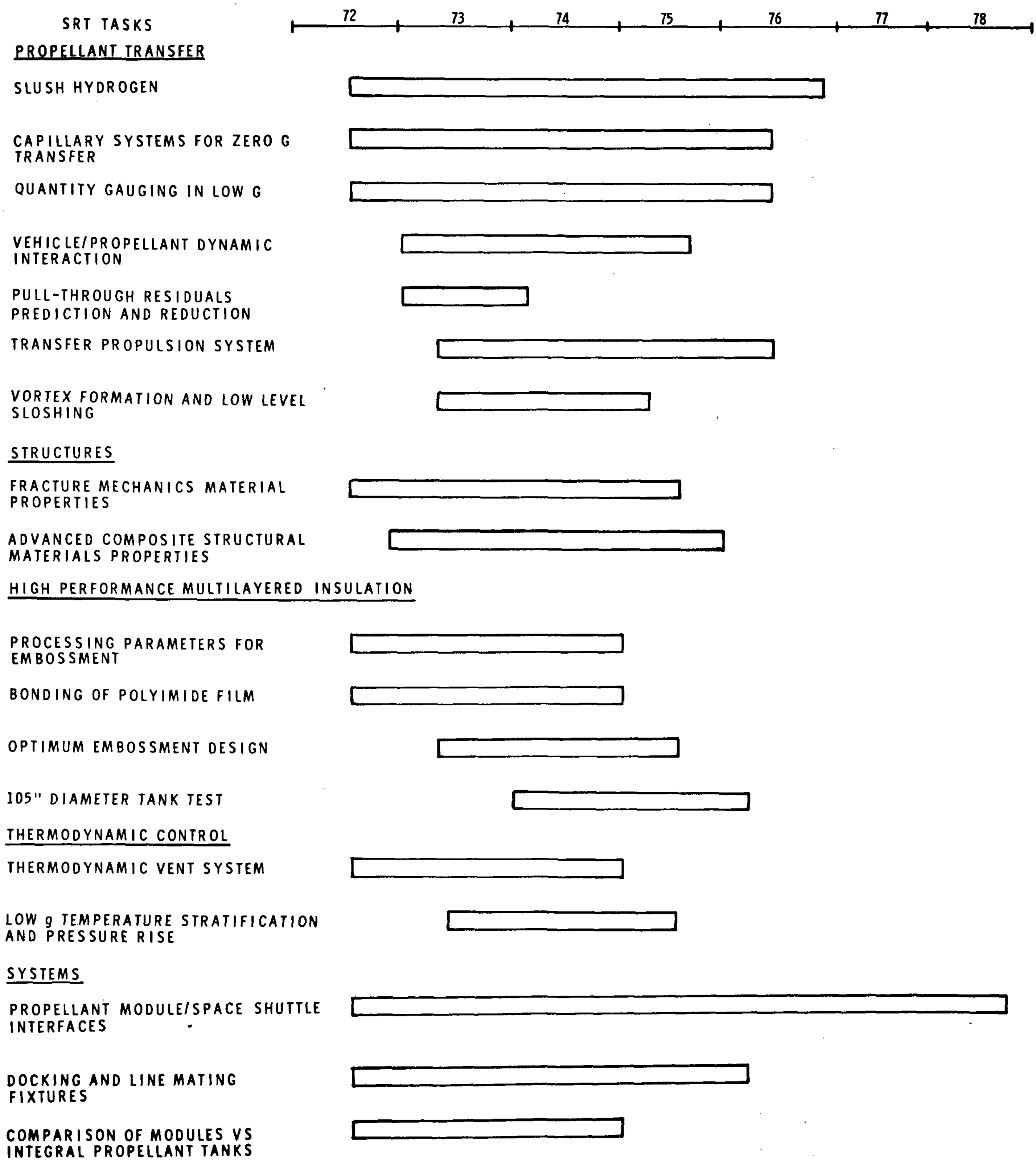


Figure 5.0-1 Supporting Research & Technology Schedule

TABLE 5.0-1 ISPLS Supporting Research and Technology Costs

	GFY 73	GFY 74	GFY 75	GFY 76	GFY 77	Total
PROPELLANT TRANSFER						
Transfer Propulsion System						
Manpower (man-years)	4	7	7	4	1	23
Material/equipment ($1000)	50	50	15	5	5	125
Facilities ($1000)	65	65	20	5	5	160
Pull-Through Residuals						
Manpower (man-years)	4	6				10
Material/equipment ($1000)	12	50				62
Facilities ($1000)	15	75				90
Vehicle Propellant Dynamic Interaction						
Manpower (man-years)	2	5	7	1		15
Material/equipment ($1000)		50	65			115
Facilities ($1000)		50	65			115
Vortex Formation and Low-Level Sloshing						
Manpower (man-years)	3	5	4			12
Material/equipment ($1000)	5	15	15			35
Facilities ($1000)	35	10	10			55
Capillary Systems for Zero-g Transfer						
Manpower (man-years)	2	3	7	4	2	18
Material/equipment ($1000)		20	45	25	10	100
Facilities ($1000)		15	55	10		80
Quantity Guaging in low-g						
Manpower (man-years)	2	4	5	4	2	17
Material/equipment ($1000)		35	55	55	10	155
Facilities ($1000)		25	50	50		125
Slush Hydrogen						
Manpower (man-years)	5	8	9	8	2	32
Material/equipment ($1000)	75	95	95	55	15	335
Facilities ($1000)	80	90	50	25	5	250
STRUCTURES						
Fracture Mechanics Material Properties						
Manpower (man-years)	3	5	4			12
Material/equipment ($1000)	25	55	45			125
Facilities ($1000)	45	20	10			75

TABLE 5.0-1 ISPLS Supporting Research and Technology Costs

	GFY 73	GFY 74	GFY 75	GFY 76	GFY 77	Total
STRUCTURES (Continued)						
Advanced Composite Structures Material Properties						
Manpower (man-years)	3	5	4	2		14
Material/equipment ($1000)	35	70	50	15		170
Facilities ($1000)	55	30	15	5		105
HIGH PERFORMANCE MULTILAYER INSULATION						
Processing Parameters for Embossment						
Manpower (man-years)	3	5	3			11
Material/equipment ($1000)	35	70				105
Facilities ($1000)	50	25				75
Bonding of Polymide Film						
Manpower (man-years)	3	4	2.5			9.5
Material/equipment ($1000)	30	60				90
Facilities ($1000)	30	10				40
Optimum Embossing Design						
Manpower (man-years)		4	5			9
Material/equipment ($1000)		35	45			80
Facilities ($1000)		25	20			45
105-inch Diameter Tank Test						
Manpower (man-years)		4	7	5		16
Material/equipment ($1000)		55	125	105		285
Facilities ($1000)		50	35	15		100
THERMODYNAMIC CONTROL						
Thermodynamic Vent System						
Manpower (man-years	3	5	3			11
Material/equipment ($1000)	70	80	45			195
Facilities ($1000)	65	35	10			110
Low-g Temperature Stratification						
Manpower (man-years)	2	3	2			7
Material/equipment ($1000)						
Facilities ($1000)						

TABLE 5.0-1 ISPLS Supporting Research and Technology Costs

	GFY 73	GFY 74	GFY 75	GFY 76	GFY 77	Total
SYSTEMS						
Logistic Tanker/Space Shuttle Interfaces						
Manpower (man-years)	1.5	2	2.5	2	2	10
Material/equipment ($1000)						
Facilities ($1000)						
Docking and Mating Fixtures						
Manpower (man-years)	2	4	4	2		12
Material/equipment ($1000)	40	50	25	10		125
Facilities ($1000)	60	25	10	5		100
Comparison of Modules vs Integral Tank						
Manpower (man-years)	5	7	2			14
Material/equipment ($1000)						
Facilities ($1000)						
Total Manpower (man-years)	47.5	86	78	32	9	253
Total Material/equipment ($1000)	377	790	625	270	40	2,102
Total Facilities ($1000)	500	550	350	115	10	1,525

with the vortex formation tests and the majority of the pull-through residual tests. However, in many of the tests, use of cryogenic propellant is required. Additionally some of the tests must be performed in special environments, such as low-gravity or high vacuum.

Manpower, costing, and schedules were determined by the above-mentioned considerations. Estimates are believed to be realistic and it is believed that the required results can, indeed, be obtained if the programmed funds and manpower are allocated.

5.1 PROPELLANT TRANSFER

5.1.1 Transfer Propulsion System with Long Duration Firing Capability

5.1.1.1 Problem Statement

The use of continuous linear acceleration for vapor/liquid interface control for transfer times of the order of 10 hours requires SR&T in the area of engine development. As thrust must be maintained for long durations, it is desirable that engine specific impulse be high. A value of specific impulse of 400 sec. has been used in the Trade Study Section of this report. This requires development of a LOX/LH_2 system.

However, existing technology in the thrust range of interest (about 10 lbs) is limited to earth storable propellant with lower values of specific impulse. Morever, even engines using storable propellants have not yet demonstrated long duration operations.

The life limiting factor influencing system and engine operation is the operational mode. The cyclic or pulsing mode, typical of attitude control systems, is the most stringent and limits manifest themselves in valve seat wear, thermal fatigue (expansion and contraction), injector erosion, and wear on bearings and other rotating equipment. On the other hand, steady-state operation, which permits the system to reach thermal equilibrium, minimizes wear from on-off operation and, of course, the fewer times the components are actuated, the longer they will last. As the transfer propulsion system is to operate continuously, the development problem is mitigated.

