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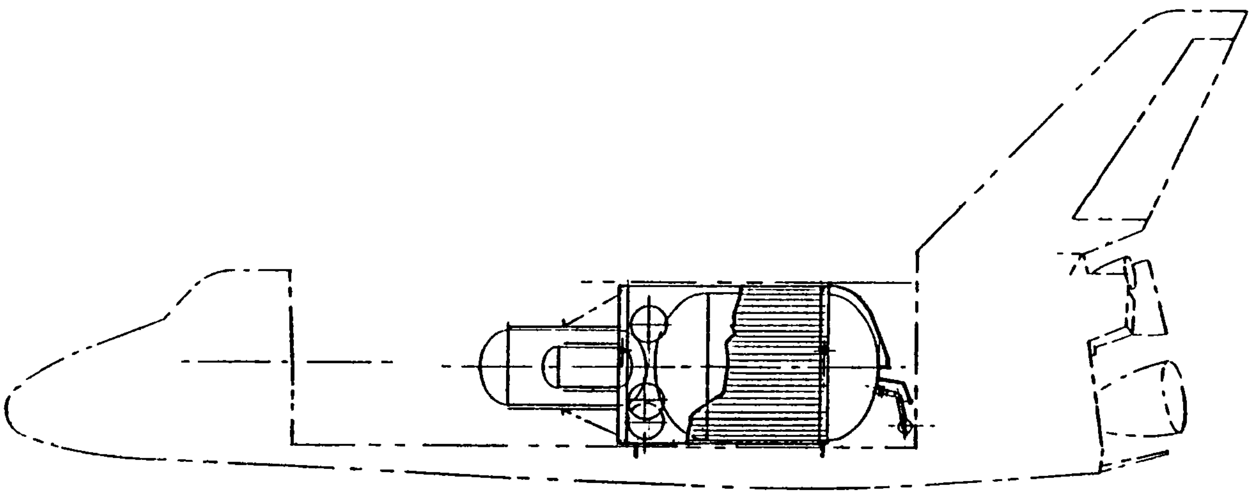

CONCEPTUAL DESIGN OF AN ORBITAL PROPELLANT TRANSFER EXPERIMENT

VOLUME II • STUDY RESULTS

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GENERAL DYNAMICS
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VOLUME I	EXECUTIVE SUMMARY
VOLUME II	STUDY RESULTS

NASA CR-165150
GDC-ASP-80-013

CONCEPTUAL DESIGN OF AN ORBITAL PROPELLANT TRANSFER EXPERIMENT

VOLUME II • STUDY RESULTS

August 1980

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Cleveland, OH 44135

Under
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16 Abstract

The primary objective of this study was to provide the NASA Lewis Research Center with a conceptual design and development plan for a large scale orbital propellant transfer experiment. The scope of this effort was twofold. First, OTV configurations, operations and requirements planned for the period from the 1980's to the 1990's were reviewed and a propellant transfer experiment was designed that would support the needs of these advanced OTV operational concepts. Second, an experiment development plan was prepared to aid NASA LeRC in the preparation of an overall integrated propellant management technology plan for all NASA centers.

The development program for this experiment starting with the phase C/D effort is three years. The preliminary cost estimate (for planning purposes only) is $56.7M, of which approximately $31.8M is for Shuttle user costs.

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FOREWORD

This report, consisting of Volume I Executive Summary and Volume II Study Results, summarizes the technical effort conducted under Contract NAS3-21935 by the General Dynamics Convair Division from May 1979 to July 1980. The contract was administered by the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.

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All new data are presented with the International System of Units as the primary system and English Units as the secondary system. The English system was used for the basic calculations. Some NASA source data from previous studies used English units. These data are presented in English units as originally documented in the contractor reports.

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TABLE OF CONTENTS

			Page
1	INTRODUCTION		1-1
	1.1	SCOPE	1-1
	1.2	OBJECTIVE	1-1
	1.3	CONDUCT OF STUDY	1-1
2	SURVEY OF OTV CONCEPTS AND REQUIREMENTS (TASK I)		
	2.1	MISSION AND CONFIGURATION REQUIREMENTS	2-1
	2.2	OTV SUBSYSTEM INTERFACE	2-9
	2.2.1	OTV/Subsystem Analyses	2-9
	2.2.2	OTV System Design	2-14
3	PRELIMINARY EXPERIMENT DEFINITION (TASK II)		3-1
	3.1	ANALYSES	3-1
	3.1.1	Transfer Line Chilldown	3-1
	3.1.2	Fundamental Experiment Design Drivers	3-17
	3.2	PRELIMINARY EXPERIMENT CONCEPTS	3-33
	3.2.1	Transfer Line Chilldown	3-34
	3.2.2	Receiver Tank Pre-Chill	3-35
	3.2.3	Receiver Tank Fill	3-37
	3.2.4	Multi-layer Insulation	3-40
	3.2.5	Start Basket	3-40
	3.2.6	Autogenous Pressurization	3-41
	3.2.7	Auxiliary Equipment Tests	3-41
	3.3	PRELIMINARY EXPERIMENT DESIGNS	3-42
	3.3.1	Experiment Sizing and Arrangements	3-43
	3.3.2	Preliminary Experiment Installation Concepts	3-47
	3.3.3	Preliminary Tank and Integrated System Concepts	3-49
4	SELECTED EXPERIMENT CONCEPTUAL DESIGNS (TASK III)		4-1
	4.1	EXPERIMENT DESIGN LAYOUTS/CONFIGURATIONS	4-1
	4.1.1	Supply Tank Design	4-2
	4.1.2	Supply Tank Insulation System	4-7
	4.1.3	Half-Scale Receiver Tank Design	4-10
	4.1.4	Half-Scale Receiver Tank Insulation System	4-15
	4.1.5	Half-Scale Receiver Tank Acquisition Device	4-19
	4.1.6	Quarter-Scale Receiver Tank	4-23
	4.1.7	Supply and Receiver Tank Support Structure	4-23
	4.1.8	Experiment Module Assembly	4-28
	4.1.9	Installation in the Shuttle	4-31

TABLE OF CONTENTS, Continued

			Page
	4.1.10	Center of Gravity and Weight Summary	4-31
	4.2	PRE-FLIGHT PROCEDURES	4-33
	4.2.1	Ground Operations	4-33
	4.2.2	Preliminary Safety and Hazard Design Analyses	4-39
	4.3	TYPICAL EXPERIMENT CONCEPTS	4-44
	4.3.1	Transfer Line Chilldown	4-44
	4.3.2	Receiver Tank Pre-Chill	4-47
	4.3.3	Receiver Tank Fill	4-50
	4.3.4	Secondary Experiments	4-51
	4.3.5	Sensor Identification	4-52
5	EXPERIMENT DEVELOPMENT PLAN (TASK IV)		5-1
	5.1	PROGRAM PLANS AND SCHEDULES	5-1
	5.1.1	Approach	5-1
	5.1.2	Groundrules and Assumptions	5-1
	5.1.3	Program Milestones	5-2
	5.1.4	Phase C/D Master Schedule	5-3
	5.2	EXPERIMENT COST ESTIMATE	5-6
	5.2.1	Work Breakdown Structure	5-6
	5.2.2	Cost Methodology	5-8
	5.2.3	PMTE Payload Technical Description	5-12
	5.2.4	Cost Estimate	5-17
	5.2.5	Annual Funding Requirements	5-19
6	CONCLUDING REMARKS		6-1
7	REFERENCES		7-1
APPENDIX A	PROPELLANT MANAGEMENT TECHNOLOGY EXPERIMENT WBS DICTIONARY		A-1
APPENDIX B	DISTRIBUTION LIST FOR CONTRACT NAS3-21935		B-1

LIST OF FIGURES

Figure		Page
1-1	OTV Propellant Transfer Scenario	1-2
1-2	Typical Propellant Transfer Experiment System	1-2
1-3	Experiment Design Summary	1-3
1-4	Annual Funding Requirements	1-4
2-1	SPS Propellant System Requirements	2-2
2-2	Space Mission/OTV Requirement Summary	2-3
2-3	Typical All-Propulsive OTV Stage Configuration	2-4
2-4	OTV Hardware Requirements	2-4
2-5	OTV Configuration Candidates	2-5
2-6	Baseline Orbiter Tanking Arrangement	2-5
2-7	Typical OTV Operational Interface	2-7
2-8	Typical On-Orbit Resupply Operations	2-8
2-9	Typical On-Orbit Resupply Operations	2-8
2-10	LH_2 Acquisition Device	2-12
2-11	Typical LO_2 Tankage and Subsystems	2-16
2-12	LO_2 Acquisition Device	2-18
3-1	Propellant Transfer Areas of Interest/Concern	3-2
3-2	Transfer Line Chilldown Aids	3-4
3-3	Heat Capacity of 18-8 Stainless Steel at Low Temperature	3-7
3-4	Transfer Line Chilldown Rate for Condition Where Initial Wall Temperature is 306K (550R) and LH_2 is Injected as Spray at 101 kN/m^2 (14.7 psia) and 20K (36R)	3-7
3-5	Gas Velocity Through Transfer Line as Function of Gas Temperature for Various Mass Flow Rates	3-8
3-6	Minimum Overall Heat Transfer Coefficient Required to Satisfy Various Conditions Between Exit Gas and Average Wall Temperature of LH_2 Transfer Line	3-9
3-7	LH_2 Transfer Line Chilldown Using Saturated Gas at Entrance 101 kN/m^2 @ 14.7 psia Line Pressure	3-10

LIST OF FIGURES, Contd

Figure		Page
3-8	Exit Overheat at Various Wall Conditions During Childown of LH_2 Line	3-11
3-9	Fundamental Design Drivers	3-18
3-10	Propellant Transfer System With Autogenous Pressurization	3-22
3-11	Propellant Transfer System With Helium Pressurization	3-22
3-12	Propellant Transfer System With Pump	3-23
3-13	Helium Pressurant Required for 73.6 m^3 (2600 ft^3) LH_2 Supply Tank at 138 kN/m^2 (20 psia) Total Pressure	3-24
3-14	Mass Inflow Required to Provide Autogenous Pressurization of 73.6 m^3 (2600 ft^3) Receiver Tank at 138 kN/m^2 (20 psia)	3-25
3-15	Equilibrium Pressure Varies as the Initial Wall Temperature for Pre-Chill of an Empty Receiver Tank	3-29
3-16	Minimum LH_2 Mass Required to Cool Receiver Tank From 289K (520R)	3-30
3-17	Preliminary Definition of Propellant Transfer Experiments	3-33
3-18	Expected Behavior of Parametric Data	3-34
3-19	Location of Instrumentation for Line Childown	3-35
3-20	Pressure Transient for a Series of Three Runs on a Single Nozzle	3-36
3-21	Instrumentation Layout for Pre-Chill Tests	3-37
3-22	Proposed Tank Fill Experiments	3-38
3-23	Pressure Difference From Equilibrium for Available Nozzle Options in Quarter-Scale Receiver Tank	3-38
3-24	Instrumentation for Receiver Tank Fill Tests	3-39
3-25	Typical MLI Behavior During Early Phase of Mission	3-40
3-26	Propellant Positioning for Start Basket Test	3-41
3-27	A Possible Time Schedule for the Experiment	3-42
3-28	Preliminary Maximum Scale POTV Hydrogen Tank Layout	3-44
3-29	Articulating Receiver Tank Installation	3-45
3-30	Receiver Tank/Docking Adapter Configuration	3-46

LIST OF FIGURES, Contd

Figure		Page
3-31	Maximum Scale Receiver and Supply Tank Instrumentation	3-48
3-32	Preliminary Experiment Installation	3-50
3-33	Half-Scale Receiver Tank	3-51
3-34	Half-Scale Receiver Tank Support Arrangement	3-53
3-35	Quarter-Scale Receiver Tank	3-54
3-36	LH_2 Supply Tank	3-56
3-37	Preliminary System Installation and Weight Estimate	3-57
3-38	Baseline OTV LH_2 Tank	3-59
4-1	Supply Tank	4-3
4-2	Supply Tank Insulation	4-8
4-3	Half-Scale Receiver Tank	4-11
4-4	Half-Scale Receiver Tank Insulation	4-16
4-5	Half-Scale Receiver Tank Acquisition Device	4-20
4-6	Tank Support Structure	4-24
4-7	Half-Scale Tank Support Structure	4-27
4-8	Experiment Module Assembly	4-29
4-9	Shuttle Installation	4-32
4-10	Center of Gravity and Weight Summary	4-34
4-11	Propellant Transfer Experiment (PTE) Ground Operations (KSC Pre-Flight Integration Scenario)	4-35
4-12	Experiment Flow Schematic and Instrumentation Location	4-45
4-13	Suggested Circuit Schematic for Transfer Line Wall Heaters	4-48
4-14	Typical Nozzle Schematic for Receiver Tank Pre-Chill and Fill Experiments	4-48
4-15	Suggested Circuit for Experiment Heaters	4-49
5-1	PMT Schedule Summary	5-2
5-2	Propellant Management Technology Experiment - Master Schedule	5-4
5-3	PMTE Work Breakdown Structure	5-7

LIST OF FIGURES, Contd

Figure		Page
5-4	Cryogenic Tankage First Unit Cost Relationship	5-9
5-5	Cryogenic Tankage Development Cost Relationship	5-10
5-6	Shuttle Installation of PMTE Payload	5-12
5-7	PMTE Payload Assembly	5-13
5-8	PMTE System Schematic	5-14
5-9	PMTE Annual Funding Requirements	5-20
6-1	Experiment Design Summary	6-2
6-2	Annual Funding Requirements	6-2
6-3	Summary of Study	6-3

LIST OF TABLES

Table		Page
2-1	Potential Missions Requiring OTV's	2-2
2-2	OTV On-Orbit Resupply Interactions	2-9
3-1	System Requirements for Various Experiment Designs	3-27
3-2	Receiver Tank Parameters Which Affect Pre-Chill	3-28
4-1	Experiment Tankage and Support Systems	4-1
4-2	Hazard and Safety Analysis of Propellant Transfer Experiment Conceptual Designs	4-40
4-3	Valves Required for Experiments	4-46
4-4	Typical Experiment Concepts	4-46
4-5	Summary of Sensor Requirements (English Units)	4-52
4-6	Summary of Sensor Requirements (SI Units)	4-56
5-1	PMTE Physical Characteristics	5-15
5-2	Instrumentation Sensors	5-16
5-3	PMTE Program Cost Summary	5-17
5-4	PMTE Cost Estimates	5-18
5-5	Cost Uncertainties for PMTE Payload	5-19

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SUMMARY

The primary objective of this study was to provide the NASA Lewis Research Center with a conceptual design and development plan for a large scale orbital propellant transfer experiment. The scope of this effort was twofold. First, OTV configurations, operations and requirements planned for the period from the 1980's to the 1990's were reviewed and a propellant transfer experiment was designed that would support the needs of these advanced OTV operational concepts. Second, an experiment development plan was prepared to aid NASA LeRC in the preparation of an overall integrated propellant management technology plan for all NASA centers.

The following table summarizes the basic findings of this study regarding: 1) compatibility of the experiment concept with planned OTV development and operational scenarios, and 2) the meeting of the primary experiment objectives along with the flexibility to perform many secondary, as well as presently undefined experiments in the propellant management technology area.

THE CONCEPTUAL EXPERIMENT DESIGN SATISFIES A BROAD RANGE OF OTV PROPELLANT MANAGEMENT SCENARIOS
• SINGLE STAGE/SINGLE BURN/MULTI-BURN • MULTI-STAGE/MULTI-BURN • PROPELLANT TANKS (LH_2 - LO_2) WET OR DRY • SHUTTLE OR DEPOT REFUELING BASE • MISSIONS OF SEVERAL DAYS TO SEVERAL MONTHS • SUBSYSTEM VARIATIONS - PRESSURIZATION, INSULATION, VENTING ACQUISITION, ABORT DUMP

THE CONCEPTUAL EXPERIMENT DESIGN PROVIDES A HIGH DEGREE OF EXPERIMENT FLEXIBILITY		
PRIMARY OBJECTIVES	SECONDARY OBJECTIVES	SUPPORTING RESOURCES
FILL LINE CHILLDOWN TANK PRECHILL RECEIVER TANK FILL	PRESSURIZATION (He) PROPELLANT ACQUISITION TANK INSULATION TVS START BASKET REFILL/ PERF. ABORT DUMP	– ZERO-G MASS GAUGING – MODIFIED OTV GROUND SUPPORT EQUIPMENT FOR INTERFACE OF EXPERIMENT LH_2 & He REQUIREMENTS

THE CONCEPTUAL EXPERIMENT DESIGN REPRESENTS AN EXPERIMENTAL TOOL TO INVESTIGATE THE PROPELLANT TRANSFER TECHNOLOGY REQUIREMENTS OF A BROAD RANGE OF SPACE-BASED OTVs

The development program for this experiment starting with the phase C/D effort is three years. The preliminary cost estimate (for planning purposes only) is \$56.7M, of which approximately \$31.8M is for Shuttle user costs.