Although technological development of low thrust LOX/LH_2 engines is lacking, Rocketdyne has conducted a program for NASA-LeRC on a 1500 lb thrust, regenerative cooled LOX/LH_2 engine (Contract NAS3-14352). Based on a life analysis performed by Rocketdyne, the life of this engine is estimated as 1000 hours in the steady state mode. Such a life capability, if developed for a low thrust LOX/LH_2 engine (installed on the propellant module) would meet the life requirements of the transfer propulsion system.

5.1.1.2 Required Effort

Research, analysis, and testing leading to the development of a low thrust (about 10 lbs) LOX/LH_2 engine with specific impulse of 400 sec. is required. Analytic studies and test programs to assure thermal isolation of the engine valve and to prevent overheating of the thrust chamber should be conducted. These studies should be oriented towards determining the optimum combination of mixture ratio, film cooling and flow rate to control thermal degradation. This work should be oriented towards steady-state engine operation. However, some pulse mode testing should be included to assure stability under transient operating conditions.

5.1.1.3 Expected Results

A low thrust, LOX/LH_2 engine system with an overall specific impulse including system losses, of 400 sec. and a steady state life of several hundred hours will be developed. This system will provide continuous linear acceleration for vapor/liquid interface control for in-orbit propellant transfer.

5.1.1.4 Timing/Criticality

It is anticipated that engine system development will require three to five years. Therefore, work should be initiated in 1972. As the effort can proceed in parallel with the development of the logistic module, completion can be as late as early 1977 (beginning of the Phase C study).

5.1.2 Improved Data on Pull-Through Residuals for Various Tank Bulkheads and Baffles

5.1.2.1 Problem Statement

Vapor pull-through is caused by the non-uniform velocity of the flow into the outlet lines of the propellant module. As the liquid surface nears the outlet line the non-uniformities cause the interface to deform, leading to gas ingestion and noncomitant trapped residual. This study, as well as preceeding ones, has shown that pull-through residuals are a large portion of the total losses involved in transferring propellant. Furthermore, trade studies conducted in this study phase have shown that auxiliary propulsion system (APS) propellant used to generate thrust for vapor-liquid interface control acts to decrease pull-through residuals. These pull-through residuals and APS propellant losses, which constitute the majority of the propellant losses during transfer, are related. The trade studies show that transfer time and total propellant losses are very sensitive to pull-through residuals.

Previous work (Reference 5.1.2.1-1) has shown that pull-through residuals depend primarily upon tank geometry, Froude number, and Bond number. Reliable data are available for flat-bottomed tanks with an axisymmetric outlet under conditions of Bond numbers greater than 300, Reference 5.1.2.1-1, and Bond numbers less than 0.1, Reference 5.1.2.1-2. Experimental data at intermediate values of Bond number, which are often of practical interest, are lacking. The situation with regard to other geometries is considerably worse. NR/SD has developed data for various tank bottom geometries for Bond numbers above 300 (Reference 5.1.2.1-3) for limited ranges of D/d, where D is the tank diameter and d is the outlet diameter. The configurations studies were hemispherical bottom,conical bottom (45 and 30 degrees half angle), S-II reverse bulkhead type bottom, flat bottom with off-center outlet, and several bottom configurations with sump and/or baffle. The data from Reference 5.1.2.1-3 for hemispherical bottomed tanks, when compared to similar work done at NASA-LeRC (Reference 5.1.2.1-4) showed a factor of four discrepancy. This difference appeared to be due to different values of D/d and to data normalization techniques. For the other configurations,data at intermediate and low values of Bond number are generally lacking. Finally, future emphasis is anticipated in pull-through reduction techniques, such as use of a sump and pull-through baffles and screens.

5.1.2.2 Required Effort

a. Conduct one-g scale model tests for the baseline geometry of the logistic tanks over a range of Froude numbers for several values of D/d. Present baseline geometry for logistic module tanks is as follows:

   For Tug and CIS - Reverse bulkhead, S-II type tank for LH_2.
   Forty-five degree conical bottom tank for LOX.

   For RNS - Elliptical bottomed tank with pull-through baffle for LH_2.

   Photographic measurements of pull through residuals will be made.

b. Conduct one-g scale model tests over a range of Froude numbers for alternatives to the LOX tank conical bulkhead and for improved tank outlet configurations. These configurations will incorporate a sump and/or baffles and screens. Additionally, the effect of anti-vortex and low level anti-slosh baffles on pull-through residuals will be established by model tests.

c. The above tests as they are conducted at one-g are of necessity conducted at Bond numbers above 300. These data will be adequate to similate accelerations as small as 3 X 10^{-3} lb f/lb m for the logistic modules. However, transfers are expected to take place under an acceleration level of 10^{-4} to 10^{-5} lb f/lb m at which level Bond numbers are sufficiently low that capillary effects become of some importance. Therefore, a limited number of drop tower tests of the pull-through phenomenom should be conducted. These tests should be conducted on the selected configurations over a small range of conditions near that of the normal design. Photographic measurements of pull-through residuals are to be made.

5.1.2.3 Expected Results

Pull-through residuals will be characterized as a function of D/d and Froude numbers for the baseline configurations. Performance verification of the LOX tank conical bulkhead will be obtained or an alternate bulkhead chosen and tested. Advantages associated with the use of a sump and/or baffles and screens will be assessed. Optimized outlet configurations will be identified and tests conducted to predict residuals for these configurations as a function of D/d, Froude number, and Bond number.

5.1.2.4 Timing/Criticality

As the proposed type of testing has been done before for simpler configurations, and the tests are relatively straightforward compared to, thermodynamic tests, it is anticipated that this work can be accomplished shortly after the end of Phase A. Accomplishing this work at this early time will provide visibility and enhance flexibility. However, this timing is not critical and the test program could slip to the end of Phase B without serious impact.

5.1.3 Vehicle and Propellant Dynamic Interaction

5.1.3.1 Problem Statement

Transfer of propellant from the logistics vehicle to the user vehicle causes dynamic interactions between the propellant and the vehicle combination. The magnitude of the interaction problem increases as the ratio of propellant weight to total weight increases, and the problem exists with the three preferred methods for achieving propellant positioning (linear acceleration, centrifugal acceleration, and capillary devices).

Aside from the dynamic forces introduced by propellant transfer, fluid behavior is affected by changes in vehicle motion due to the firing of attitude control system (ACS) thrusters and docking impact. The firing of ACS thrusters and docking impact result in new mass distributions due to induced propellant sloshing. An understanding of the transition mechanism from one fluid mass distribution to another is required to permit design of a workable ACS. Without this understanding, the sloshing and thruster firing (to counteract the sloshing) may reinforce the kinetic energy of the system and promote vehicle oscillation. Similarly, design data are required for establishing an ACS rate damping mode for damping vehicle and fluid oscillations produced during docking operations. During attitude hold operations, the periodic firing of ACS thrusters will cause the stored propellants to oscillate in some manner related to the thruster firing frequency. Data concerning the amplitude of the propellant oscillations and the phase relationship between thruster firing and fluid sloshing are needed to determine the upper and lower bounds of thruster size and acceptable limit cycle frequency.

5.1.3.2 Required Effort

The means available for the prediction of propellant behavior in large tanks during transfer is considered inadequate. Analyses and experiments are required to provide data for math model verification and update prior to the selection of an optimum logistics module and user vehicle design. To obtain the necessary data, the effort outlined in the following task statements is proposed.

a. Using existing computer programs and empirical data, perform an analysis of propellant hydrodynamics during transfer and establish dynamic interaction effects. Include in the math model the influences on fluid behavior of the following variables:

   1. Momentum of entering fluid

   2. Viscous damping

   3. Acceleration level

   4. Capillary forces

Establish the conditions under which fluid dynamic behavior will result in:

1. Premature uncovering of the source tank outlet

2. Inability to assure liquid-free vapor return from the receiver to the source tank
3. Use of excessive amounts of propellant for attitude control

b. Determine the slosh damping effect of adding baffles, screens, and/or inlet diffusers to source and receiver tanks. Perform tradeoff studies of the additional weight and complexity of these devices against the reduction in ACS propellant usage during transfer.

c. Perform a literature search and tabulate applicable theories and data for low-g slosh behavior. Compare these data with study objectives and establish required additions to data.

d. Derive a set of exact analytical equations relating vehicle dynamics to docking impact, ACS thruster firing, internal mass flow rates, and internal slosh mass distributions. These equations will involve the fluid/vehicle tank interface dynamics and fluid properties in addition to the basic body dynamics. Simplify the equations in order to permit the derivation of approximate solutions by analysis and/or digital simulation. Develop a comprehensive digital computer program for simulating dynamic phenomena with the exact equations. Using both the simplified and comprehensive programs, determine the influence of representative disturbances on propellant dynamic behavior. Determine this influence as a function of the ratio of propellant weight to total weight and as a function of propellant transfer phase (beginning, middle, or termination).

e. With the vehicle/propellant transition dynamics (described as time functions of disturbances in Task d) as input, use an operational 3-D attitude control program for stability studies. Obtain stability boundaries as functions of slosh influences. Identify slosh parameter sensitivities and select influence phenomena for test verification. Develop ACS compensation logic for various propellant slosh influences. Identify areas of contradictory requirements between slosh and attitude control.

f. Using the results obtained in (a) through (e), identify desirable, required, and mandatory zero-g test requirements. Define test facilities necessary to satisfy these test requirements. Prepare detailed test plans. Fabricate test hardware and provide facilities.

g. Conduct experiments to verify predicted vehicle and propellant dynamic behavior. These experiments will involve one or more of the following:

1. One-g tests

2. Drop tower tests

3. Zero-g tests in a KC-135 aircraft

4. Zero-g tests on board Skylab

h. Correlate test results with propellant and vehicle behavior predicted by analysis. Modify computer programs as necessary to obtain the desired agreement between analysis and experiments.