1

INTRODUCTION

1.1 SCOPE

With the continued development of the Space Transportation System (STS) the free world is on the threshold of a new and expanding space era. Some of the challenging space programs being proposed include space construction bases, large antenna systems, solar powered satellites, and propellant depots. The commonality within these diverse programs is the use and need of orbital transfer vehicles (OTV) to support the development and ultimate operational phases of these space activities. In turn the OTV has the requirement for space based re-fueling in order to effectively carry out its assigned function.

The area of propellant management and in particular that of orbital propellant transfer of cryogens has long been identified as a critical technology area by the NASA LeRC and Convair. A family of precursor studies, both NASA sponsored and independently pursued by Convair (References 1-1, 1-2, 1-3 and 3-3) provide the basis for this, the ultimate experimental program.

1.2 OBJECTIVES

The objectives of this study were to define the largest practical experiment scale of an OTV propellant tank that could be accommodated within the cargo bay of a single Shuttle flight. This scaled OTV propellant tank became the focal point for the conceptual design of an orbital propellant transfer experiment and the definition of the companion development plans and cost estimates.

1.3 CONDUCT OF STUDY

This study contained four major task areas which are briefly described below. The description also indicates the report sections which provide the details of the study effort.

<u>TASK I - Survey of OTV Concepts & Requirements</u> (See Section 2.0)

Task I of the study effort provided mission requirements and OTV configurations based on previous NASA study results. Emphasis was on defining the propellant management requirements for on-orbit resupply and operations of the OTV during a typical mission. Figure 1-1 is an example of a propellant transfer scenario involving the use of space-based OTVs.

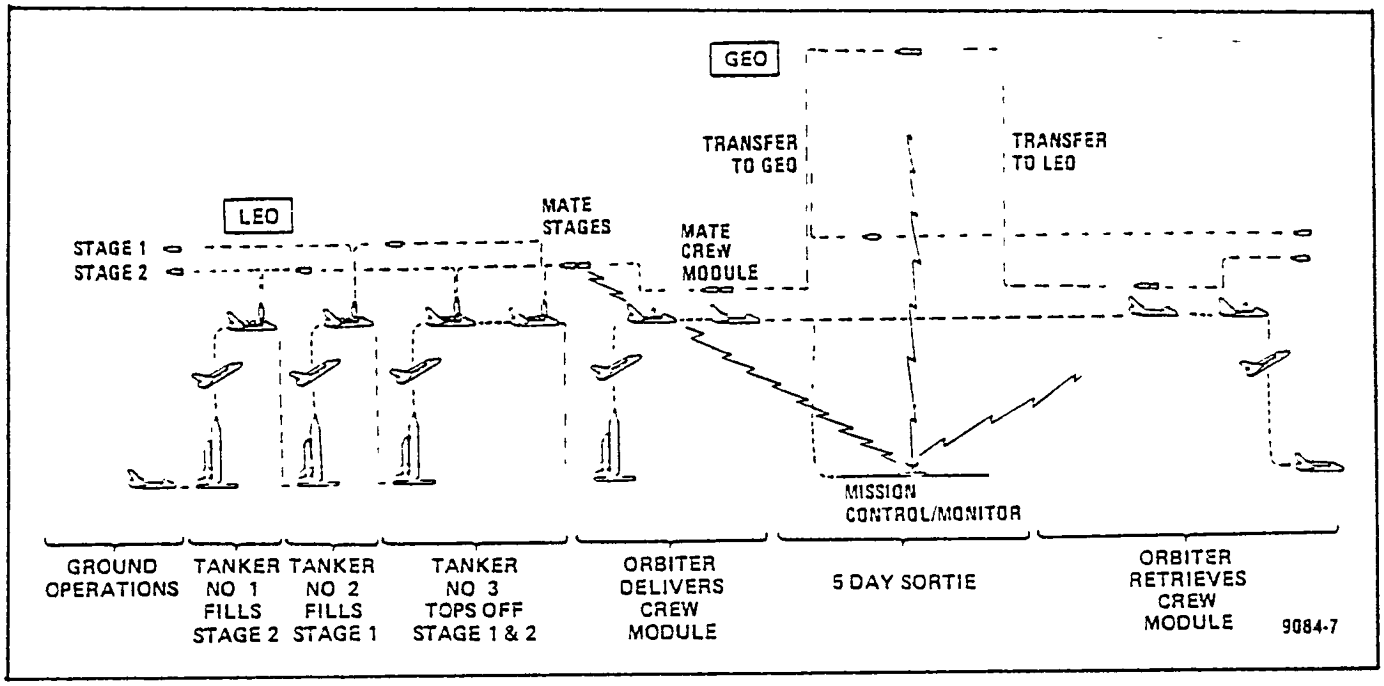


Figure 1-1. OTV Propellant Transfer Scenario

Task II - Preliminary Experiment Definition (See Section 3.0)

Task II provided the preliminary experiment definition of the experiment configuration, test fluid, instrumentation, and both ground and orbital testing procedures. In addition, potential secondary objectives (i.e., insulation evaluation, demonstration of pressure control technique) were established. The experiment was sized to meet the above objectives in an economical manner; however, the maximum size of the experiment was restricted to the total volume of the cargo bay of the Shuttle. The recommended experiment approach was presented to NASA for approval before proceeding with Task III. Figure 1-2 outlines the preliminary testing areas and the flow schematic that was defined.

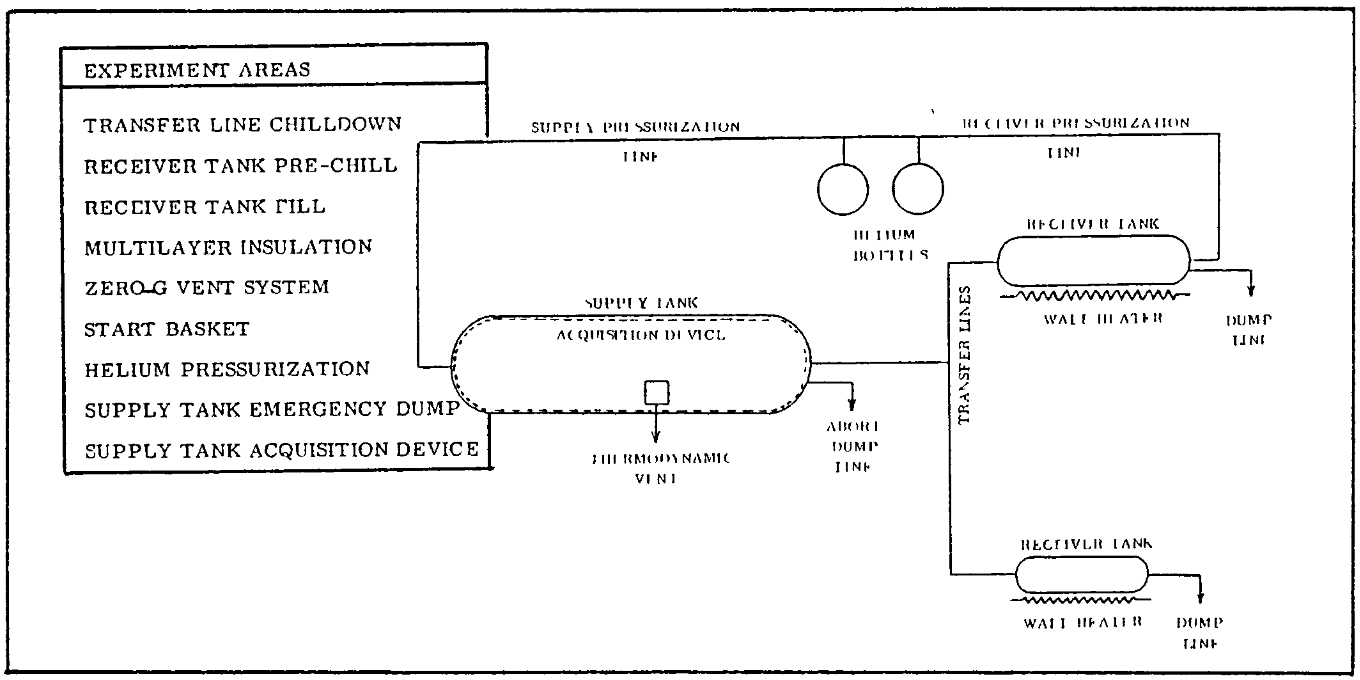


Figure 1-2. Typical Propellant Transfer Experiment System

Task III - Conceptual Design of Experiment (See Section 4.0)

Task III provided a conceptual design of the recommended propellant transfer experiment to the depth of detail necessary to allow cost estimates and schedules to be generated. In addition, the ground and inflight operational procedures required to perform the experiment were defined. Figure 1-3 provides the overall experiment installation concept and weight summary that was defined.

EXPERIMENT ELEMENT	WEIGHT KG	(LBS)
SUPPLY TANK SYSTEM	752.3	(1652)
1/2 SCALE RECEIVER TANK	131.9	(291)
1/4 SCALE RECEIVER TANK	49.4	(109)
PRESSURIZATION SYSTEM	725.6	(1600)
INSTRUMENTATION & WIRING	181.4	(400)
SUPPORT STRUCTURES	1097	(2419)
CONTROLS, RAU, DISPLAYS	145.1	(320)
TOTAL DRY WEIGHT	3082.7	(6791)
TOTAL WET WEIGHT (LH_2 & He)	8253.5	(18199)
PLUS ENERGY KIT (840 KWH)	740.1	(1632)
SUPPORT ELEMENTS		
RCS PROPELLANT	725.6 Kg (1600 LB)	
ELECTRICAL ENERGY	47.4 Kw-h	
ORBITAL EXPERIMENT TIME	3 + DAYS	
SECONDARY EXPERIMENTS	6	

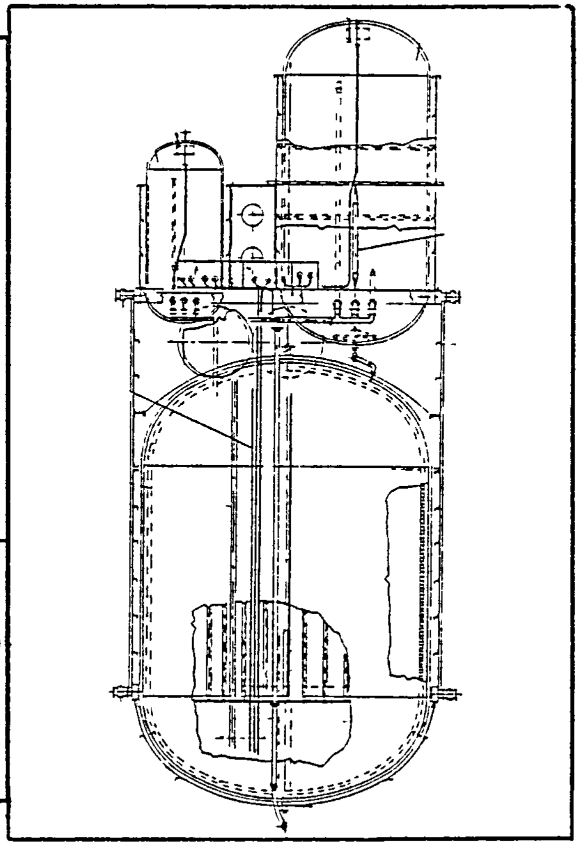


Figure 1-3. Experiment Design Summary

Task IV - Experiment Development Plan (See Section 5.0)

Task IV provided the experiment development plan. This included a definition of the ground and flight qualification tests and shuttle installation requirements. It also provided a schedule for design, fabrication, ground testing, and shuttle integration. In addition, it also provided estimated costs for the total experiment development. Figure 1-4 provides the estimated cost spread and cost categories that were developed.

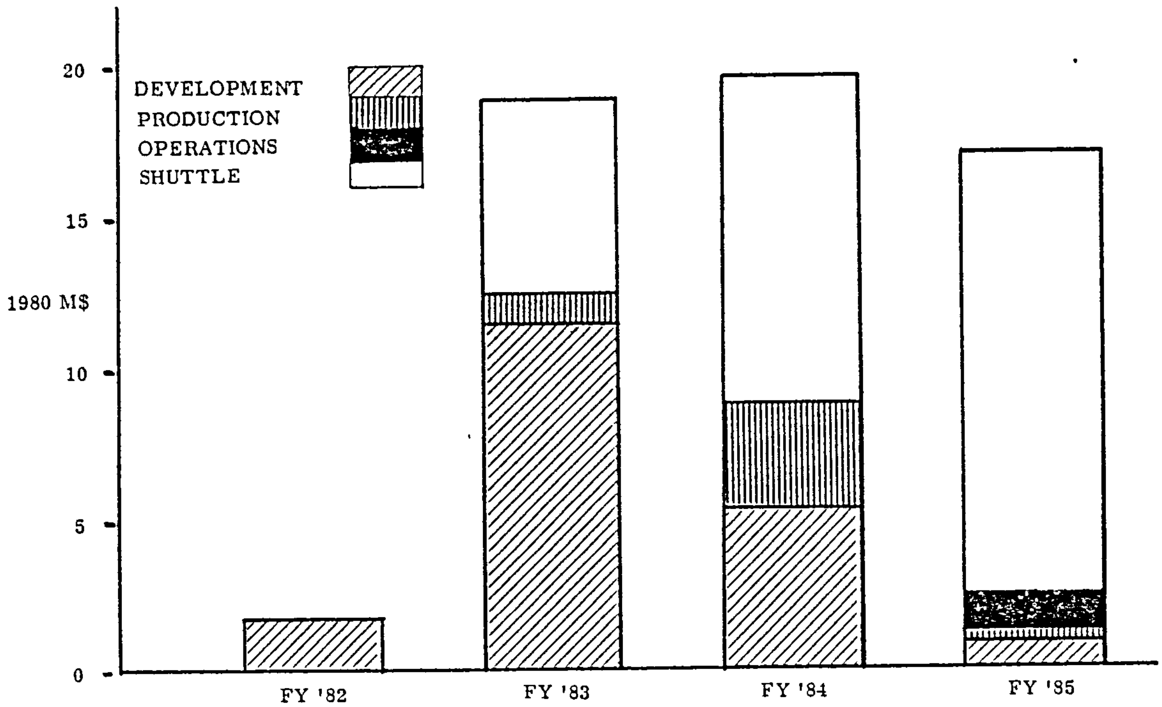


Figure 1-4. Annual Funding Requirements

2

SURVEY OF OTV CONCEPTS AND REQUIREMENTS (TASK I)

This section presents a brief review of Orbital Transfer Vehicle (OTV) concepts being considered for future mission applications (References 2-1, 2-2, 2-3 and 2-4). The basic need for in-space propellant transfer is tied directly to the planned use of space-based OTVs. The important OTV programmatic and operational drivers to be considered in the preliminary design of a propellant management experiment are 1) the potential missions requiring OTV's, 2) the planned OTV development and concept evolution; 3) the typical OTV operational interfaces, 4) the likely OTV propellant tank configurations and 5) the typical on-orbit resupply operations.

These elements along with typical OTV subsystem interface data have been used to justify the pursuit of in-flight propellant transfer experiments. Section 2.1 covers the broad aspects of OTV mission requirements. Section 2.2 covers the potential interfaces between the OTV subsystem and the propellant transfer operation.