5.1.3.2 Expected Results

Completion of this effort will result in a computer program, backed up by experimental data, for a parametric study of propellant slosh characteristics and vehicle dynamic interactions. This program can then be used for establishing ACS thruster size, and acceptable limit cycle frequency, methods for vehicle stabilization, methods of efficient slosh control, and methods of vapor/liquid interface control.

5.1.3.3 Timing/Criticality

This work should be completed by the end of Phase B to support specification of vehicle and subsystem design requirements and operational characteristics.

5.1.4 Vortex Formation and Low Level Liquid Sloshing

5.1.4.1 Problem Statement

In this present study phase the pull-through phenomenon has been emphasized, compared to other logistic module vapor/liquid interface disturbances. Pull-through residuals were important in establishing auxiliary propulsion system propellant requirements, total propellant requirements, and preferred transfer times. However, during transfer for low liquid levels in the logistic module, sloshing can aggravate the pull-through problem and increase residuals. Vortex formation due to induced propellant swirling is potentially more deleterious than the pull-through phenomenon because vortex formation may occur at any time during the transfer while pull-through is limited to low liquid levels.

In the past, for booster and spacecraft propulsion systems, the above problems have been prevented by anti-vortex and anti-slosh baffles (References 5.1.4.1-1 and 5.1.4.1-2). Similar hardware fixes are expected to be applicable to in-orbit propellant transfer; however, the low-g levels, long transfer times, and spacecraft perturbations and orbital dynamics may require new baffle design, and, in addition, may entail operational constraints during transfer.

5.1.4.2 Required Effort

Analyses should be conducted to establish upper and lower limits on the vorticity that might be added to logistic module propellant prior to and during orbital propellant transfer to the representative user vehicle. In performing this evaluation, due consideration must be given to vehicle configuration and attitude, orbit, anticipated perturbations and maneuvers, and mission and transfer time duration. Work done for the "Vehicle and Propellant Dynamic Interaction" task will be utilized where possible. Based on vorticity generated, tank geometry, and acceleration level an assessment is to be made of the potential for vortex formation, the intensity of the vortex, and the concomitant free surface deformation. Based on this assessment, anti-vortex baffle design requirements should be formulated. A test program should be conducted to verify the performance of the anti-vortex baffle design.

The "Vehicle and Propellant Dynamic Interaction" task should be utilized to determine the range of propellant sloshing characteristics expected at low liquid levels. Propellant anti-slosh baffle design requirements should be formulated for these low liquid levels. A test program should be formulated to verify that the anti-slosh baffle will perform as required.

Finally, results of these studies should be utilized in the "Pull-Through Residual Prediction and Reduction," Task, paragraph 5.1.2. In particular, pull-through tests should be conducted with the anti-vortex and anti-slosh baffles in place, to determine the effect of the baffles on pull-through residuals. Baffle modification required so as not to compromise the anti-pull-through function should be developed.

5.1.4.3 Expected Results

The propensity for vortex formation and low liquid level slosh will be determined. Design provisions to prevent or control these deleterious effects will be formulated. Tests will be conducted to verify the performance of baffle design. The effect of these baffles on pull-through residuals will be determined and modifications developed.

5.1.4.4 Timing Criticality

This work should be completed by the middle of Phase B to support conceptual vehicle design and allow timely interaction with the pull-through residuals task.

5.1.5 Capillary Systems for Zero-G Transfer

5.1.5.1 Problem Statement

Although trade studies conducted in this study show that the preferred vapor/liquid interface control technique is linear acceleration, there are some major advantages associated with the use of a capillary system for propellant acquisition and vapor/liquid interface control. Use of such a system permits an appreciable reduction in auxiliary propulsion system propellant usage for thrust generation. This method of interface control requires no moving parts, reduces appreciably maneuver requirements compared to linear acceleration, and is compatible with a wide range of receiver configurations (i.e., c.g. location is not as important if only limited maneuvers are involved).

The proposed capillary system consists of capillary collector tubes in the logistic module tanks for propellant acquisition from any region of the tanks under very low g conditions. The tanks in the receiver vehicle require fill and vapor/liquid interface control baffles to permit orderly filling and vapor return to the logistic module tank. A number of technology problems must be solved if capillary devices are to become a practical alternative. In particular, liquid-free vapor return to the logistic module tank under low g conditions when the receiver tank is, say, more than 2/3 full may be most difficult. Vapor/liquid interface control baffles are proposed to provide the vapor return capability. However, the ability of these baffles to cope with propellant sloshing due to maneuvers or disturbances is not proven at this time. The critical problem as regards the logistic module is the integration of the thermal control system with the capillary system. The requirement that the capillary devices contain sub-cooled propellant must be compatible with propellant temperature and tank pressure requirements.

5.1.5.1 Required Effort

Supporting research and technology effort for the logistic module capillary system should use the results of the recently completed "Cryogenic Acquisition and Transfer" Study (Reference 5.4.2.1-1) as a starting point. Among the problems addressed in that study were design requirements for steady state feedout of adversely located propellant as well as the thermodynamics of the capillary collectors during hot gas pressurized feedout and during long term coast. Follow-on work should include the following tasks:

a. For a variety of capillary collector geometries and designs, determine hydrodynamic stability and structural integrity during flow start-up and shut down transients.

b. Verify flow loss characteristics of various capillary collectors and associated manifolds, elbows, etc.

c. Evaluate alternate collector designs and configurations to minimize logistic tank trapped residuals.

d. Establish the compatibility of the capillary collectors with the thermodynamic control system, including verification that vapor formation within the collectors can be prevented or held to negligible levels.

The four tasks above involve primarily subscale experimental tests at one g. Tasks (a) and (b) require non-cryogenic testing with limited confirming experiments with cryogenic propellant. Task (c) requires limited verification testing under low-g conditions. Potential test facilities for these tests are the drop tower, the KC-135 aircraft, and Skylab. Task (d) requires a comprehensive test program using cryogenic propellant. For this last task the effect of various parameters will be investigated including collector design, type of thermodynamic control system, percentage helium in ullage, and ullage fraction.

SR&T is also required to support the design and operational capability of the user vehicles. Here the bulk of the testing will require a weightless condition. A small amount of refill testing of the baseline design should be conducted under weightless conditions to verify that orderly refill can be achieved. The required testing can be limited because it is anticipated that the drop tower tests conducted by NASA-LeRC will provide the bulk of the required data.

To assure that liquid-free vapor return can be realized, the capability of the baffles to control the vapor/liquid interface during maneuvers and perturbations must be proven. Towards this end drop tower tests where the model tank is translated or rotated (pitch or yaw) during the free fall in a manner to simulate the range of expected disturbances should be conducted. Various baffle configurations should be investigated. Confirmation testing with a scaled-up model should be conducted in the KC-135 or Skylab. Cryogenic fluid need not be utilized in these fluid dynamic experiments.

5.1.5.2 Expected Results

For the logistic module the proposed program will yield basic data on fluid flow and thermodynamic phenomena within the capillary collectors. Hydrodynamic stability, flow losses, trapped residuals and propensity for vapor formation will be determined for a variety of capillary collectors. The above results will provide the basis for a choice of an efficient reliable capillary collector design and thermodynamic control technique.

For the user vehicle the proposed program will provide sufficient data to allow specification of refill and vapor/liquid interface control baffle design requirements. Selection of a baseline baffle system can be accomplished with a high degree of confidence.

5.1.5.3 Timing/Criticality

The work must be well along by the beginning of Phase B to permit a timely evaluation of capillary systems as an alternative to linear acceleration for vapor/liquid interface control. The SR&T effort must be completed by the beginning of Phase C to support the design effort, should capillary systems be selected for vapor/liquid interface control.

5.1.6 Quantity Gauging in Low Gravity Environment

5.1.6.1 Problem Statement

Gauging of cryogenic propellant in a low or zero-g environment remains a critical technology area. Technology development emphasis over the past decade has been on radio frequency gauging, sonic gauging, and nuclear radiation gauging with the intent of developing a zero-g capability. The objective of this work has been to develop systems that would function reliably for any distribution of liquid and vapor (e.g., sloshing liquid, froth, etc.). To date, this work has not been fruitful in leading to the development of a reliable, accurate zero-g gauging system.