2.1 MISSION AND CONFIGURATION REQUIREMENTS

Specific mission requirements defined by the study are limited to operations of an OTV between Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO) using LO_2 and LH_2 as propellants. Additional guidelines limit the vehicle concepts to those that are space-based which implies reusable vehicles refurbished in LEO. These space-based reusable vehicles have applications in the future when space activity is high. Some of these applications, as discussed in Reference 2-1, along with the propellant requirements are shown in Figure 2-1.

The Aerospace Study (Reference 2-2) describes the mission payload requirements through the year 2000. Table 2-1 was taken from that report and indicates the broad cross-section of potential missions and OTV requirements.

Figure 2-2, from that same report, shows that two vehicle configurations with propellant transfer will satisfy these requirements. The predominant requirement driving the vehicle size and performance is the manned round-trip mission. The proposed vehicles are the "all propulsive" variety, one using 21,315 Kg (47K pounds) of propellant, roughly the size of the 1973 Space tug, and the other a version which dimensionally fills the Shuttle cargo bay and requires propellant transfer of 66,667 Kg (147K pounds). These concepts defined by Aerospace require the transfer of liquid oxygen only. The liquid hydrogen is carried in the OTV.

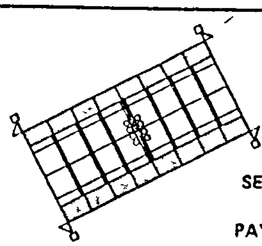
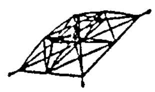
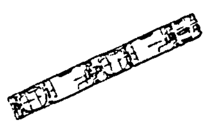
CANDIDATE SPS OTV VEHICLES	PROPELLANT REQUIREMENT	DEPOT	CONSTRUCTION SITE
 SPS MODULE SELF PROPULSION PAYLOAD 8700 MT	MASS ARGON 2000 MT I_{SP}~ 7000 SEC LO_2/LH_2 1000 MT I_{SP}~440 SEC	INTEGRAL WITH LEO CONSTRUCTION BASE — CAPACITY ARGON – 2000 MT LO_2/LH_2 – 1000 MT	LEO
 ELECTRIC OTV CARGO MODULE PAYLOAD UP 4000 MT DOWN 200 MT	MASS ARGON – 469 MT I_{SP}~8000 SEC LO_2/LH_2 – 46 MT I_{SP}~ 440 SEC	INTEGRAL WITH LEO STAGING BASE – CAPACITY ARGON – 469 MT LO_2/LH_2 – 46 MT	GEO
 POTV CREW & CREW CARGO PAYLOAD UP 151 MT DOWN 90 MT	MASS LO_2/LH_2 – 830 MT I_{SP}~ 475 SEC	CAPACITY LO_2/LH_2 – 2075 MT	LEO
		CAPACITY LO_2/LH_2 – 1212 MT	GEO

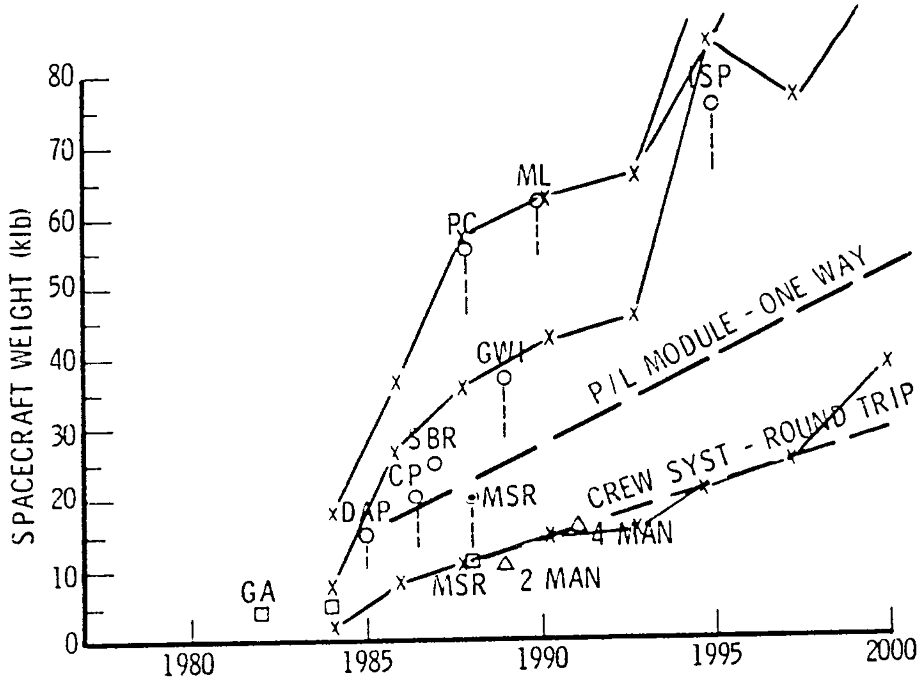
Figure 2-1. SPS Propellant System Requirements

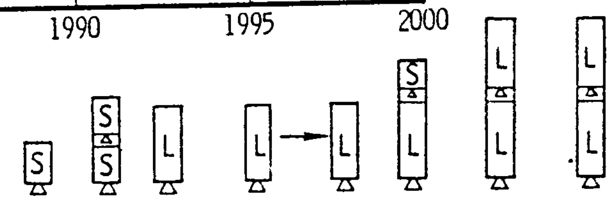
Table 2-1. Potential Missions Requiring OTV's*

PRIMARY MISSION	DESTINATION	ESTIMATED SPACECRAFT WEIGHT (lb)	NOMINAL TIME FRAME		IMPULSIVE TRANSFER(1)	
			DEMONSTRATION	OPERATION	ΔV (ft/sec)	ONE-WAY TRANSFER TIME
ELECTRONIC MAIL	GEO	6,000	1984	1987	14 000	6 HR
EDUCATIONAL TV	GEO	10 000	1984	1987	14 000	6 HR
PERSONAL COMMUNICATION	GEO	54,000	1986	1989	14,000	6 HR
DATA ACQUISITION PLATFORM	GEO	15 000	1989	1992	14,000	6 HR
INFORMATION SERVICES PLATFORM	GEO	75,000	1989	1992	14,000	6 HR
GEOSTATIONARY COMMUNICATION PLATFORM	GEO	19 000	1985	1988	14,000	6 HR
ORBITING DEEP SPACE RELAY SAT	GEO	19 000	1983	1986	14 000	6 HR
SOLAR/TERRESTRIAL OBSERVATORY	GEO	22,000	1988	1991	14,000	6 HR
PINHOLE X-RAY/GRAVITY WAVE INTERFEROMETER	L_1	37,000	1988	1991	12 600	4 DAY
NUCLEAR WASTE DISPOSAL	0 86 AU	21,000(2)	-	1987	14,600	170 DAYS(4)
JUPITER BUOYANT PROBE	ESCAPE	6,000	-	1990	21,300(3)	800-900 DAYS
MARS LANDER/SAMPLE RETURN	ESCAPE	62 000	-	1990	11 700 TO 16,700(3)	200-500 DAYS
SAT POWER SYSTEM TEST ARTICLE	GEO	15,000	-	1985	14 000	6 HR
SPACE STATION	GEO	250,000	1993	1996	14 000	6 HR

*NASW-3141

(1) FROM 160 nm/160 nm/28 5 deg ORBIT UNLESS OTHERWISE STATED
(2) INCLUDES KICKSTAGE
(3) EARTH DEPARTURE ONLY (Ref Boeing Aerospace Company, 'Future Space Transportation Systems Analysis Study " Final Report, Vol 2, D180-20242-2, Dec 31 1976)
(4) TWO-BURN HOHMANN TRANSFER FROM LEO TO 0.86 AU



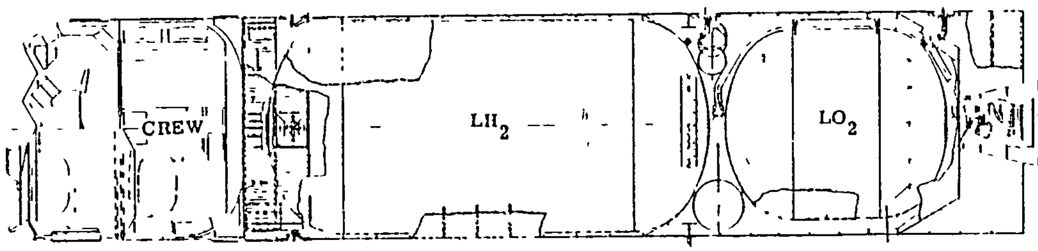


PAYLOAD TO GEO									
ONE WAY - OTV EXPENDED	(klb)	18.2	37.8	58.4	63.1	65.1	96.1	98.1	126.5
ONE WAY - OTV RECOVERED	(klb)	8.4	27.9	36.8	43.6	45.6	86.2	77.0	105.9
ROUND TRIP	(klb)	2.3	8.5	11.2	15.2	15.2	21.3	24.7	39.2
VEHICLE PROPELLANT	(klb)	47	94	147	147	147	194	294	294
OTV PROPULSION SYS I_{sp}	(sec)	445			>470				
SHUTTLE CAPABILITY	(klb)	65				100			125
PROPELLANT TRANSFER		NO		YES					

Figure 2-2. Space Mission/OTV Requirement Summary

Figures 2-3, 2-4 and 2-5 illustrate various versions of OTV's that might be used in the next 10 to 15 years. Generally these vehicles would have propellant requirements less than 68,000 Kg (150K pounds) per stage. Specific hardware requirements shown in Figure 2-4 will be described in Section 2.2.

Prior to committing to a space-based OTV, it would be desirable to perform an experiment which models a Shuttle tanker/OTV configuration and its refueling operation. Figure 2-6 illustrates a tanker/OTV tanking arrangement which for the present appears reasonable. This hard-docked configuration seems to be a better option than the tanker/OTV free-flying undocked arrangement.



EACH OF TWO COMMON STAGES

- FITS IN ORBITER PAYLOAD BAY 4.48 m DIA × 16.46 m LENGTH (14.7 FT × 54 FT)
- 53,000 kg (117,000 LB) HYDROGEN AND OXYGEN (MAY BE TANKED ON ORBIT)
- ENGINES· ASE OR ADVANCED RL-10

Figure 2-3. Typical All-Propulsive OTV Stage Configuration.

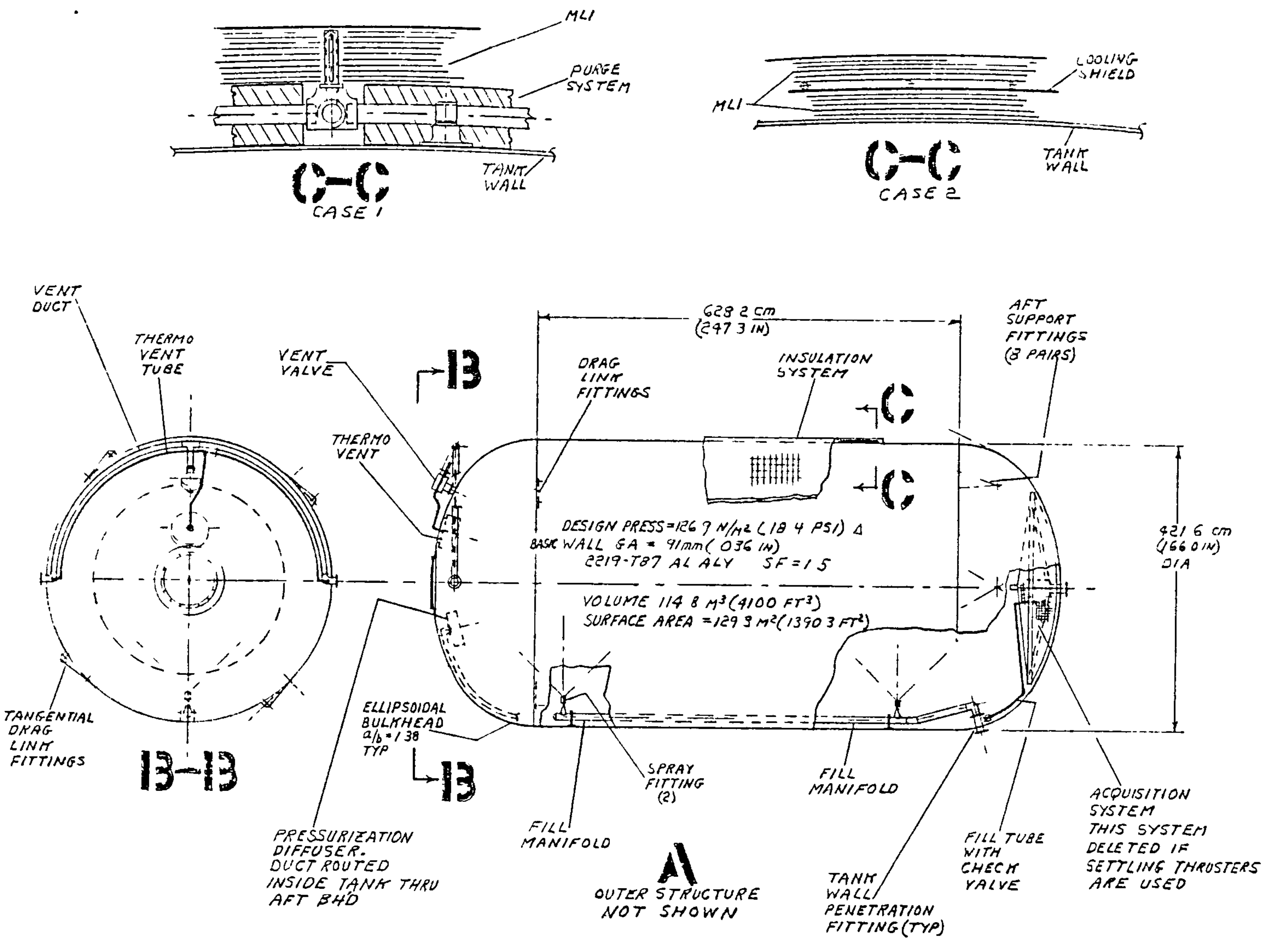


Figure 2-4. OTV Hardware Requirements.

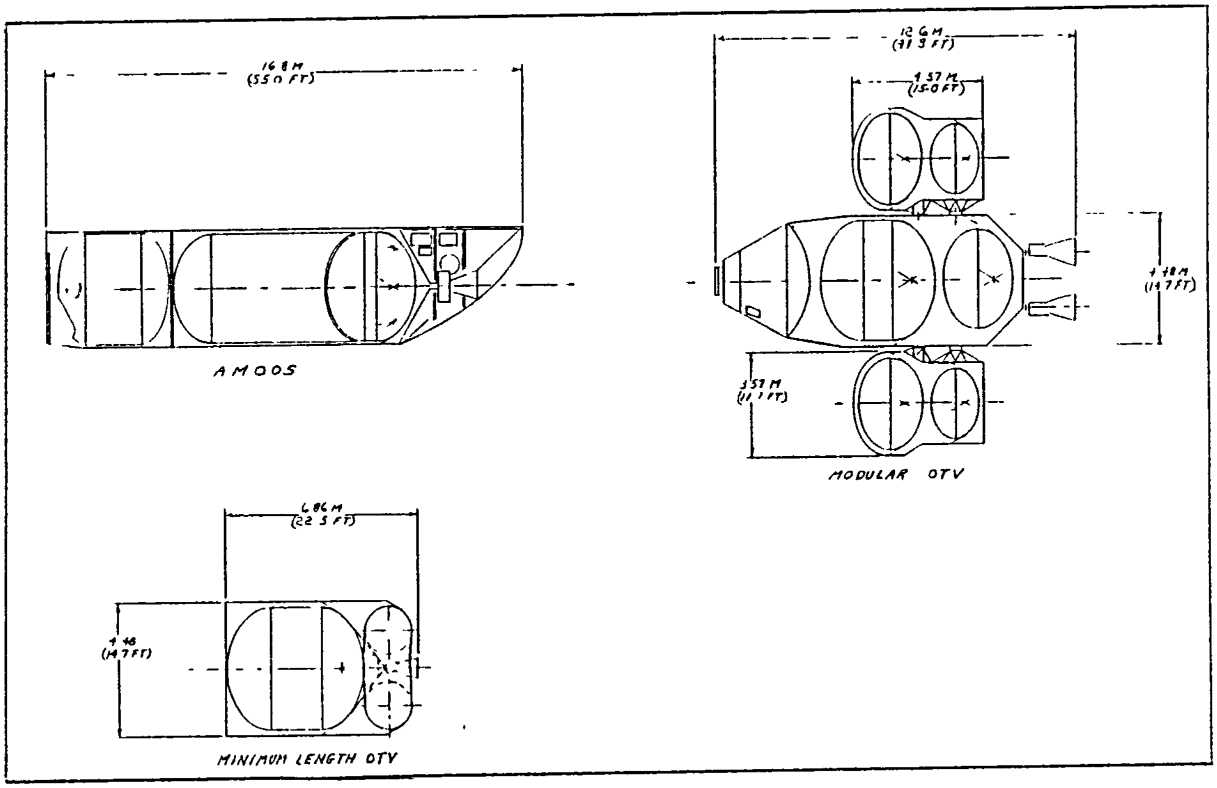


Figure 2-5. OTV Configuration Candidates.

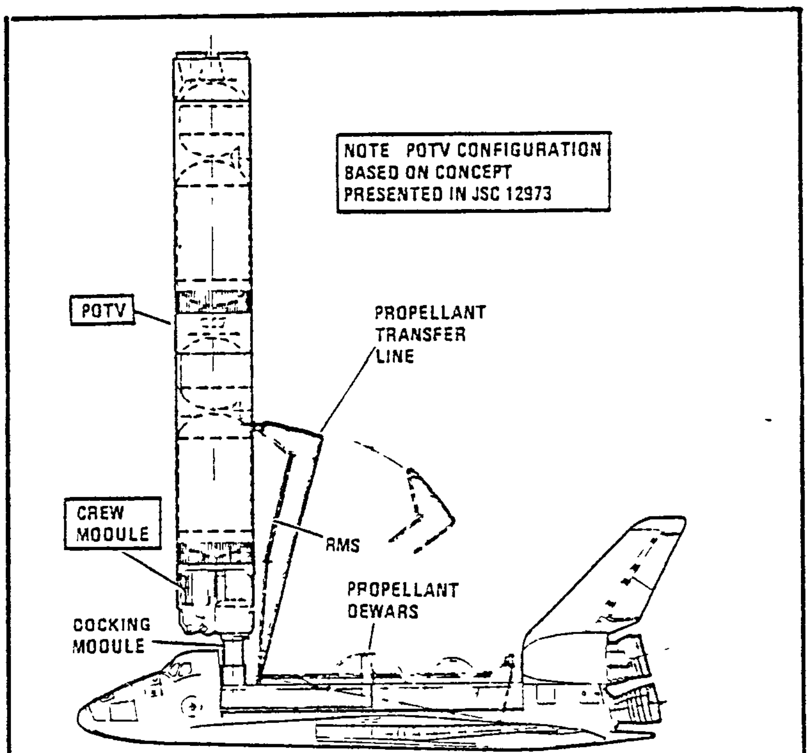


Figure 2-6. Baseline Orbiter Tanking Arrangement.

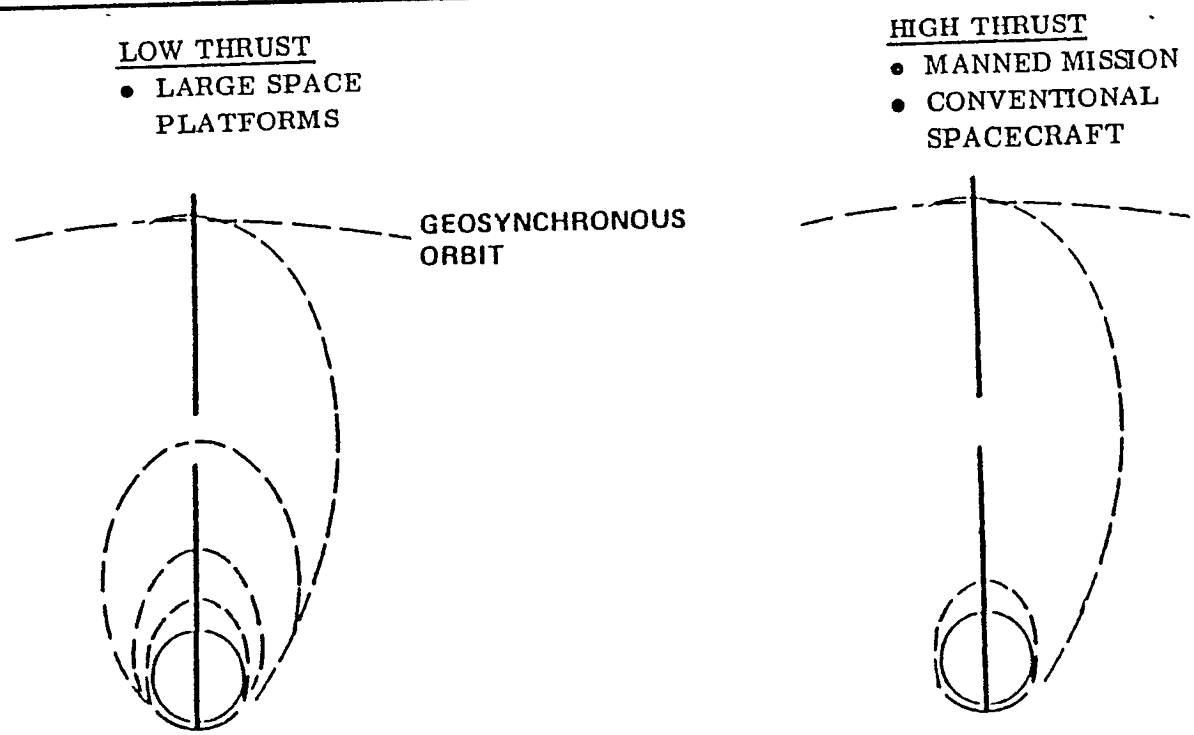
There are some important factors that should be considered for this tanking arrangement other than just the transfer of propellant from one system to another. One is the dynamics between the two systems. As propellants flow and mix, various loads may be set up between the two vehicles which require evaluation. Shuttle control requirements during preparation, loading, and post loading operations should be considered; a timeline for these events will be discussed later. The interactions of the remote manipulating system (RMS) and the transfer lines swivels and disconnects should also be analyzed. Another requirement is that the OTV propellant tanks must have the capability of receiving propellants both in a warm condition (dry) or in a cold condition (wet). Space-based vehicles may require loading soon after the completion of a mission before all propellants have boiled-off.

The OTV may operate both in a high or low thrust acceleration mode as shown in Figure 2-7. These requirements may be of secondary importance to the actual propellant flow experiment. However, any element of design or operation that may affect the final experiment conceptual design must be considered.

Figures 2-8 and 2-9 show the timelines involved in tanking and mission operations derived from Reference 2-3. The proposed fill-time for approximately 43,500 Kg (100,000 lbs) of propellants is only three hours as shown in Figure 2-8. This time was based on transferring both liquid oxygen and hydrogen to a space-based vehicle. Compared to the time requred for all other events (60 to 85 hours) the propellant transfer time is insignificant. Therefore, if extending the transfer time becomes an important trade consideration it is important that the total time line be re-evaluated for operational acceptability.

During a recent propellant handling study, Reference 2-1, ground turnaround time of the Shuttle was found to be significant in overall mission duration. Figure 2-9 shows this time to be approximately 136 hours based on the groundrules shown. The analysis was based upon supplying propellant from a 43,500 Kg (100,000 lb) capability Shuttle to a dual stage 53,000 Kg (117,000 lb) All Propulsive OTV (APOTV) capable of transporting 6,800 Kg (15,000 lb) round trip from LEO-GEO-LEO. Based on using one tanker and one launch pad the duration between partially filling the second stage of the APOTV and final topoff of that stage on the third Orbiter flight, was approximately 4 weeks.

Another factor which must be considered in the propellant transfer operation is the propellant loading accuracy. Table 2-2 illustrates that a one percent loading error yields a 6 to 13 percent loss of payload for the dual-or single-stage, APOTV, respectively. A status review of zero-gravity mass measurement devices was accomplished under contract NAS3-21360. The results of this survey can be found in Reference 3-3. The zero-gravity tanking accuracy problem is presently unresolved.



REQUIREMENT CONSIDERATIONS

- ENGINE FIRINGS: ASCENT: 3 TO 9 TIMES
  DESCENT: 3 TO < 9 TIMES
- COAST DURATIONS: 90 MIN. TO 5 1/4 HRS BETWEEN BURNS
- LOITER TIME AT GEO: 1 → 30 DAYS
- POWER AND APS FOR LOW THRUST PROFILES REQUIRE LARGER TANK SIZES
- LOW THRUST MISSION DURATION FOR ASCENT AND DESCENT IS APPROXIMATELY 60 HRS (8 PERIGEE BURNS)

Figure 2-7. Typical OTV Operational Interface.

EVENT	ELAPSED TIME (HR)	CUMULATIVE TIME (HR)
ORBITER LAUNCH	1	1
RENDEZVOUS PHASING*	0 - 24	1
RENDEZVOUS	5	6
CLOSING AND DOCKING	2	8
POTV CHECKOUT/INSPECTION - IVA	2 (EST)	10
CREW SUSTAINING ACTIVITY	14	24
POTV MAINTENANCE - EVA**	10 (EST)	34
CREW SUSTAINING ACTIVITY	14	48
PROPELLANT TRANSFER	3	51
SEPARATION	—	51
THERMAL CONDITIONING + ENTRY PHASING	< 12 - 15	63
REENTRY	0.5	64

DAYS 0 1 2 3

*ASSUMED ORBIT PHASED WITH LAUNCH SITE (31° INCLINATION, 478 km (258 N MI.) ALTITUDE), OTHERWISE RENDEZVOUS PHASING IS 0 - 24 HR.

**NOMINAL ALLOWANCE FOR ROUTINE INSPECTION OF OTV WITH MMU AND REPLACEMENT OF MODULES REQUIRING MAINTENANCE (CONDITION MONITORED MAINTENANCE).

EVENTS PRIOR TO PROPELLANT TRANSFER MUST BE CONSIDERED AS PART OF THE PROPELLANT MANAGEMENT OPERATION

Figure 2-8. Typical On-Orbit Resupply Operations

EVENT/DAYS
GROUND TURNAROUND - 136 HR
PREPARE FOR LAUNCH - 24 HR
MAINTENANCE, PROP TRANSFER, STG 2
GROUND TURNAROUND - 136 HR*
PREPARE FOR LAUNCH - 24 HR**
MAINTENANCE, PROP TRANSFER, STG 1
GROUND TURNAROUND - 136 HR*
PREPARE FOR LAUNCH - 24 HR
TOPOFF STG 1 & STG 2, MATE CREW MODULE
5 DAY SORTIE
RETURN CREW & CREW MODULE

WEEKS 1 2 3 4 5 6 7

ORBITER COMMITTED FOR 47 DAYS

*2 SHIFTS, NO WEEKEND OPERATION

**3 SHIFTS FOR PAD PROCESSING

INSULATION SYSTEMS MUST CONSIDER LOITER TIMES OF 4 WEEKS WITH PARTIALLY FULL TANKS

Figure 2-9. Typical On-Orbit Resupply Operations

2.2 OTV SUBSYSTEM INTERFACE

The candidate OTV concepts were used as the basis for: (1) OTV subsystem analyses and (2) OTV subsystem designs. These task elements represent the technology and operational problems that are considered typical of the OTV family that the preliminary experiment definitions of Task II will consider (see Section 3).

Table 2-2. OTV On-Orbit Resupply Interactions

One percent loading error* yields:

Vehicle	Stage	Payload Reduction, Percent
Dual Stage	1	1.7
	2	5.0
Single Stage	1	13.0

*Present technology indicates loading error of 2 to 4 percent.

2.2.1 OTV/SUBSYSTEM ANALYSES. The space-based OTV will be configured on the basis of mission and space-based requirements. However, because of the volume impact of the Shuttle payload bay, some of these OTVs may be loaded with propellant during their initial launch and, therefore, require the dual capability for propellant tanking both in space and at the launch site. A list of subsystems influenced by mission requirements will include tank size, pressurization system, propellant acquisition system, insulation system and vent system. Subsystems influenced by space-basing requirements will include insulation system and vent system. Rationale for selection of subsystems influenced by mission requirements will be discussed first. This selection process will be followed by a description of a "typical" OTV scenario from which potential problems can be identified and subsystems selected.

An OTV propellant transfer technique and subsequent experiment can be influenced by the vehicle configuration; thus, the need to adequately identify vehicle subsystems. It is possible, however, that a few subsystems will have little or no influence upon orbital propellant transfer. For these cases selection will be made on the basis of compatibility with mission requirements.

Before discussing how subsystem selection may influence the orbital propellant transfer procedure, the potential precursor tanking concept selected from Reference 3-3 (NAS3-21360) will be briefly discussed. The following steps will serve as the primary elements of an acceptable propellant transfer procedure: initial vent, prechill, fill.

2.2.1.1 Initial Vent. The propellant tank will be vented to 13.8 KN/m^2 - 27.6 KN/m^2 (2-4 psia) prior to transferring propellants. This step is performed for two purposes: First, helium may be present and it should be removed to avoid excessive helium partial pressure at small ullage volumes. Second, a near-zero initial pressure will minimize peak pressures and the number of charge and vent cycles required during prechill. Venting of a partially full tank is not considered as normal operation, the details of this type of venting procedure is presented in Reference 3-3.

2.2.1.2 Receiver Tank Prechill. Prechill is required whenever initial temperature is such that the stored tank energy will result in excessive pressure during the chilldown mode. Prechill is accomplished by introducing liquid into the propellant tank at a velocity that provides good heat exchange between the high temperature walls and the cooling fluid. This procedure has the advantage of requiring little mass to effect tank cooling.

The primary requirement for system prechill is to reduce tank temperatures sufficiently that the fill process will be accomplished with a locked-up tank. It is implicit in this requirement that venting is unacceptable during the fill mode because an unknown quantity of liquid could be lost overboard, since propellant control cannot be maintained during this process. Venting is acceptable during prechill, however, because the elevated tank temperatures will quickly evaporate liquid during this phase.

2.2.1.3 Tank Fill. Tank fill will be initiated after the prechill requirements have been satisfied. The single requirement for tank fill is to maintain an acceptably low pressure during the process. Tank pressures will be at minimum if thermal equilibrium conditions are maintained during fill.

The intent of the tank fill process will be to create conditions conducive to attaining near-thermal equilibrium. These conditions may be achieved by introducing liquid into the tank through spray nozzles; the resulting spray will create a large liquid/vapor surface area. The combination of large surface area and fluid turbulence will provide the high heat-transfer rates needed to attain near-thermal-equilibrium conditions.

2.2.1.4 Subsystems Influenced by Mission Requirements. The mission extremes for which subsystem compatibility must be assured were previously identified in Figure 2-7. These extremes included the low thrust, multi-burn missions required for placing large space platforms in geosynchronous orbit, and the high thrust mission (with fewer engine firings) required for placing more conventional payloads in orbit.

2.2.1.5 Tank Size. Tank size and shape can influence the orbital propellant transfer procedure or technique, but not the concept. Figure 2-5 shows three potential vehicle configurations. It appears obvious that the internal fluid flow pattern will differ for each configuration during the prechill or tank fill process. Since heat and mass exchange between tank wall and fluid, or between the liquid and vapor phases, will be influenced by the flow pattern, this mechanism will be different for each vehicle configuration. Consequently, analysis or experimental data applicable to a single vehicle configuration will not necessarily apply to others. We are left with the task of selecting a representative vehicle for experimentaion. The POTV configuration of Figure 2-4 will be less restrictive than the toroidal tank or modular OTV concepts of Figure 2-5.