It is believed that violent agitation is an exceptional situation and certainly not one for which a vital gauging requirement exists. As the present baseline employs low-g thrusting for vapor/liquid interface control, it is appropriate to develop a gauging system for propellant under reasonable control in a low-g (10^{-4} to 10^{-5} lb f/lb m) field. Two possibilities to achieve this end are point sensors which are contoured to prevent capillary wetting, and continuous sensors in the form of a thin resistance-type wire covering the desired length of the tank. Such a wire, because of its small diameter and vertical mounting, would have only a tiny meniscus. Of course, a correction would be required for the meniscus at the tank wall and at tank internal hardware. Both approaches are based on the principle that heat transfer from an electrically heated wire is different depending upon whether the wire is in liquid or vapor. This is reflected in changes of temperature and electrical resistance of the wire which can be measured remotely as an indication of wetting. The same basic principle was used for the existing Saturn S-II point sensors, except that capillary effects and heat transfer rate variation with acceleration level was of little concern for the S-II high acceleration level.

The major problem associated with the use of resistance wire is that heat transfer from the wire will differ greatly over the 10^4 to 10^5 fold range in acceleration level from earth to orbital conditions. To overcome errors introduced by stray resistance changes and variations in heat transfer conditions, it may be necessary to use self-calibration techniques and circuitry. One of the techniques considered involves the alternate application of a high and low current level to each sensor to calibrate its inflight resistance at ambient temperatures vs self-heating temperatures. These functions could be handled automatically by the on-board general purpose computers and data processing equipment presently planned on new-generation space vehicles.

5.1.6.2 Required Effort

A preliminary analysis followed by a test program is required. The analysis will identify favorable point sensor and continuous sensor designs, including configuration and materials, as well as determine instrumentation requirements and current levels. The first phase of testing will be conducted at one-g using model and cryogenic fluids. Cryogenic testing will be conducted in a low heat leak dewar system at current levels appropriate to one-g conditions. Heat transfer from the electrically heated wire to the liquid and vapor phases is affected by the acceleration level. The very low acceleration levels of space will result in roughly a 10-to 20-fold decrease in free convection heat transfer rates and are likely to change the mechanism of heat transfer from free convection to conduction or film boiling.

As severe difficulties are expected in simulating all of the aspects of low-g heat transfer at one-g conditions, low-g testing will also be required. A progression of testing is required, proceeding from drop tower tests, through KC-135 tests, to long-term orbital tests in the Skylab or post-Skylab orbital test beds. These tests will investigate low-g capillary wetting (meniscus effect) and heat transfer phenomena associated with low-g gauging applications.

5.1.6.3 Expected Results

Materials, operating conditions, and instrumentation required for discrete or continuous heated wire systems for low-g gauging applications will be determined. Preferred designs and instrumentation will be identified from one-g testing. Low-g testing will determine necessary modifications to provide accurate, reliable low-g gauging systems for LOX and LH_2.

5.1.6.4 Timing/Criticality

Low-g quantity gauging presents formidable development problems and supporting research and technology will be required through the beginning of Phase C.

5.1.7 Hydrogen Slush Manufacture, Storage, and Transfer

5.1.7.1 Problem Statement

Slush hydrogen, SH_2, has been evaluated for potential application to the propellant logistic program in Volume 3 of this report. There it was shown that the advantages of slush over normal boiling point hydrogen depend greatly on user vehicle size, traffic model, and propulsion system duty cycle.

For user vehicles which require large quantities of hydrogen and for which many missions are programmed the use of SH_2 may be feasible. With a high-rate traffic model the anticipated large costs of developing SH_2 facilities, equipment, and technology can be amortized over more flights which may yield lower costs per pound of SH_2 placed into orbit. Thus it is unlikely that SH_2 can be applied economically to low level space programs or where the tug is the main user. However, for the more ambitious programs where the CIS or the RNS stage are the primary propellant users, significant cost savings may be realized. Application of SH_2 to these programs depends upon technology advances in several areas. These technology problems are described in Volume 3 and therefore are only enumerated below:

a. Compatibility of low vapor pressure of SH_2 with atmospheric pressure during ground handling.

b. Manufacturing state-of-the-art advances, e.g., manufacturing SH_2 directly in the tanker.

c. Instrumentation and measurements

d. Rheological properties

e. Temperature stratification

f. Percolation in dead-ended lines.

g. Aging process

h. Special provisions for orbital transfer

Investigations in most of these problem areas have been and are presently being conducted at NASA/MSFC, National Bureau of Standards, Government contractors, etc. Schedule and costing data assume the continuing use of these facilities, modified as required, to support the logistic module requirements for SH_2.

5.1.7.2 Required Effort

a. Investigate hydrogen slush manufacturing and transfer techniques applicable to the propellant module. Based on this investigation develop a procedure for loading slush into a propellant module designated to fit into the cargo bay of the space shuttle and featuring thin-walled, lightweight construction. Include in the procedure considerations for thermal stratification and details of a helium pressurization technique to prevent collapse of the module due to negative pressure differentials during ground operations. Identify requirements for special equipment, e.g., transfer pump, mixers, and helium pressure expulsion.

b. Develop procedures and instrumentation for the measurement of hydrogen slush mass and quality.

c. Conduct analyses to establish operations and design requirements for storage of SH_2 in the propellant modules on the ground, during boost, and in orbit prior to transfer.

d. Conduct analyses to establish special procedures and design requirements for orbital transfer of SH_2.

e. Conduct a sub-scale test program at one-g to verify the analyses of tasks a, b, and c, and to obtain data to design zero-g tests to verify task d.

f. Conduct drop tower and KC-135 tests to obtain data to support and confirm the analyses of task d. If required, plan and conduct a post Skylab orbital test to assure that desired performance and system functioning will be achieved. Manpower and cost for this orbital test are not reflected in Table 5.0-1, as it is not clear at this time that such testing will be necessary.

5.1.7.3 Expected Results

The required technology to manufacture, store, and transfer SH_2 for propellant module applications will be achieved.

5.1.7.4 Timing/Criticality

Considerable work on this alternative needs to be conducted. Work must continue until the beginning of Phase C to complete all of the required tasks, and yet allow support of the Phase C effort.

5.2 STRUCTURES

5.2.1 Fracture Mechanics Material Properties

5.2.1.1 Problem Statement

The fracture mechanics analytical procedures for selecting the material and determining the necessary skin thickness for the pressurized tanks require that three material properties be known:

K_{IC}	Critical plane strain-stress intensity
K_{TH}	Stress intensity at which a given flaw will continue to grow under a sustained load.
da/dN	Flaw growh rate for different cyclic variations in stress intensities (K)

Utilizing these properties, it is possible to determine the largest flaw which could exist in a pressurized vessel after a proof test and the amount of flaw growth which would occur during the operational cycles, such that no flaw growth would occur under sustained load and the flaw could not grow through the thickness of the material.

The material properties indicated above are available for many materials, including 2219-T87 and 2014-T651 aluminums being considered for the propellant tanks of the logistic module. However, when dealing with very thin materials (less than 0.2 inches) the commonly accepted values of K_{IC} and K_{TH} are no longer applicable. The thickness of material being considered for the logistic module design is generally less than 0.1 inch. Therefore, material properties must be developed for the materials and thickness ranges being considered.

Without these data it would be impractical to perform a fracture mechanics analysis of the propellant tanks. With no fracture mechanics analysis, it would be necessary to apply an additional safety factor to the propellant tanks to guard against failure resulting from undetected flaws. The impact of the resulting high safety factor would be an unnecessarily heavy logistic module with reduced LOX/LH_2 payload capacity.

5.2.1.2 Required Effort

A fracture mechanics material properties test program is needed to provide sufficient data to enable the final selection of the propellant tank material and to establish material properties so that a fracture mechanics analysis of the final design can be performed. The program will involve obtaining data on at least two materials being considered for the propellant tanks and will include parent and welded metal testing to determine:

a. Failure stress vs initial flaw size for various flaw configurations (long, short, shallow, and deep).

b. Sustained load flaw growth threshold stress vs flaw size for various flaw configurations.

c. Spot check of flaw growth rate data (da/dN) to assure that existing data are valid in the thickness ranges being considered.

Data will be obtained at room and cryogenic temperatures for three different thicknesses in the thickness ranges being considered.

5.2.1.3 Expected Results

Initial data received from the test program will be used to screen and select the material to be used in the design of the propellant tanks. Subsequent data will provide remaining information needed to develop the design curves required for performing a fracture mechanics analysis.

Results of the test program and subsequent analysis will dictate the proper operating stress of the propellant tanks. The data will also indicate which proof test, pneumostat test, or cryoproof test will be most effective in verifying structural integrity of the tanks. The final product of the program will be the ability to design an efficient lightweight propellant tank structure for the logistics module.

5.2.1.4 Timing/Criticality

The development of the fracture mechanics material properties is considered essential to the logistics module development program and critical in terms of selection of the material, establishment of realistic design margins, and, hence, attainment of realistic propellant tank design weights.

Consequently, the test program should be initiated before the Phase B system study so that material selection can be made during this phase. Complete fracture mechanics material properties for the selected material must also be made available at initiation of the Phase C effort so that final sizing of the propellant tanks can be accomplished.

5.2.2 Advanced Composite Structure Material Properties

5.2.2.1 Problem Statement

Extreme emphasis on low inert weight for the logistics module design necessitates the consideration of advanced composite materials. Current technology, which is adequate for fabrication, consists of hand layup techniques in conjunction with some mechanized equipment used for flat panel layups and filament winding of tubular structures similar to that used in aircraft design. Since the aircraft industry is the major user of composite materials and is not concerned with cryogenic temperatures, sufficient data for reliable design allowables at cryogenic temperatures is limited. Consequently most of the cryogenic mechanical property data being used for design are based either on engineering judgement or extrapolation from limited cryogenic test data.

5.2.2.2 Required Effort

Design allowable data will be generated at room temperature and -300°F for boron epoxy, graphite epoxy and S-glass filament wound composites which are being considered for the logistics module. Properties to be determined include orthotropic values of F_{tu}, F_{cu}, F_{su}, E, E_c and G. The investigation will also evaluate effects of layup orientation, composite thickness, fastener attachment parameters (optimum hole diameter and spacing), and specimen configuration.

5.2.2.3 Timing/Criticality

This research should be accomplished prior to the completion of the Phase B program study so that the influence on system design analysis and program costing can be evaluated.

5.3 HIGH PERFORMANCE MULTILAYER INSULATION

5.3.1 Processing Parameters for Producing a Permanent Embossment Pattern in Plastic Film Used for Multiple Layer Insulation

5.3.1.1 Problem Statement

The most efficient thermal insulation, per unit weight, for cryogenic liquid tanks consists of multiple layers of thin plastic film which have been metallized and embossed. The embossment pattern minimizes direct thermal conduction through the insulation by maintaining space with minimum direct contact area between film layers. Other types of multiple layer thermal insulation systems use flat layers of film or foil which are held apart with mechanical spacers that add additional weight and bulk to the insulation system.

The embossment pattern in plastic film material normally tends to flatten out when the film is exposed to elevated temperatures. Embossed polyester (Mylar) film loses embossment height during exposure to temperatures as low as 140 F. The loss of embossment height by plastic films depends on many factors which have not yet been quantitatively established.

These factors include time and temperature used to produce the embossment pattern in the film, and the post-embossment exposure conditions of temperature and compressive load for specific time intervals. The generic type and the thickness of the film are also important factors. Since the multiple layer insulation used on the logistics module will be exposed to 200°F in service, Mylar film is inadequate for this application.

The embossed shield material is procured commercially and the patterns utilized to date were chosen on basis of availability, but were not optimized to provide the best reflective surfaces. Recent procurements by NR have also demonstrated that suppliers cannot duplicate prior orders; therefore, successive batches are unpredictable.

Because of these two conditions, the following problems relating to the material must be solved.

a. Identify a better substrate material than Mylar and/or develop a superior embossing technique. Kapton film is believed to be the best available candidate material, but its ability to hold a deep embossment has not been shown.

b. Analyze the commercial patterns provided by suppliers, determine how the patterns should be changed to provide optimum layer density, fabricate experimental patterns as determined in (a) and demonstrate acceptability. A plan is needed to ensure that commercial suppliers can produce the material with the optimized embossment pattern.

5.3.1.2 Required Effort

a. Polyimide (Kapton) film material, one-quarter mil thick, is to be embossed at various temperatures up to 750°F for various time periods up to 15 minutes. The Kapton film is a good candidate because it has high temperature resistance and is available in relatively thin gages. Specimens of Kapton film embossed under each of several different conditions of time and temperature are to be measured to determine their embossed thickness and linear dimensions. The specimens are then to be exposed to a temperature of 200°F for one hour while under a compressive load of 0.1 psi. After cooling, the embossed thickness and linear dimensions of the specimens are to be remeasured and the effects of the exposure to temperature determined. The effect of 10 exposure cycles of 200°F for one hour under a 0.1 psi load is to be determined for the specimens by the same method.

b. Samples of materials provided by various suppliers for prior programs will be analyzed to determine the number of peaks in the embossment pattern per unit area. Suppliers will be contacted to determine if other patterns are available. New patterns will be defined to optimize the depth of embossment and the number of peaks per unit area. Samples will be produced using the materials and techniques developed in (a). These will be tested to demonstrate acceptability. A plan will be set up to coordinate production and quality control of the optimized pattern by commercial suppliers.

5.3.1.3 Expected Results

a. This test program is expected to establish processing parameters for producing an embossment pattern in Kapton film which will remain dimensionally stable during exposure to 200°F under low compressive loading. Kapton film was experimentally embossed at a relatively low temperature and did not have as deep an embossment pattern as is desired for multiple layer insulation film. However, the specimen did show that Kapton film can be embossed. Because Kapton is a thermosetting plastic, it can be expected to retain its embossment pattern better during heating than does Mylar, a thermoplastic material

b. The results of this program are expected to identify causes of discrepancies in prior studies. It is also expected that this program, when coupled with improved metallized coatings and commercial production techniques, will provide a superior insulation system with optimum thermal performance, low weight and simple manufacturing characteristics.

5.3.1.4 Timing/Criticality

Development of this embossing procedure is required in time to assure that the environmental conditions which will be imposed on the insulation system during purging of the insulation and entry heating inside the cargo bay will not degrade the embossment pattern. Therefore, the research should be accomplished prior to the end of the Phase B study.

5.3.2 Bonding of Polyimide (Kapton) Film to Itself

5.3.2.1 Problem Statement

During fabrication of multiple layer insulation systems, it is necessary to join individual sheets of film together along the edges to produce continuous layers of film which will not shift during mechanical loading in service. Where polyester (Mylar) film is used, the edges of the film can be quickly heat-bonded together. However, where higher service temperatures are expected, as in the case of the logistic module, it will be necessary to use polyimide (Kapton)film. Kapton film is thermosetting and is not heat-sealable. Therefore, some method must be developed for bonding Kapton film to itself.

To solve this problem, the duPont Co. manufactures a form of polyimide film, designated Kapton Type F, which is coated on one surface with FEP Teflon resin to produce a heat-bondable surface. However, this type of material is unsuitable for multiple layer insulation, both because the weight of the Teflon resin coating causes an unacceptable increase in the insulation density and because metallizing the uncoated surface of the polyimide results in processing difficulties. For example, Teflon could contaminate the opposite surface of the film and prevent good adhesion of the metallized coating, or the heat-rise which occurs during metallizing could cause premature bonding of the film. Several different types of adhesives are recommended by duPont for bonding polyimide film. None of these adhesives is considered acceptable for fabricating cryogenic insulation systems because they all require either a heat cure for at least twenty minutes or a much longer room-temperature cure.

On the basis of the foregoing information it appears that the most acceptable method for bonding polyimide film to itself is to apply an FEP Teflon dispersion coating locally to cut sections of film where the material is to be bonded during fabrication and installation of the insulation. The material can then be heat bonded easily and quickly, using a conventional hand-operated heat sealer. The FEP Teflon dispersion coating can be applied to local areas of polyimide film either by spraying or brushing. Teflon coatings applied by this procedure do not adhere to film as well as commercially applied heat-bondable coatings which usually are heat-cured onto the film. However, these dispersion coatings do adhere well enough to remain intact during normal handling of the film in fabricating the insulation system, and following the heat-bonding operation the FEP Teflon can be expected to exhibit good adhesion to both film surfaces with which it is in contact.

5.3.2.2 Required Effort

Various quick-setting cements will be obtained and tested to determine their bonding strength and curing times when used to bond Kapton film to itself. Also, various FEP Teflon dispersion coatings will be applied to Kapton films which will then be heat-bonded together at various temperatures, pressures and time intervals. The resulting heat bonds will be tested to determine their strength.

The efficiency of each of the bonding methods investigated will be determined at cryogenic, room temperature, and the maximum expected service temperature of 200°F. In addition, Eastman 910 cement and Devon Corp. "Zip Grip" 10 cement which cures in a matter of seconds at room temperature, should be tested as adhesives for Kapton film. Cements with appreciably longer curing times would increase fabrication time of the insulation system and would not be acceptable.

5.3.2.3 Expected Results

The test results are expected to identify both a quick-setting adhesive for Kapton film and a system for heat-bonding Kapton film. The adhesive-bond and heat-bond are both expected to be acceptable for service temperatures up to 200°F.

5.3.2.4 Timing/Criticality

Development of a procedure for bonding Kapton film to itself is necessary to assure proper fabrication of multiple layer insulation systems over the liquid hydrogen tank on the logistic module. Therefore, the research should be accomplished during the Phase B study.

5.3.3 Calorimeter Test of Optimized Embossed Multiple Layer Insulation

5.3.3.1 Problem Statement

Recent studies and test programs at NR show that lightweight high performance multi-layer insulation systems can be produced utilizing commercially supplied embossed aluminized Mylar for reflective shields. These programs disclosed that best thermal performance occurs when natural shield density is 30 to 40 layers per inch. Substituting Kapton for Mylar raises the operating temperature limit from +140 F to approximately +300 F (as required for the logistic module).

Test programs were proposed in paragraph 5.3.1.2 to optimize the embossment pattern and to develop techniques for embossing the Kapton material. Laboratory tests are proposed to verify the adequacy of the new pattern and procedures. A calorimeter test is needed to verify thermal performance of a system utilizing the new patterns and material in the cryogenic environment.

5.3.3.2 Required Effort

After the optimized material becomes available, a test program will be conducted in which a guarded calorimeter will be insulated with the new material. It will be tested with LH_2 in a chamber capable of maintaining a vacuum below 10^{-4} Torr.

Following the test runs in which structural integrity and thermal performance will be determined, the specimen will be sectioned. Coordinating data will be obtained from flat plate calorimeter.

5.3.3.3 Expected Results

This test program is expected to demonstrate thermal performance of the optimized embossed aluminized Kapton multilayer insulation system. The system is expected to be competitive with other concepts yet weigh less.