2.2.1.6 Pressurization System. The selected pressurization system will require helium for propellant tank pre-pressurization for each main engine start. Pressurization requirements during main engine firing will be autogenous for the liquid hydrogen tank and helium for the liquid oxygen tank. Main engine start helium usages will not be excessive because engine start NPSP requirement will be approximately 3.5 KN/m^2 (0.5 psid) (LH_2 tank) and 7 KN/m^2(1.0 psid) (LO_2 tank). Total mission helium usages will be relatively small for the LO_2 tank because helium will be bubbled through the liquid bulk. The tank pressure increase will be primarily due to propellant evaporation into the helium bubbles. Autogenous pressurization was selected for the hydrogen tank because 1) it is a simple and proven approach, and 2) the alternative helium pressurization approach will be considerably heavier. This type of pressurization system was analyzed in contract NAS3-20092 (Reference 2-5).

The presence of helium within a propellant tank can complicate an orbital tanking procedure because of the need to expel most of the helium before propellant transfer can be initiated. Unfortunately, in the near term, there is no viable alternative to helium pressurization for main engine start because main engine NPSP requirements must be satisfied. An advanced engine with "bootstrap" capability, i.e., with no NPSP requirements, may be developed in the future. A major benefit from this development may be a greatly simplified refueling procedure. Until then, refuelling operations must be capable of dealing with helium inside the propellant tanks.

2.2.1.7 Propellant Acquisition System. Analyses were performed in reference 2-5 to assess the benefits of a partial propellant acquisition system for OTV. The acquisition system combined with a thermal subcooler was analyzed to determine if these subsystems could replace helium pressurization and RCS subsystems. A preliminary assessment indicates that an acquisition system is not performance effective over current pressurization systems for a number of OTV missions. Furthermore, partial acquisition devices, different from that shown in Figure 2-10, may be required for low thrust vehicle missions. At this time, it is judged that a partial screen acquisition device will not be included as part of an OTV configuration. However, an exception to subsystem selection is made in this case as explained below.

A partial screen acquisition device has tentatively been selected for the orbital experiment because the possibility exists that such a device may be employed in the future. The presence or absence of a screen device should have little or no impact upon the ability to demonstrate orbital refuelling techniques. It may be necessary to alter propellant tank internal plumbing in order to assure the start basket is "vapor-free" at the end of tanking. But, such an alteration would have no impact upon the refuelling process. Furthermore, a screen device would allow additional flexibility in designing secondary experiments because pure liquid expulsion from the receiver tank could be assured with a partial acquisition device.

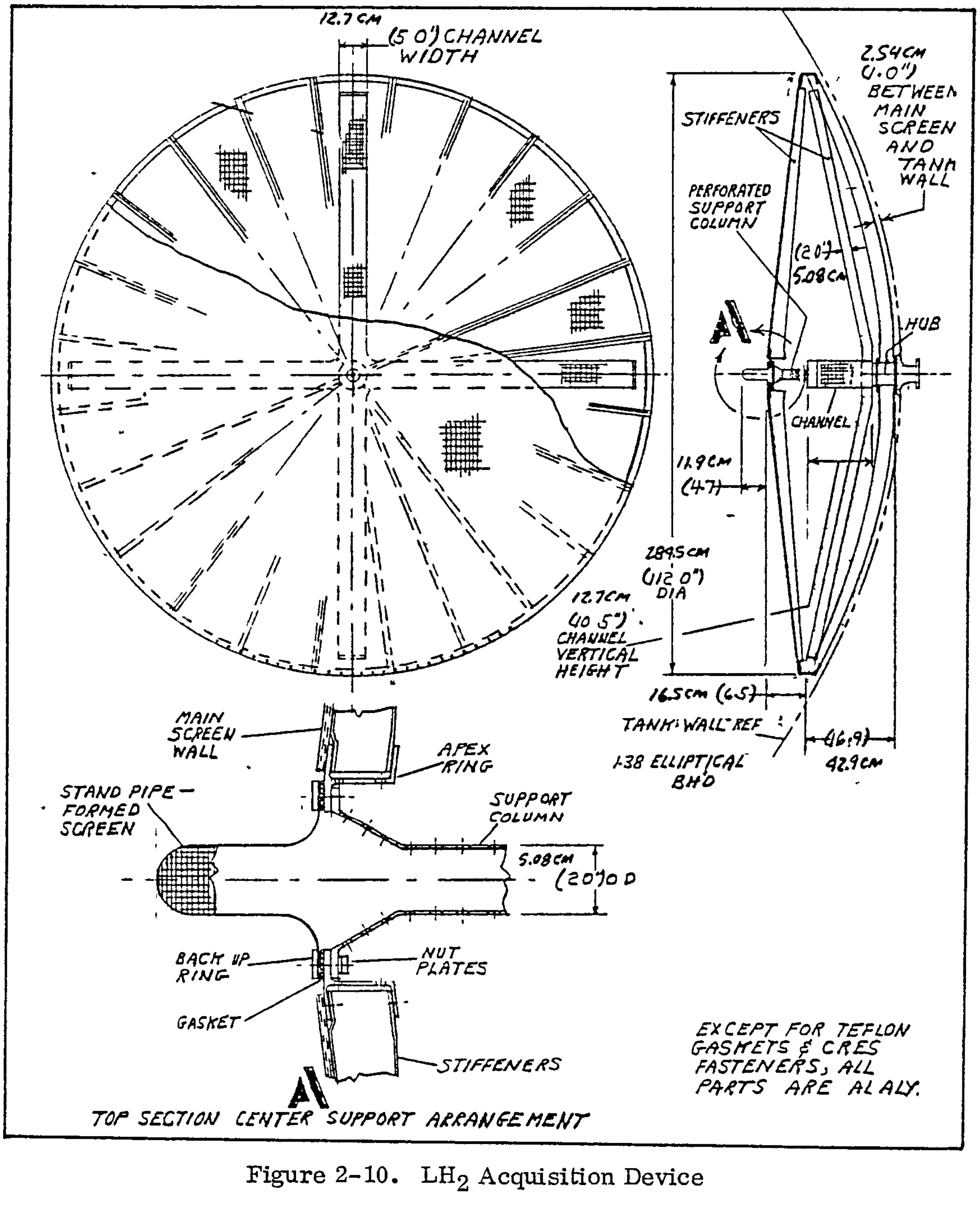


Figure 2-10. LH_2 Acquisition Device

2.2.1.8 Insulation System. A multilayer insulation (MLI) system was selected as representative of thermal protection systems which may be employed for OTV. The other alternative considered was a combination of MLI and a vapor-cooled shield. Introducing a vapor-cooled shield will improve the thermal performance of the combination because vented propellant will intercept solar heat addition. It is suspected, however, that the reduced boiloff or vapor residuals due to improved performance will not compensate for the weight addition.

The only influence that an MLI system selection may have upon the propellant transfer technique will be due to vehicle thermal mass. If a vapor-cooled shield adds substantial mass to that vehicle mass which is chilled to cryogen temperatures, then peak pressures and boiloff during tanking will be greater. These changes would have to be factored into orbital tanking procedures. As before, the propellant tanking concept would not be affected by subsystem selection.

2.2.1.9 Vent System. A thermodynamic vent system will provide adequate vent capability for the proposed OTV mission profiles. Analyses conducted on previous studies (Reference 2-5 and 2-6) indicate that mission vent requirements will be in the range of 4.5 to 9.1 Kg/hr (10 to 20 lb/hr), which can be adequately satisfied with thermodynamic vent systems previously designed by GD/Convair. These vent rates can be reduced, if necessary, by adding more layers of MLI. There was no alternative vent system considered.

The vent rate capability of the thermodynamic vent system appears to be inadequate for refuelling procedures on-orbit. Additional consideration for supplemental vent capability may be necessary to avoid impact in selecting a refuelling procedure. Further discussion will be postponed until after the influence of space-basing requirements upon this subsystem has been evaluated.

2.2.1.10 Subsystems Influenced by Space-Basing Requirements. Space-basing conditions are defined as those conditions affecting the OTV from final MECO of each stage until first main engine start of the next mission. The period where OTV and orbiter are docked is exempted since it is considered to be part of the tanking duration. Any subsystem capability needed to maintain the OTV in a "safed" condition for subsequent refuelling operations is considered to be a space-basing vehicle requirement. The insulation and vent systems selection will be influenced by space-basing considerations. At this time, no other system is identified as being influenced by these considerations.

Insulation System — In addition to the mission requirements previously identified, the insulation system must provide thermal protection for propellants where multiple orbiter flights are needed to support a single OTV mission. For this scenario, it is likely that the OTV stages will reside in orbit for several weeks before tanking is complete. Too little insulation will result in excessive propellant boiloff prior to a mission. Conversely, excessive thermal protection (i.e., a vapor-cooled shield) may unnecessarily penalize OTV payload capability. As mentioned earlier, an analysis will be conducted in task II to determine which insulation system should be selected.

Vent System — There is an advantage to performing propellant tank blowdown to a low pressure 13.8-27.6 KN/m^2 (~ 2-4 psia) prior to initiating orbital refill. This operation could be performed with the thermodynamic vent system except that its vent capability could result in an extremely long blowdown mode. The propellant mass vented during this orbital period is likely to be at least an order of magnitude greater than the mass vented during the mission. Furthermore, the long blowdown duration could delay rendezvous by several days. It appears, therefore, that a requirement exists for another vent system capable of vent rates that are at least an order of magnitude greater than those of the thermodynamic vent system. We have selected the non-propulsive vent system for the LH_2 tank identified in Figure 2-4.

2.2.2 OTV SUBSYSTEM DESIGNS. The fundamental OTV operational and environmental considerations used for the preceding subsystem analyses were also used to develop a set of typical subsystem designs.

Figure 2-4 (Layout 1) shows a LH_2 tankage system for a baseline two stage OTV, that is originally tanked with propellant on the ground and subsequently tanked at a space-based propellant depot. The total system is a cylindrical tank equipped with a fill circuit, non-propulsive vent circuits, a pressurization circuit, an acquisition system and an insulation system.

The tank is a 421.6 cm (166.0 in.) diameter cylinder equipped with elliptical bulkheads at each end. Both bulkheads have plumbing penetration fittings for the vent, fill and electrical circuits. An access opening is provided in the forward bulkhead. The material is 2219-T87 aluminum alloy. The support system is a series of low conductive struts arranged in "V" pairs on the aft bulkhead and a set of tangential drag links located near the girth line of the forward bulkhead. This support system provides for thermal isolation from the main body structure and compensates for dimensional changes between tank and outer body structure.

The fill circuit is a single tubular manifold extending the full length of the tank. The manifold is equipped with two spray fittings in the aft bulkhead. This penetration fitting has a side outlet boss which in turn is connected to the interior of the acquisition device through a check valve and a tube section. The outboard flange of the penetration fitting is attached to a flex duct which routes to a disconnect valve located in the body structure. This flex duct and disconnect valve are not shown on the drawing.

The tank has two vent systems. One system is an external vent valve with a non-propulsive "steer horn" type duct. The second system is a thermodynamic vent device located inside the tank. This device is vented to the outside through a tube which is supported from the "steer horn" vent duct (see View B-B of Figure 2-4.

The LH_2 tank is pressurized with helium gas at engine start. During engine firing, pressurization is accomplished by boot strapping hot H_2 gas from the engines (autogenous pressurization). The helium source for the initial pressurization is preloaded spherical bottle modules attached to the outside of the body structure. These modules are plumbed to the tank through a valve and regulator system. The pressurizing gas is injected into the tank through a diffuser located at the forward bulkhead. This diffuser is plumbed to an aft bulkhead penetration fitting with a duct assembly supported from the inside of the tank wall.

Figure 2-4 (Layout 1) also shows an acquisition system located in the aft bulkhead. Some typical details for this system are shown in Figure 2-10 which was previously configured under NASA Contract NAS3-20092 (Reference 2-5). The system is basically a capillary device consisting of an external dish type shell equipped with an internal channel assembly and a central support column. The walls are screen mesh supported with perforated sheets.

Two insulation approaches using MLI blankets are shown in View C-C on Figure 2-4. The first approach Case 1 uses MLI blankets mounted on a purge system that is used only during the ground tanking of propellant prior to normal space-based operations. The purge system is a network of tubing (mounting from the tank wall) which distributes dry gas between the insulation layers. Foam blocks located between the tubes and bonded to the tank wall provide a uniform mounting base for the MLI. In this case, the outer body structure serves as the purge enclosure. Additional purge enclosures at each end of the LH_2 tank may be required to isolate the LH_2 tank from the second stage engine compartment and from the LO_2 tank.

In Case 2, a cooling shield is located midway in the MLI buildup. This is an aluminum alloy shield equipped with tubes through which H_2 vent gas passes. Local standoff fittings support the shield from the tank wall. A purge system would also be required for this system to ensure insulation conditioning prior to accent.

Figure 2-11 (Layout 2) shows a LO_2 tankage system for a baseline two-stage OTV. Similar to the system described in Figure 2-4 (Layout 1), the tank is a 381.0 cm (150.03 in.) dia. cylinder equipped with an elliptical bulkhead at each end. Both bulkheads have plumbing penetration fittings for the fill vent and electrical systems. An access opening is also provided in the forward bulkhead of this 2219-T87 aluminum alloy tank. The support system is the same as that described for the LH_2 tank. All outer surfaces of the tank are covered with MLI.

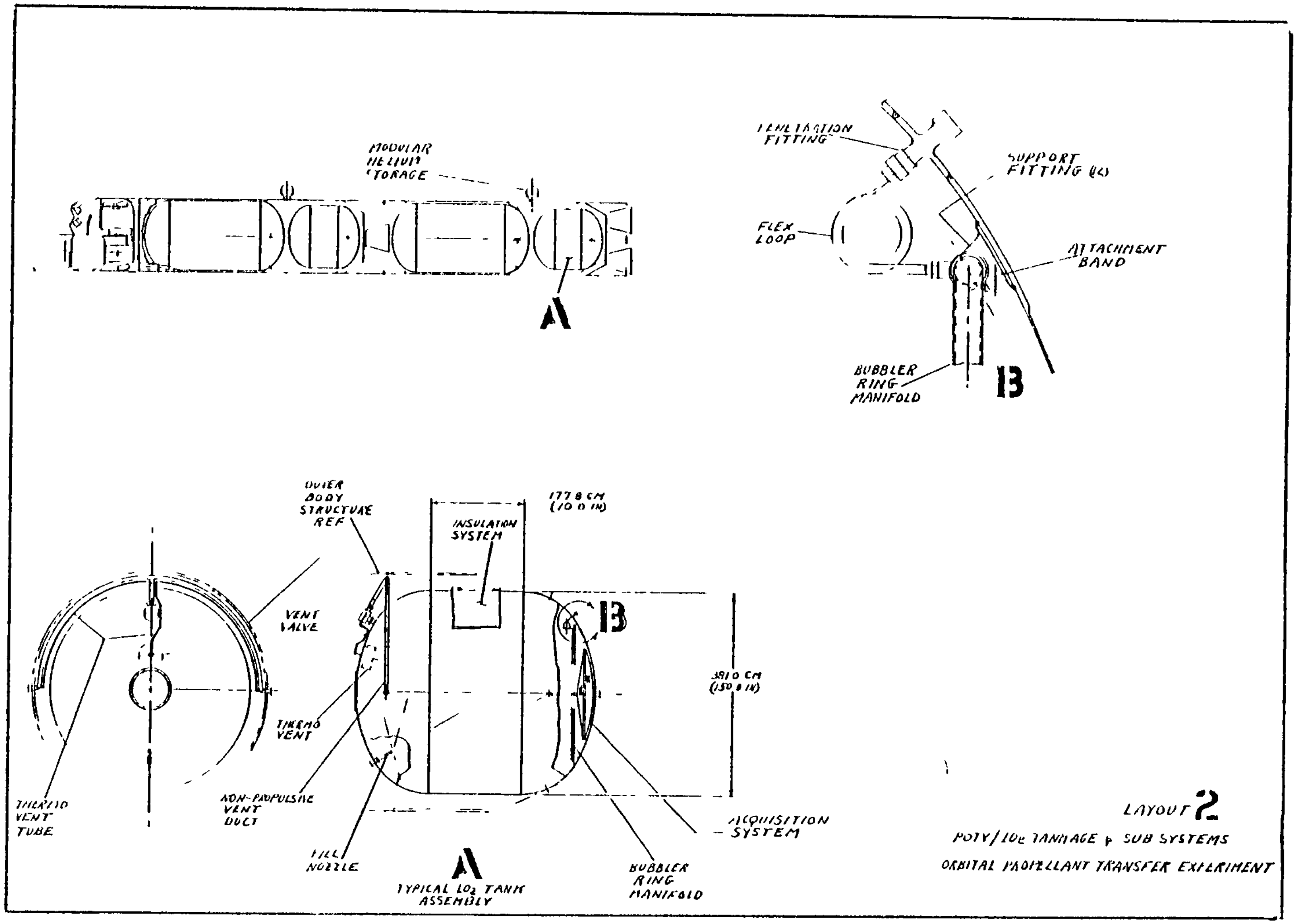


Figure 2-11. Typical LO_2 Tankage and Subsystems

The fill circuit is a single nozzle assembly located at the forward bulkhead. This location was chosen so that the LH_2 and LO_2 fill disconnects located in the body structure can have common station locations. This location minimizes the fill duct lengths and reaching requirements for the RMS.

The vent systems described for the LH_2 tank are basically the same for the LO_2 tank.

Pressurization for the LO_2 tank before and during engine firing is with helium only. A ring manifold with a series of holes is supported from the inside surface of the aft bulkhead as shown in detail "B" of Layout 2. The helium storage concept is the same as that described for the LH_2 system. After leaving the storage module, the helium flows through a control and regulator systems and on to the ring manifold. The gas is injected into the tank through the holes in the ring manifold.

Figure 2-11 (Layout 2) shows an acquisition system located in the aft bulkhead. Except for size, the system is basically the same as that required for the LH_2 tankage system. Some typical details are shown in Figure 2-12.

The insulation system for the LO_2 tank is the same as Case 1 previously described for the LH_2 tank.

A wide range of propellant tankage is represented in the OTV configurations shown in Figure 2-5 (Layout 3). The AMOOS vehicle for example uses separated tanks which are nested to minimize the overall length. The modular vehicle which uses "strap on" propellant assemblies features separate conventional ellipsoidal tanks which are not nested. A third configuration called a minimum length OTV uses a cylindrical LH_2 tank coupled with a LO_2 toroidal tank. The propellant transfer systems described earlier are also applicable to the tanks shown in Figure 2-5. For example, the single fill nozzle shown in Figure 2-11 for a conventional LO_2 tank can also be applied to the toroidal tank by using an internal manifold equipped with two or more spray nozzles. For the nested or compartmentized tanks, the fill nozzle is relocated to the sidewall or aft bulkhead of the LO_2 tank. Except for location and plumbing routes, vent systems are also basically common for conventional and non-conventional tanks.

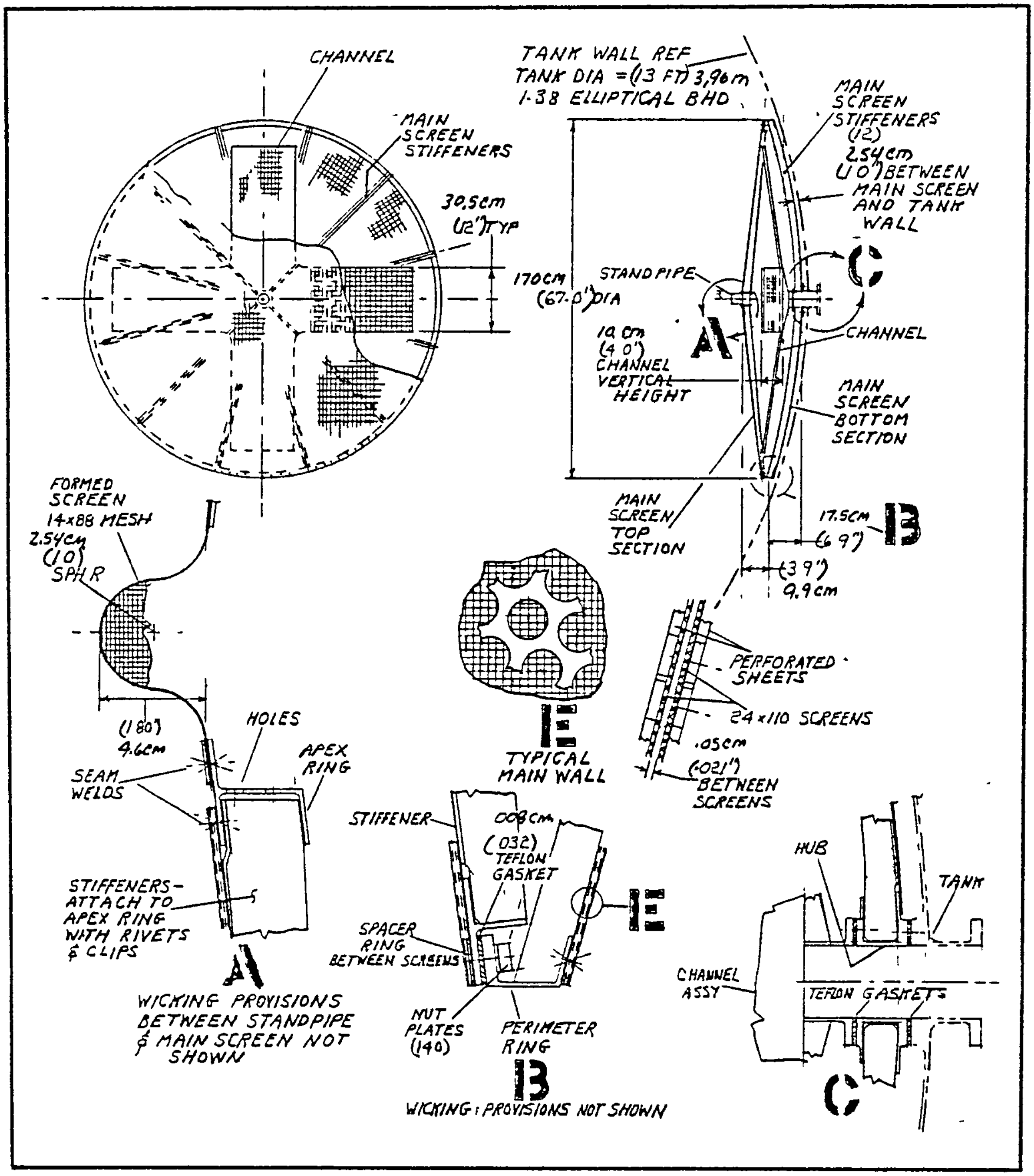


Figure 2-12. LO_2 Acquisition Device

3

PRELIMINARY EXPERIMENT DEFINITION (TASK II)

During recent years NASA has developed, both through in-house and contracted effort, an extensive background of low gravity propellant management technology. References 3-1, 3-2, and 3-3 are typical of these pertinent studies. It was not required nor the intent of this study to expand upon this fundamental technology data base. This available source of published data was used as the basis for the preliminary definition of a large-scale propellant transfer experiment for the Shuttle experiment program.

The individual study task outputs are organized into three separate sections. Section 3.1 describes the basic analyses; Section 3.2 presents the preliminary experiment concepts; and Section 3.3 defines the preliminary experiment designs.

3.1 ANALYSES

The preliminary experiment definition required that the most impacting areas of concern be analyzed at this stage of the study. Figure 3-1 presents an overview of these preliminary, yet fundamentally important, factors associated with the experiment design. The schematic represents the three major hardware elements of the experiment concept and the specific technology areas relevant to the specific hardware items. The general areas selected for analyses during this task are: 1) the chilldown and 2) the fundamental experiment design and operational drivers. The results presented for this phase of the study should be considered preliminary. The final results presented in Section 4.0 of this report represent those actually used to develop the conceptual designs and program plans.

3.1.1 TRANSFER LINE CHILLDOWN. When chilldown is initiated, liquid and vapor flow in the transfer line together create pressure transients and chugging. These transients, together with the motion of slugs of liquid in the vapor medium, may transmit damaging loads to the OTV during the line chilldown period. Several possible methods of avoiding this difficulty have been suggested. These include propellant pre-heating, alternate propellant delivery systems during chilldown, and pre-launch chilling.

To obtain an estimate of a reasonable time for the chilling of the transfer lines, an analysis was made assuming liquid enters the line in a saturated condition and evaporates completely prior to leaving the line. Using a flow rate of 0.45 kg/min (1 lb/min), results indicate the LH_2 line can be cooled from 305K to 20K (550R to 36R) in about 14 minutes. Since chilldown time varies inversely with mass flow rate, these results may be used to estimate times for other flowrates within a reasonable range.

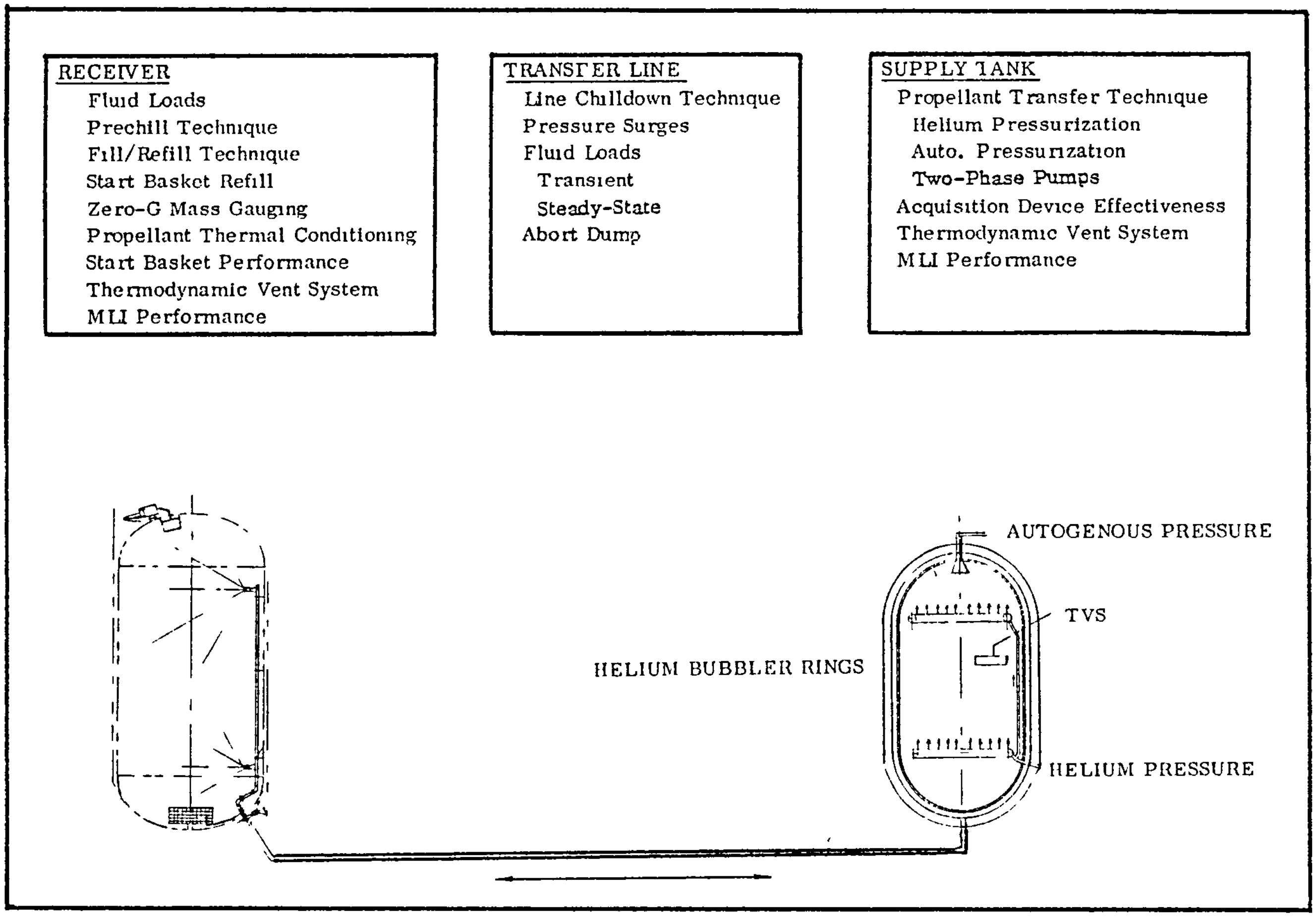


Figure 3-1. Propellant Transfer Areas of Interest/Concern

When the transfer line valve is first opened, cold liquid will contact the hot walls so that a certain amount of vapor and liquid will flow in the line together. Under 1-g conditions, studies (References 3-4 and 3-5) have shown that severe pressure transients, some as high as 100% above the supply pressure, can result. These excursions, together with the prospect of slugs of liquid battering the OTV at the hook-up point, give cause for apprehension about loads transferred to the OTV and ultimately to the connecting fixture between it and Shuttle. Hence, it is desirable to avoid formation of liquid slugs, pressure surging, and chugging during the chilldown process.

3.1.1.1 Transfer-Line Chilldown under One-g Conditions. Many studies (both experimental and analytical) have been made regarding transfer-line chilldown; however, none have been found that were conducted for low-gravity conditions. Generally, in a two-phase flow, a number of flow regimes are possible, characterized by the relative amounts and location of the liquid and vapor. Some of the possibilities are mist flow, annular flow, slug flow, wavy flow, stratified flow, plug flow, and bubble flow. It is apparent that gravity plays a role in the development of some of these regimes. Although methods have been proposed (Baker plot) which attempt to predict which regime is most likely, these methods do not correlate the data well for all regimes.

According to Steward, Smith, and Brennan (Reference 3-4), who studied the chilldown times and characteristics of horizontal LN_2 and LH_2 transfer lines, the following factors aggravate surging:

1. High degree of inlet liquid subcooling

2. Long transfer lines

3. Higher density liquids

4. Rapid valve opening

They recommend saturation conditions at inlet and gentle introduction of fluid into the line. Pressure surges were found to vary directly with the length of the line, and surges with nitrogen were 2 to 4 times as high as with hydrogen.

Manson and Miller (Reference 3-5) studied the flow of LH_2 in lines constructed from CRES 321 and K Monel steels, Titanium, and Tens-50 Aluminum. Flow-rate stability was optimized by restricting the entrance rather than the exit of the line. The type of wall material was found to affect the heat flux-temperature curve. Presumably the presence of a certain amount of restriction to heat flow at the wall extends the nucleate-boiling regime into the normal film-boiling regime (thus enhancing heat transfer). One may not find this kind of result in low-gravity situations since there is some doubt about the existence of zero-gravity nucleate boiling.

3.1.1.2 Transfer Line Chilldown in Low Earth Orbit (LEO). If the transfer lines are to be chilled in low-gravity conditions, it is questionable how much of the above data can be used to advantage. It would seem reasonable to meter-in small quantities of the propellant at saturation conditions, probably as a spray. A small by-pass line which avoids the main valve in the transfer line appears desirable. Some introductory swirl may enhance mixing and help minimize direct impingement on the hot walls (thus avoiding cold spots which collect liquid).

One might expect 2 regions of the line to be a problem in regard to liquid collection. Those are the entrance where cold liquid spray will always be present to cool the wall and the point in the line where flow impinges on a bend. The wall in these regions will cool faster and tend to collect liquid at a correspondingly faster rate. An obvious remedy at the bend is to straighten the line as much as possible prior to chill-down. However, in order to minimize liquid collection at other points in the line (such as the entrance), one might wish to consider the distribution systems depicted in Figure 3-2.

In part (a) of Figure 3-2, a separate small line is run along the outside of the main line to meter cryogen into it at various locations. This line can be operated at supply tank pressure and will undergo less severe transients than the main line. Chugging and pressure surges in the small line will transfer much smaller loads to the orbiter. In part (b), the small line is located internally with spacers. Part (c) suggests an annular space in which to meter small amounts of liquid for cooling. The inner wall could be solid or screen. Again, the problem of collection of large amounts of liquid is addressed by confining the fluid to a smaller volume. A feed system at the entrance, separate from the main flow, would be required.