5.3.3.4 Timing/Criticality

Demonstration of this concept and these materials is necessary to assure proper selection of an insulation system for the logistics module. Therefore, the program should be accomplished prior to the end of the Phase B study.

5.3.4 105-Inch Diameter Tank Insulation System Test

5.3.4.1 Problem Statement

Studies are currently underway to develop a lightweight, high performance insulation system concept using commercially produced embossed aluminized Mylar for the reflective shields. It has been shown that performance can be improved up to 50 percent by optimizing and stiffening the embossment pattern. It was also shown that the shield material should be changed to Kapton if the system will experience compressive loads at temperatures in excess of +150°F.

Studies are proposed in paragraph 5.3.1.2 to optimize the embossment pattern and to provide the procedures for producing the pattern in Kapton. A study is also proposed in paragraph 5.3.3.2 to permit small scale calorimeter tests on this material.

An additional study is required to extend the material development technology to large scale tests and to verify the insulation performance and weight. NR recommends the use of an existing tank such as the 105-inch diameter tank and test facility at NASA/MSFC (which is currently being used to test aluminized Mylar insulation) to minimize costs and to ensure compatibility in results with prior system tests.

It will be necessary to obtain sufficient satisfactory insulation material to apply to the large scale tank; develop the proper techniques for applying, inspecting, and repairing the insulation; and to conduct tests on the large scale tank to verify thermal performance of the installed insulation system.

5.3.4.2 Required Effort

a. From prior studies the optimized embossment pattern will be defined by the number of peaks per square inch, depth of embossment, shape of peaks, dips, etc. Process procedures for embossing the pattern on Kapton will be defined in terms of temperature of embossment process, time, chill rate, chill temperature, contact pressure, etc. Additional definitive materials properties data will be available from the prior lab studies. Capability of commercial suppliers to repeatedly produce the material will be evaluated and adequate material obtained.

b. An insulation system will be designed for the large scale calorimeter. An application model will be selected prior to start of the design. The insulation system design will be limited to the features necessary to evaluate the performance and determine operational characteristics of the materials and the concept.

   A natural-lay spacerless configuration will be utilized and will be oriented to provide maximum thermal performance with least weight penalty for the application model profile. The insulation system will be installed by manufacturing personnel with normal quality control inspection. Records will be kept to enable evaluation of producibility of the embossed Kapton compared to other materials and concepts.

c. After the insulation system is installed and checked, it will be shipped to the facility selected for testing. Tests will be of sufficient number to ensure both thermal and structural performance characteristics are measured and evaluated.

5.3.4.3 Expected Results

This program is expected to result in definition of installation, inspection, and repair procedures for fabrication of lightweight, high performance multilayer embossed insulation systems. Thermal and structural performance of the Kapton insulation system will be thoroughly evaluated with respect to other materials, combinations, and concepts.

5.3.4.4 Timing/Criticality

Assurance of availability of these enhanced materials is necessary in time to permit selection of a high performance insulation system that will ensure minimum payload penalty. It should therefore be complete prior to end of Phase B study.

5.4 THERMODYNAMIC CONTROL

5.4.1 Thermodynamic Venting System (TVS)

5.4.1.1 Problem Statement

In a low gravity environment, the containment of a cryogenic liquid is complicated by the lack of positive control of the position of the liquid and gas phases. During orbital flight prior to propellant transfer there will be, in general, no provision for positive control of the vapor/liquid interface. Boiloff vapors must be vented, or else energy must be removed from the propellant tanks to control the tank pressure. The potential loss of propellant by entrainment of liquid in the vented vapor makes usage of a thermodynamic vent system, to ensure vapor venting alone, a necessary requirement.

The thermal control system considered for control of logistics module internal thermodynamics, includes some form of thermodynamic vent heat exchange. The thermodynamic vent heat exchange system includes an expansion valve where LH_2 is throttled to a relatively low pressure and temperature. This provides the necessary temperature differential for extraction of heat from the propellant by an appropriate heat exchanger. Reliable analytical procedures have not been fully developed for this form of venting. Although the feasibility of this vent concept, using compact heat exchangers and mixers, has been experimentally established at one-g, it remains to be demonstrated at low gravity.

5.4.1.2 Required Effort

Experimental one-g tests for simulation of the low gravity internal tank thermodynamics for a cryogenic propellant, in conjunction with the operation of a TVS, should be performed.

An outline of the one-g TVS fabrication and test program for a wall mounted heat exchanger is given below:

a. Define operational parameters

   1. Heat loads to tank walls
   2. Acceleration field
   3. Tank sizes, wall thicknesses, type of metal
   4. Pressure levels

b Determine scaled test parameters for one-g earth experiment for scaled tank (high vacuum chamber tests anticipated).

c. Determine thermodynamic vent operational requirements for zero g

   1. Propellant flow rates
   2. Tube spacing
   3. Attachment points
   4. Two-phase heat transfer
   5. Throttle valve sizing

d. Scale determinations, (c), for scaled one-g test.

e. Design experiments to cover range of (a), (b), and (d).

f. Design test vessel, insulation, TVS attachment, control system.

g. Conduct experiments

h. Evaluate effectiveness of TVS relative to

   1. Operational adequacy and flexibility
   2. Reliability for liquid thermal control and pressure control

5.4.1.3 Expected Results

The primary result of this program is that the thermal effectiveness of the tube spacing and TVS flow rate controls will be determined and the overall feasibility of this method of thermodynamic control verified. In addition, the results of the experimental program will be used in the further development and verification of analytic models to predict liquid temperature stratification and tank self-pressurization under low gravity.

5.4.1.4 Timing/Criticality

It is believed that the considerable recent work done by government agencies (e.g., NASA/MSFC and NASA/LeRC) and government contractors on TVS will reduce somewhat the necessary work required to support the TVS for the logistic module. Additionally, TVS technology required for the logistic module, which is in orbit for a relatively short time, is less than that required for the tug and the CIS vehicles which have long duration orbital missions. Hence, it is believed that the required program can be completed by the middle of Phase B, in time to support conceptual and final design of the logistic module.

5.4.2 Low Gravity Temperature Stratification and Pressure Rise

5.4.2.1 Problem Statement

During logistic tanker orbital operations prior to propellant transfer, tank pressure rise may exceed that which would occur if the cryogenic liquid and vapor phases were well mixed. Additionally, localized propellant heating may occur. Both effects are due to thermal stratification due to heat leakage. Analytical tools (Reference 5.4.2.1-1) to predict low-g stratification and pressure rise have been developed for a tanker containing non-sloshing propellant in an earth oriented attitude. Data to verify this model are not available, although one-g stratification data developed during "Thermodynamic Vent System" SR&T (as discussed in paragraph 5.4.1 are expected to be helpful in this regard. Additionally, thermodynamic analyses for an inertially oriented logistics module and a logistics module whose propellant undergoes sloshing are needed to provide a comprehensive picture of low-g temperature stratification and pressure rise.

5.4.2.2 Required Effort

One-g data from the Thermodynamic Venting System task should be compared to the low-g stratification theory developed in Reference 5.4.2.1-1, with due allowance for the different acceleration levels. Where possible, the theory will be updated in the light of these data. In addition, analyses similar to those done in the reference should be conducted for sloshing propellant and for a cryogenic tanker oriented with respect to inertial space.

5.4.2.3 Expected Result

Analyses and computer programs will be developed to predict low-g temperature stratification and pressure rise for earth oriented and inertially oriented propellant modules with and without propellant sloshing.

5.4.2.4 Timing/Criticality

This analytic effort should be completed by the middle of Phase B to support conceptual and design studies.

5.5 SYSTEMS

5.5.1 Logistic Module/Space Shuttle Interfaces

5.5.1.1 Problem Statement

Definition of logistic module/space shuttle interface requirements is an important area worthy of supporting research and technology. The problem is complicated by a number of factors including: (1) space shuttle cargo bay geometry and characteristics have been changing and are subject to future change; (2) the logistic module has undergone, and doubtless, in the future, will continue to undergo, configuration and design changes; and (3) interface requirements definition to date has emphasized the tug/space shuttle combination, and even for this combination, requirements definition has been limited.

It is logical to presume that the requirements for a tug should predominate in consideration for payload accommodation in the cargo bay. Thus the logistic module is in a sense competing with other payloads, particularly the tug, in interface definition.

Specifically, attach points, umbilicals, and structural support for the logistic module within the cargo bay must be defined with due regard to the above considerations. Other considerations include compatibility with the cargo bay basic structure and load paths, influence on space shuttle center of gravity, fluid and electrical umbilicals and line routings, and compatibility with the space shuttle manipulator concepts.

5.5.1.2 Required Effort

It will be necessary to maintain a continuing effort in the definition of logistic module/space shuttle interface provisions and operations as both elements of the space program are further defined. Cognizance of the evaluation of other payloads, particularly the tug, and of the continuing definition of tug/space shuttle interfaces will also be necessary. In this way interface definition will proceed in a comprehensive, timely manner.

In particular, it is required that the effort include optimization and definition of the structural support interface, the fluid and electrical connects and disconnects, line routings, the deployment and retrieval concept, and the docking/latching mechanism. Evaluation criteria guiding definition and selection of designs and procedures include minimum weight, compatibility with present cargo bay design features (e.g., manipulator arm design), commonality with requirements of other payloads (e.g., common propellant dumping provisions for abort conditions), simple line routing provisions, compatibility with retrieval/deployment mechanism, and location of the logistics module within an allowable center of gravity envelope.

5.5.1.3 Expected Results

Continuous study of the logistic module/space shuttle interfaces will assure that the set of compromises made results in the achievement of required end item performance without undue penalty to any one element. A low structural weight will be realized for the physical support interactions, for umbilicals, for the manipulator mechanism, and for deployment/retrieval concepts. The study will determine preferred orientations of the logistic module within the cargo bay, provide simple and reliable design provisions for removing, re-inserting, docking, and attaching the logistics module to the space shuttle, and assure that space shuttle handling and connections provisions and fluid and electrical interfaces are well designed with respect to the logistic module as well as being compatible with other payloads. In addition, due consideration will be given to ground support equipment provisions and orbital dumping provisions in defining interface requirements.

5.5.1.4 Timing/Criticality

This study should be a continuous effort beginning immediately at a low manpower level and continuing during logistic module and space shuttle Phase B and C studies.

5.5.2 Docking and Line Mating Fixtures, Connects and Disconnects

5.5.2.1 Problem Statement

Orbital transfer of propellant requires the development of a satisfactory concept and design for remote docking, transfer line hook-up, and electrical connection. Disengagement and automatic disconnect after transfer are also required. Design studies of the required mechanisms have been and are presently being conducted in the areas of neuter docking ring/cone fixtures and line interconnect fixtures suitable for transfer lines and electrical circuit hookups and disconnects. These design studies should be verified by tests.

5.5.2.2 Required Effort

a. Define the functional and performance requirements for the primary docking fixture, the line-interface rack, and electrical contacts, giving proper consideration to requirements imposed by the logistic module and all user vehicles. Select a set of requirements that are realistic in satisfying conflicting demands as a baseline for subsequent design, fabrication, and test efforts.

b. Design a docking interface test article consisting of three major elements, namely, the neuter docking fixture, the line-interface rack, and dynamic simulators. The simulators are capable of simulating five-degree-of freedom vehicle motions during docking and they are required to incorporate adjustable offsets, misalignments, and closing velocities for simulating the mating dynamics. In the design of the test article consideration will be given to a scaled-down version in order to take advantage of existing test facilities. Concurrently, the instrumentation necessary for measuring dynamic quantities and their results will be designed and developed. A complete set of drawings from which the test article can be manufactured will be prepared.

c. A docking interface test article will be fabricated with a sufficient number of alternate components to permit evaluation of all pertinent design variables.

d. A test plan will be developed that makes maximum use of existing vacuum test facilities. These facilities will be employed to obtain data on impact load effects and metallic wear-out characteristics. Included in the test plan will be a verification of tunnel seals and cryogenic connectors under cyclic loads. The required cyclic coupling and decoupling can be achieved by mechanical means that match the forces and loads of an operational automatic engagement system. The test plan will be designed for a cryogenic probe and drogue with line hook-up in an active recirculating loop containing cryogenic fluid. Simultaneously, electrical connect/disconnect performance will be evaluated.

e. Conduct atmospheric and vacuum environment tests in accordance with the test plan of Task d. Analyze test results of each phase upon completion and provide for test result utilization in the subsequent fabrication and testing of the full-scale docking interface prototype.

5.5.2.3 Expected Results

Verification of the sub-scale docking fixture will be achieved with regard to mating dynamics, docking loads evaluation, and metallic wear-out characteristics. Line hook-up capability will be verified with regard to tunnel seals, cryogenic connectors, disconnect valves, and probe and drogue operation. Electrical engagement and disengagement will also be verified. Design and performance data will be developed for full-scale prototype test article fabrication as well as for the Phase C design.

5.5.2.4 Timing/Criticality

Verification testing should be completed by the end of Phase B to support the Phase C design effort.

5.5.3 Comparison of Module vs Integral Propellant Tanks

5.5.3.1 Problem Statement

Previous studies conducted by NASA, NR, and other contractors have developed considerable depth of analysis for both modular exchange and fluid transfer for in-orbit refueling of space based propulsive vehicles. However, no single study has developed a comparison of these two transfer modes for the same set of payload placement missions. For this reason, although considerable data exist for each transfer mode, little basis of comparison exists for the selection of the most cost effective approach. The objective of this task is to develop the necessary data to facilitate comparison of these two methods of refueling. Although fluid transfer is the baseline transfer mode for this study because none of the baseline configurations of space base tug, CIS or RNS were compatible with modular tank exchange, it is still early enough in the development of orbital transfer systems to permit an objective appraisal of the alternative of modular exchange.

5.5.3.2 Required Effort

a. Identify a baseline payload placement traffic model and ground to earth orbit propellant logistics module.

b. Develop in-orbit propellant requirements as a function of propulsive payload placement vehicle mass fraction and performance characteristics. Vehicle performance characteristics similar to those of previous NR studies for the space-based tug and chemical inter-orbital shuttle (CIS) will be used. Modular and integral tank vehicles must, of course, be considered.

c. Synthesize alternate concepts for fluid and modular transfer to each vehicle. Conduct a trade study and select the most efficient and predictable concept for fluid transfer and for modular transfer. The trade study approach will be similar to that applied in this present study. The analysis required for fluid transfer will draw heavily on the results of this study. Additional effort will be required for modular transfer analysis since a lesser amount of work has been completed in this area. Consideration will be given to propulsive vehicle payload placement capability as a function of propellant consumption. Parameters to be evaluated will include:

   1. hardware weight
   2. vehicle system complexity
   3. operational complexity and flexibility
   4. safety
   5. propellant losses

d. For the case of no orbital storage facility, develop detailed characteristics for each of the selected transfer concepts for both modular and fluid transfer. This detail will include propellant losses, propulsive vehicle and logistics module configuration and weight characteristics, subsystem schematics, functional and physical interfaces, operational requirements, and conceptual layouts.

e. Conduct cost analysis including development, production, and operational costs. Select most favorable concept (fluid or modular) on the basis of cost per pound of delivered payload.

f. Identify and assess the penalties and benefits of incorporating an orbital storage facility. Determine the influence, if any, on the selection of propellant transfer mode.

g. Conduct sensitivity analysis to determine the influence on the selection of transfer mode of:

   1. boiloff losses
   2. transfer losses
   3. payload traffic rate
   4. propulsive vehicle performance characteristics
   5. earth-to-earth orbit delivery vehicle payload weight and size capability.

5.5.3.3 Expected Result

For direct propellant transfer (no intermediary depot), basic comparative data will be developed to allow an assessment of the relative merits of modular vs fluid transfer, subject to a variety of criteria including cost per pound of delivered payload. The penalties and benefits of incorporating an orbital storage facility will be determined with regard to the two methods of transfer. Sufficient information will be developed to either confirm the present baseline of fluid transfer with no storage facility or indicate that an alternative, such as modular exchange with an orbital storage facility, is superior to the baseline.

5.5.3.4 Timing/Criticality

The work must be completed by the beginning of the Phase B study to allow sufficient time for profitable redirection of effort, should a promising alternative be uncovered.

REFERENCES

5.1.2.1-1 Gluck, D. F., J. P. Gille, E. E. Zukoski, and D. J. Simkin, "Distortion of a Free Surface During Tank Discharge," J. Spacecraft and Rockets, Vol. 3, No. 11, pp. 1691-2, (1966).

5.1.2.1-2 Abdalla, K. L., and S. G. Berenyi, Vapor Ingestion Phenomenon in Weightlessness, NASA TN D-5210, (May 1969).

5.1.2.1-3 Chen, I. M., and E. E. Zukoski, Experimental Investigation of Liquid Interface Distortion in a Draining Tank, North American Rockwell, SD68-867, (November 1968)

5.1.2.1-4 Berenzi, S. G., and K. L. Abdalla, Vapor Ingestion Phenomenon in Hemispherically Bottomed Tank in Normal Gravity and in Weightlessness, NASA TN D-5704, (April 1970).

5.1.4.1-1 McCrary, C., Slosh and Vortex Control Subsystem Report for Saturn S-II, North American Rockwell, SID 62-147, (June 1964).

5.1.4.1-2 Gluck, D. F., Propellant Acquisition and Feedout for Tug MPS and APS, NR/SD Internal Letter SLV-193-603-71-134, (Dec. 13, 1971).

5.4.2.1-1 Hines, W. J. et al., Saturn S-II Advanced Technology Studies, Study 8, Cryogenic Acquisition and Transfer, North American Rockwell, Space Division, SD71-268 (Dec. 21, 1971)

6.0 PROJECT IMPLEMENTATION PLAN

The project implementation plan presents the major steps to be taken for establishing an orbital propellant logistics capability by January 1985. The plan integrates the previous sections of this volume into a summary plan.

Figure 6.0-1 Preliminary Master Logistics Module Development Schedule, covers a period of 13 years starting in mid 1972. A logical sequence of events and milestones are presented which lead from the early study phases, through the design, development and operations of the logistics module for confidently achieving operational capability. The initial seven years represent a very low level of applied research, analysis and test activities. These tasks are directed at an efficient solution to the zero-g propellant transfer problem which will minimize propellant losses and hazards and provide a reliable design.