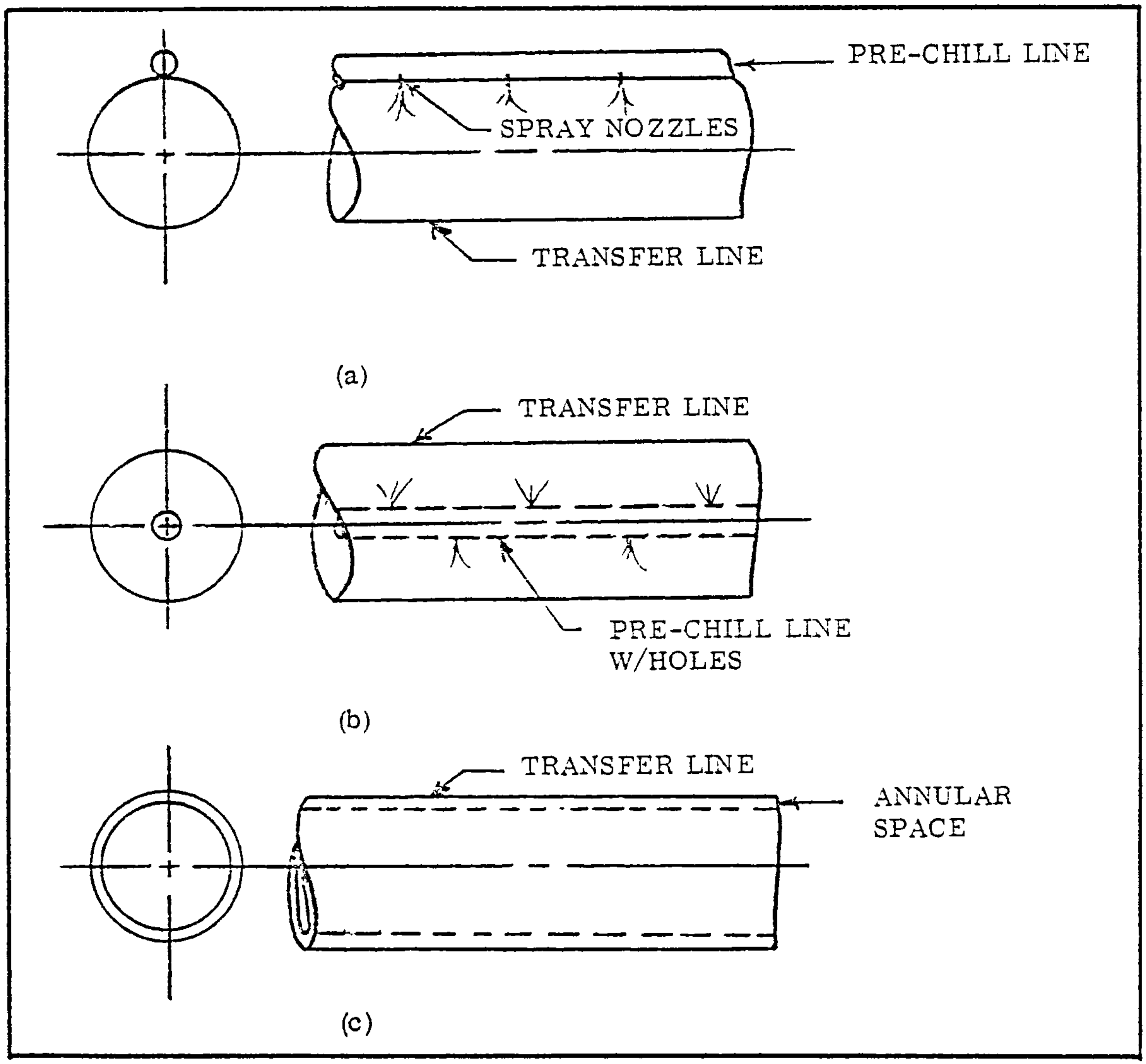


Figure 3-2. Transfer Line Chilldown Aids

Disadvantages common to all these chilldown aids are:

1. Introduction of additional thermal mass to the system to be chilled

2. Reduces useful payload weight available

3. Increased line fabrication complexity.

Another method for decreasing the amount of liquid collection is to install static mixers in the line. Briefly, the mixers work by splitting the flow into two streams and twisting it in a helix pattern until encountering the next downstream element where the process is repeated. The process serves to expose the flow to more wall area. Disadvantages include:

1. Addition of thermal mass and decreased useful payload.

2. Increase in pressure drop (though modest)

3. Increased line fabrication complexity.

A final method to avoid liquid in the line is to pre-heat the liquid in a boiler prior to entry. Only vapor at saturation temperature would be introduced into the line. Disadvantages include:

1. Increased chilldown time

2. Increased energy in the vapor at exit

3. Decrease in useful payload

4. Increased complexity of system

3.1.1.3 Disposition of Vapor in Transfer Line. The problem of disposing of the helium initially, and later the warm vapor in the line must be addressed. Although the total mass of this vapor is small compared to the total mass of propellant to be transferred, it should be vented. A vent might be provided at the OTV-end of the line. Back-pressure in the line could be controlled more effectively; and compared to tank venting, the possibility of losing liquid in any quantity would be minimized. This vent would also be used for transfer line pre-launch purging operations.

Alternatively, the vapor could be dumped into the receiver tank and take on more heat before venting through the tank vent system. However, this increases the tank ullage and increases the venting time required of the tank vent.

3.1.1.4 Analysis of Transfer-Line Chilldown. In order to obtain an estimate of line chilldown time, some assumptions were made, and the flow in the propellant transfer lines defined in Reference 3-6 was analyzed. It was assumed that:

1. Spray enters the transfer line in saturated condition at 103 KN/m^2 (15 psia) line pressure. For LH_2 this is approximately 20K (36R) and for LO_2 about 90K (162R).

2. The flow is predominantly vapor and is steady.

3. The wall of the line is at uniform temperature at any instant of time.

4. Exit temperature of the vapor approaches that of the hot wall.

5. Losses from radiation are negligible.

6. Initial wall temperature is 306K (550R).

The total amount of heat which must be extracted from the LH_2 line can be calculated from:

$$q = \int m C_V dT$$

where:

m = mass of line, valves, fittings, insulation

C_V = heat capacity of mass

T = wall temperature

A plot of the heat capacity of 18-8 stainless is shown as Figure 3-3. Composition is similar to CRES 304. Assuming the mass to be predominantly of this material the area under the curve can be integrated between 20K (36R) and 306K (550R) for LH_2 and 90K (162R) and 306K (550R) for LO_2. Total mass is 122 Kg (268 lb) for the LH_2 line and 155 Kg (333 lb) for the LO_2 line. The heat stored in the LH_2 line is calculated at 11130 KJ (10550 BTU) and in the LO_2 line at 12502 KJ (11850 BTU).

The details of a transient analysis of line chilldown for LH_2 are included in Section 3.1.1.5. Figure 3-4 depicts the results for a flow rate of 0.45 Kg/min (1 lb/min). The points shown on the plot were determined by incremental application of the solution. Properties for each increment were updated to reflect temperature dependence; hence, the points do not lie on a continuous curve. The line is an estimated best fit of these points. Time varies inversely with flow rate so that a corresponding time for any flow rate and temperature is available. For the 0.45 Kg/min (1 lb/min) flow rate, it can be seen that a chilldown time of 14-15 minutes is predicted. Gas velocities for various flow rates as a function of temperature are shown in Figure 3-5. For the .45 Kg/min (1 lb/min) value, gas velocity will not exceed 21 m/sec (70 ft/sec). This is well below sonic conditions which range from 355 m/sec (1165 ft/sec) @ 20K (36R) to 1329 m/sec (4359 ft/sec) @ 306K (550R).

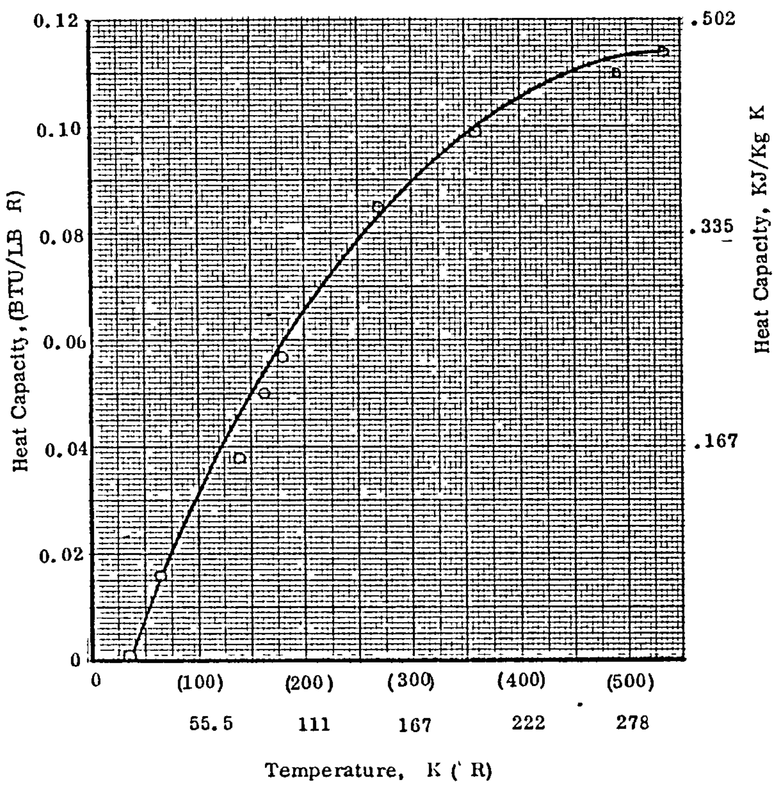
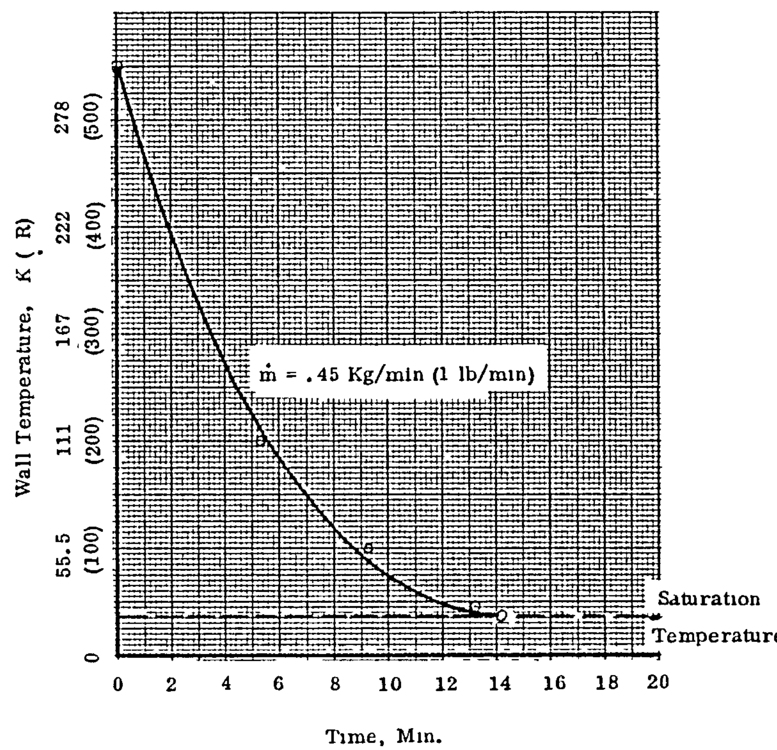
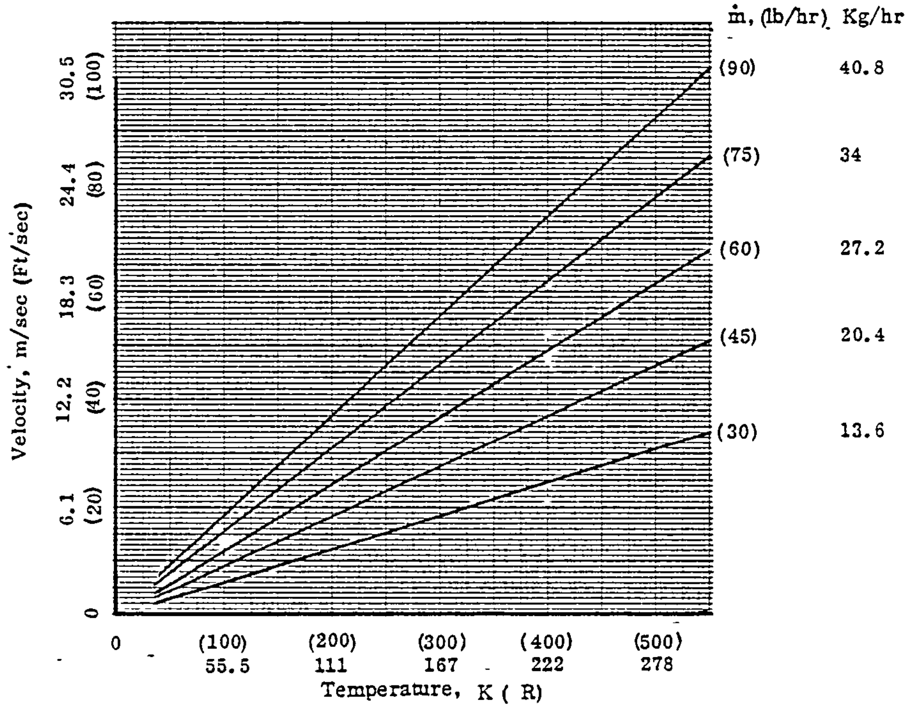


Figure 3-3. Heat Capacity of 18-8 Stainless Steel at Low Temperature



NOTES
1. Time inversely proportional to flow rate.
2. Radiation losses presumed negligible.
3. Gas flow only - no slug or annular flow.
4. Presumes sufficient heat transfer occurs to bring exit gas temperature up to wall temperature.

Figure 3-4. Transfer Line Chilldown Rate for Condition Where Initial Wall Temperature is 306K (550R) and LH_2 is Injected as Spray at 101 kN/m^2 (14.7 psia) and 20K (36R)



NOTE Line Pressure is 101 KN/m^2 (14.7 psia)

Figure 3-5. Gas Velocity Through Transfer Line as Function of Gas Temperature for Various Mass Flow Rates

The transient analysis was based on the assumption that exit gas temperature would approach the wall value. To verify that assumption, a solution was obtained for the overall heat transfer coefficient (U) necessary for exit temperature differences of 0.5K, 6K and 8.3K (1, 10, and 15R). The analysis is included in Section 3.1.1.5, and the results are shown in Figure 3-6. A curve for the convective heat transfer coefficient (h), assuming gas flow alone, is also shown.

Although the curve for h crosses the U - curves in the 111K (200R) region (for exit temperature differences of 5.5 - 8.3K (10 - 15R), it is to be expected that the actual value of h will be substantially higher than indicated by this model. Phase changes and the presence of liquid on the wall, even in small amounts, will augment heat transfer considerably. It is not unreasonable to expect values for U in excess of 612 KJ/m^2-hr-K (30 BTU/hr-ft^2-R). Even so, the model loses validity in the last few degrees of cooling. As the target temperature is approached, it will undoubtedly be possible to introduce larger quantities of liquid without undesirable consequences.