The principal products of the Phase C design activities are the system and subsystem design, CEI Part 1 specifications, program plans, and costs. Preliminary design review is scheduled for the last quarter of 1978. Detailed design activity will begin with the start of Phase D development/operations activities during which specifications and drawing will be released to start fabrication and procurement of hardware. Critical design review and 100% drawing release are scheduled for the first and fourth quarter of 1980, respectively. The laboratory material, component and subsystem testing activities are in support of the engineering design and development, starting in January 1979.

The ground support equipment/modification and facility activation supports and implements the manufacturing and development ground and flight test programs. This activity covers a duration of five years beginning at the end of Phase C and ending in December 1983. It involves design, fabrication and modification of GSE and facilities for support of post-manufacturing checkout, major test article ground testing, and launch site operations. A facility plan identifying modified and new requirements will be released in 1979.

The manufacturing, fabrication and acceptance test operations cover a period of approximately five years starting in the first quarter of 1979. These operations commence with the release of structural drawings and the start of tooling, and covers the fabrication, assembly and checkout of the five major test articles. The flight test article activities cover checkout and acceptance at the contractor facility, cold flow tests at MTF, thermal vacuum tests at MSC, and shipment to the launch site in the last quarter of 1983. First article configuration inspection occurs in the second quarter of 1983 with flight readiness review in the last quarter of 1983, approximately three months prior to the first flight test.

The Phase D development/operations cover a period of six years during which the hardware is manufactured, tested, and approved for manned orbital propellant transfer missions.

LIST OF ABBREVIATIONS AND DEFINITIONS

APS	Auxiliary Propulsion System
AFRPL	Air Force Rocket Propulsion Laboratory
B_o	Bond Number
CER's	Cost Estimating Relationships
EOS	Earth Orbital Shuttle
CIS	Chemical Interorbital Shuttle
ESS	Expendable Second Stage
Fr	Froude Number
GH_2	Gaseous Hydrogen
GSE	Ground Support Equipment
I_{sp}	Specific Impulse
I_t	Total Impulse
KSC	Kennedy Space Center
LH_2	Liquid Hydrogen
LO_2	Liquid Oxygen
LOX	Liquid Oxygen
MLI	Multilayer Insulation
NPSP	Net Positive Suction Pressure
OPD	Orbital Propellant Depot
OPSS	Orbital Propellant Storage System
OMS	Orbital Maneuvering System
RF	Radio Frequency
RNS	Reusable Nuclear Shuttle
S-II	Saturn Second Stage
SAK	Single Aluminized Kapton

SAM	Single Aluminized Mylar
SH_2	Slush Hydrogen
SMR	Specific Mass Requirements
SS	Space Shuttle
TFU	Theoretical First Unit (Used with Costs)
tug	Space Tug
W_p	Propellant Weight
Cargo sharing	The maximum utilization of a vehicle's payload volume or weight capability by carrying both propellant and dry payload
Cost effectiveness	A measure of the dollar cost and a system or program related to some measure of effectiveness, e.g. $ per lb. of propellant delivered to orbit. Cost effectiveness studies are conducted to compare the relative costs of alternate system programs or approaches in relation to measure of effectiveness
Hydrogen slush (slush hydrogen)	A mixture of small, solid hydrogen particles suspended in liquid hydrogen at the triple point
Linear Propellant Transfer	Acceleration of source tank and receiver tank in X axis direction to settle propellants and permit fluid pumping
Liquid/Vapor Interface Control	Management of the position in the tanks of the liquid to vapor boundaries
Mass Fraction	The ratio of usable full thrust propellant to gross weight for a space vehicle
Modular transfer	The package exchange of cargo (fluids); i.e., the replacement of an empty tank by a like tank that is full
Operational effectiveness	Any measure of how well the operation carries out its objective used for comparative purposes. It is synonymous with "effectiveness" as used in the term cost of effectiveness
Orbital storage	Sometimes referred to as storage. The accumulation and maintenance (saving) of fluid in earth orbit for subsequent transfer to a user vehicle
Program elements	Those propulsive vehicles and orbital stations which are the major hardware components of the space program

Propellant Logistics Module	Propellant tank and associated hardware fitting the shuttle orbiter cargo bay and employed for transporting propellant to the user vehicles
Propellant logistics system	That system which incorporates the transport from ground to space, transfer, and orbital storage (if required) for the purpose of propellant resupply of space-based user vehicles
Receiver tank	That tank accepting propellants in a propellant transfer operation
Rotational Propellant Transfer	Rotation of the propellant source tank and receiver tank about pitch axis to settle propellants and permit fluid pumping
Source tank	That tank supplying the propellants in a propellant transfer operation
Timelines	A sequence of activities in a mission with start and stop times(duration) of the activity defined
Traffic model	A description of the use of a particular vehicle or set of vehicles in terms of the number of trips per unit time, points of departure and destination, trip routes, and trip durations
User traffic model	Refers to the rate of flight of user vehicles
Logistic traffic model	Refers to the rate of flight of the propellant transport, transfer and storage vehicles defined in a propellant logistic system
Traffic rate	The aspect of a traffic model description specifying the number of trips per unit time
Transport system	System for delivering propellants from earth-to-earth orbit. The tug is not considered part of the transport system for the purpose of this definition
Transfer	The exchange of propellant or fluid from one vehicle or spacecraft to another vehicle or spacecraft
Tug	Space-launched vehicle for use with the Space Shuttle Orbiter, i.e., transportable in shuttle bay.
User vehicle	A space-based spacecraft which requires propellant refueling or makeup of life support fluids in earth orbit.

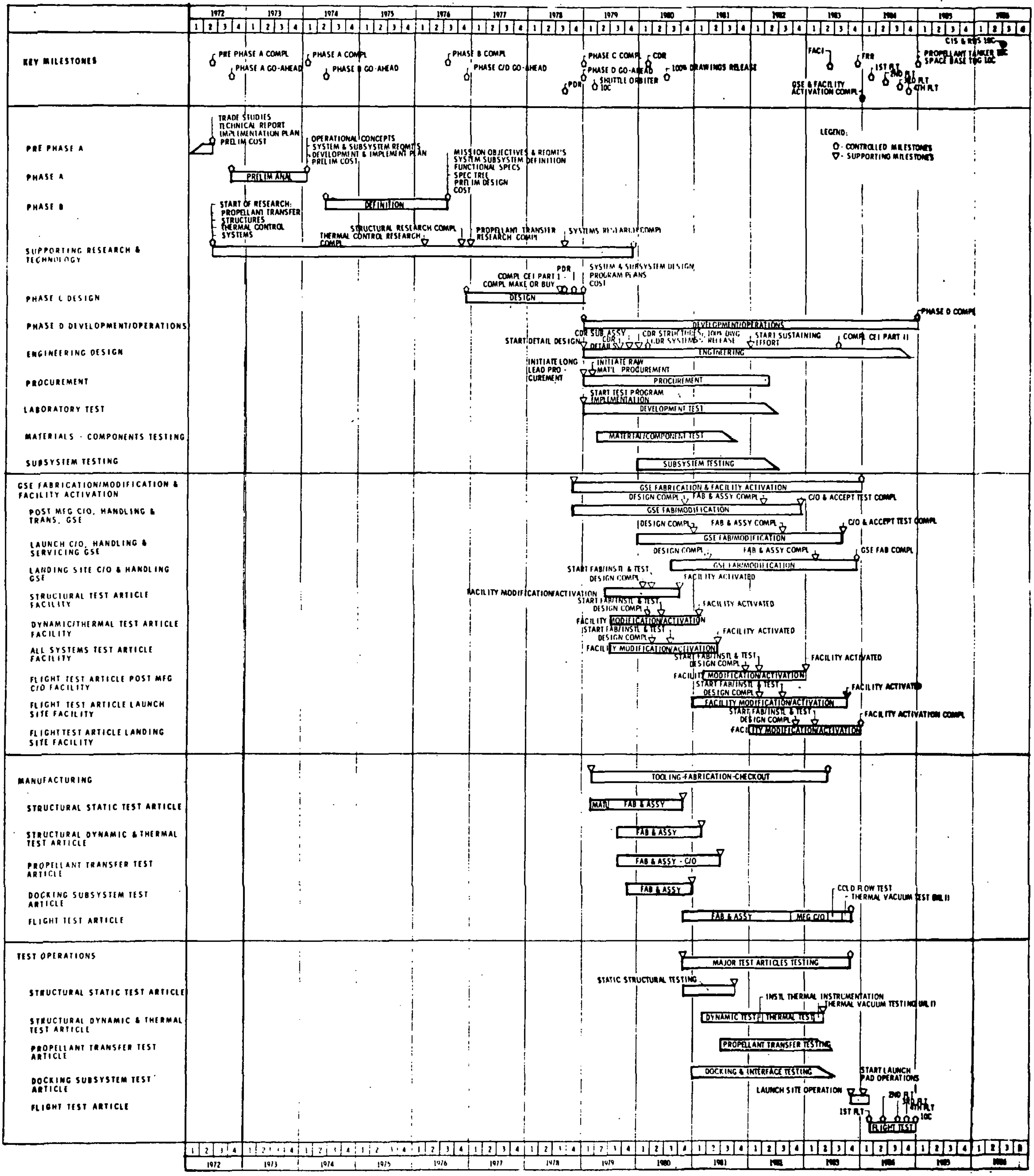


Figure 6.0-1 Preliminary Master Propellant Module Development Schedule.