It is possible that pressure transients, liquid slugs, and chugging occur during the chilldown period. The effect of these phenomena on the structure of the OTV and the linkage between the Shuttle and OTV is unknown. If it is found that a severe problem exists, several methods to address it are available. It has been

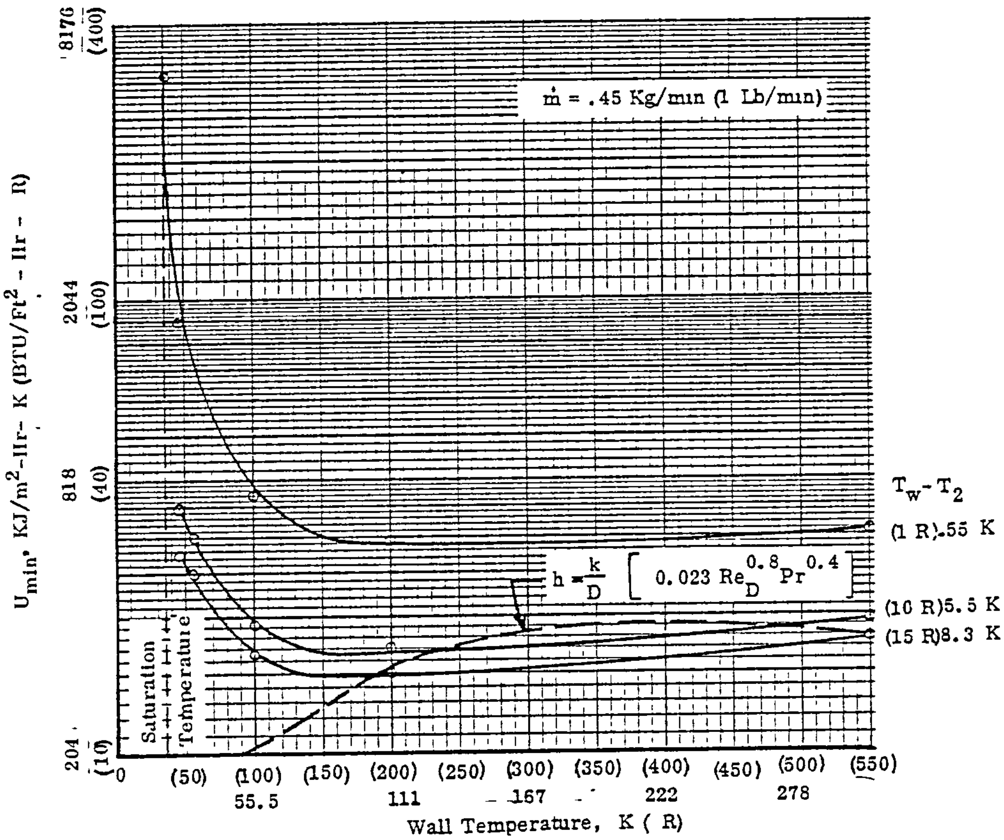


Figure 3-6. Minimum Overall Heat Transfer Coefficient Required to Satisfy Various Conditions Between Exit Gas and Average Wall Temperature of LH_2 Transfer Line

calculated that a chilldown time of approximately 1/4 hour can be achieved with a modest amount of propellant,6.8 Kg (15 lb). Since this time is a small portion of the total mission time it appears that the method which is most simple and avoids liquid collection and pressure transients should be selected at the expense of chilldown time. The best method under these criteria may well be to pre-heat the propellant so that only a gas enters the line. Whether this gas is vented prior to entry into the receiver tank or not is a matter for future consideration (see Section 4.3).

An estimate of the time required to chill the line by introducing only saturated gas was made. The heat of vaporization term in the equations developed in Section 3.1.1.5 was set equal to zero. The results are shown in Figure 3.7 for 0.45 and 0.9 Kg/min (1 and 2 lb/min) flow rates. Note that the curve drops below 28K (50R) at approximately 12.5 minutes for a 0.9 Kg/min (2 lb/min) flow rate and at 28 minutes for a 0.45 Kg/min (1 lb/min) flow rate. At this point one could probably introduce liquid into the line to accelerate cooling without the consequences of chugging and slug flow.

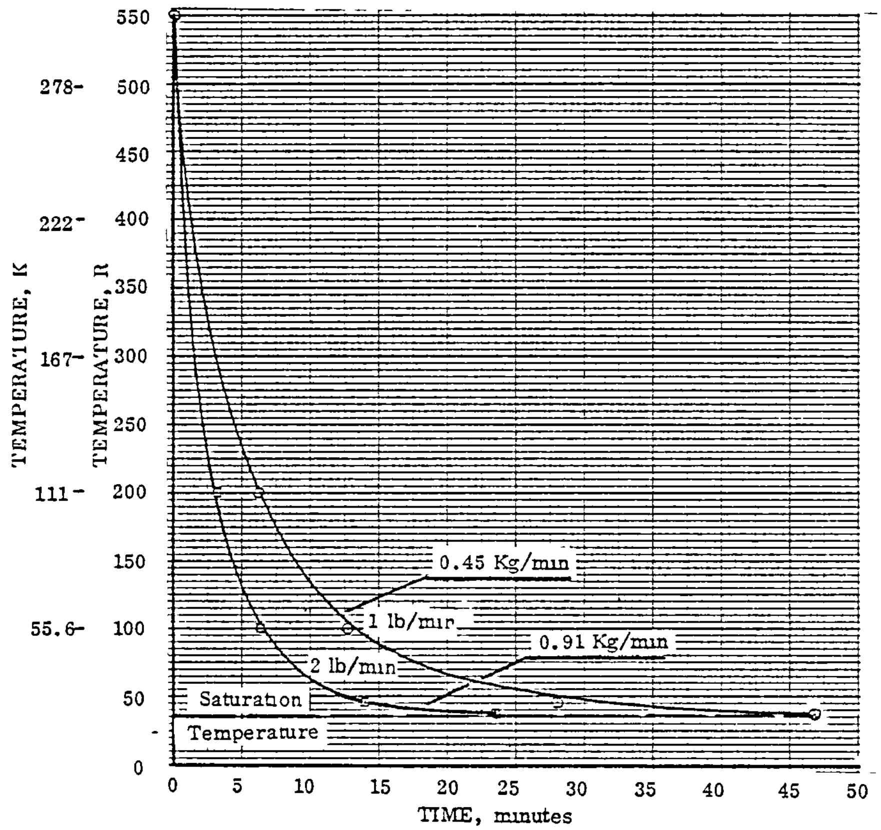


Figure 3-7. LH_2 Transfer Line Childown Using Saturated Gas at Entrance 101 kN/m^2 @ 14.7 psia Line Pressure

Figure 3-8 shows the computed values of the exit temperature above that of the wall for a flow rate of 0.9 Kg/min (2 lb/min). The model for the childown time was developed assuming the exit temperature would approach the wall value. This was done to get a closed-form solution even though it was known that this condition could not be met precisely. Also shown on the plot is the Dittus-Boelter curve for the flow. For wall temperatures of 55.5 - 278K (100-550R) the exit overheat is shown to be in the range 11-12K (20-22R), dropping off quickly for wall temperatures below 56.5K (100R). This mis-match of the assumed condition and the more likely condition will result in some lengthening of childown estimate. However, this should not mean more than a few minutes difference.

3.1.1.5 Transfer Line Transient Model. In order to construct a simple model for estimating childown time the following assumptions have been used. A comprehensive presentation of this approach can be found in Reference 3-7.

1. Entire tube wall at approximately same temperature at any time, t.

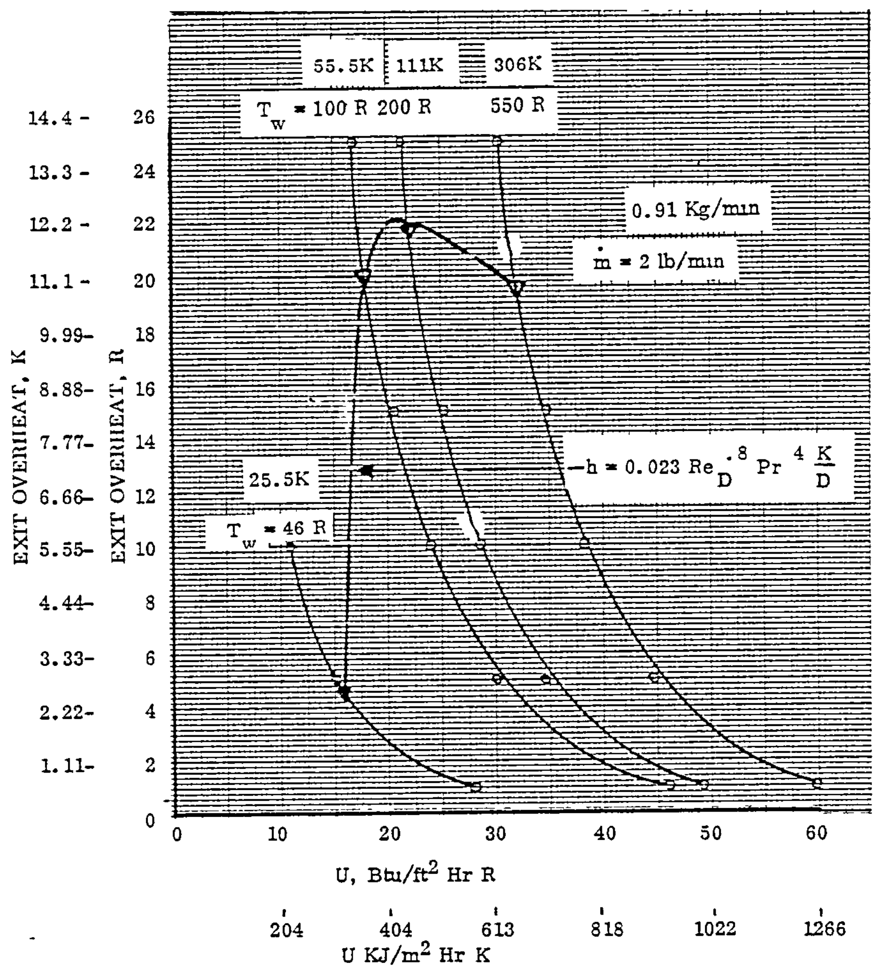


Figure 3-8. Exit Overheat at Various Wall Conditions During Childown of LH_2 Line

2. Flow consists of vapor and/or small droplets entrained in it.

3. Gas is superheated at exit and exit temperature is equal to wall temperature.

4. Flow enters as saturated liquid at line pressure.

5. Radiation losses are small during the chilldown period.

$$\dot{m}C_{pg}(T_2 - T_1) + \dot{m}h_{fg} = - \rho_w V_w C_w \frac{dT_w}{dt} \qquad (3\text{-}1)$$

where:

$\dot{m}$ = mass flow rate

C_{pg} = gas heat capacity

T_2 = exit temp of fluid = T_w

T_w = wall temp

T_s = saturation temp at line pressure

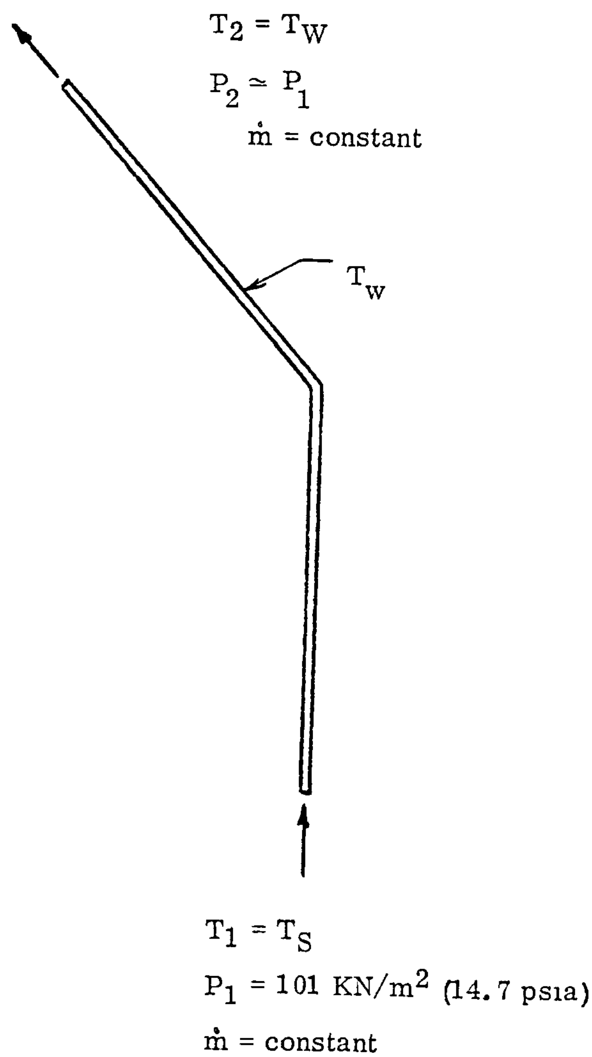
h_{fg} = heat of vaporization

ρ_w = wall density

V_w = wall volume

C_w = heat capacity of wall

t = time



and with initial condition:

$$T_w = T_{wo} \quad @ \; t = 0. \tag{3-2}$$

Now, non-dimensionalize temperature:

$$\theta = \frac{T_w - T_s}{T_{wo} - T_s} \tag{3-3}$$

Then

$$\frac{-\dot{m}}{\rho_w V_w C_w} \, dt = \frac{d\theta}{C_{pg}\,\theta + \frac{h_{fg}}{T_{wo} - T_s}} \tag{3-4}$$

with $\theta = 1$ @ $t = 0$.

Let $\beta = C_{pg}\,\theta + \frac{h_{fg}}{T_{wo} - T_s}$. (3-5)

Then: $d\beta = C_{pg}\, d\theta$ (3-6)

and:

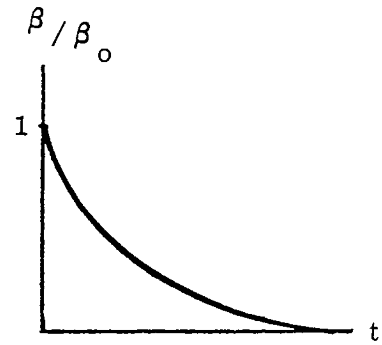
$$\frac{-\dot{m} C_{pg}\, dt}{(\rho V C)_w} = \frac{d\beta}{\beta} \tag{3-7}$$

with: $\beta = \beta_o = C_{pg} + \frac{h_{fg}}{T_{wo} - T_s}$ @ $t = 0.$ (3-8)

Integrating and applying the initial condition gives the result:

$$\beta / \beta_o = e^{-\alpha t} \quad \text{where} \quad \alpha = \frac{\dot{m} C_{pg}}{(\rho VC)_w}$$

$$\frac{\theta + \dfrac{h_{fg}}{C_{pg}(T_{wo} - T_s)}}{1 + \dfrac{h_{fg}}{C_{pg}(T_{wo} - T_s)}} = e^{-\alpha t} \qquad (3\text{-}9)$$



Calculations for LH_2

From previous calculations, it was found that for the transfer line and associated fittings to be chilled from 306 K (550 R) to 20 K (36 R) required the following heat be removed:

$$q_w = \int m_w C_w dT = 11130 \text{ KJ } (10551 \text{ BTU}) \text{ for 304 S.S.} \qquad (3\text{-}10)$$

Then a mean value of $(\rho CV)_w = m_w C_w$ can be estimated from:

$$\frac{1}{\Delta T} \int m_w C_w \, dT \qquad (3\text{-}11)$$

$$\frac{11{,}130}{306-20} = 38.94 \text{ KJ/ K} = \left(\frac{10551}{550-36}\right) = (20.53 \text{ BTU/ R})$$

At 20 K (36 R), h_{fg} = 447 KJ/Kg (192 BTU/Lb) for LH_2.

Mean values of C_{pg} for various ranges of temperature are:

$T_w - T_s \leq 35.5$ K (64 R)	:	C_{pg} = 10.5 KJ/Kg K (2.5 BTU/Lb R)
35.5 K (64 R) $\leq T_w - T_s <$ 91 K (164 R)	:	C_{pg} = 12.6 KJ/Kg K (3.0 BTU/Lb R)
91 K (164 R) $\leq T_w - T_s \leq$ 286 K (514 R)	:	C_{pg} = 15.7 KJ/Kg K (3.75 BTU/Lb R)

Since the "constants" in the equation are not being treated as constants during evaluation, one should calculate times in increments. Solve for t at 2 points to get a Δt expression:

$$\Delta t = \frac{1}{\alpha} \text{Ln} \left[(\beta_o/\beta_2)(\beta_1/\beta_o) \right] = \frac{1}{\alpha} \text{Ln} (\beta_1/\beta_2) \qquad (3\text{-}12)$$

Where β_2 and β_1 are the values at the end and beginning of a time increment respectively. A detail tabulation for these values can be found in Reference 3-7.

Required Heat Transfer Coefficient

It has been assumed that the convective coefficient is sufficient such that the exit bulk temperature approaches that of the average wall temperature (which was assumed uniform). To check that assumption, the heat coming out of the wall must be equal to the heat transfer to the fluid:

$$- \rho_w V_w C_w \frac{dT_w}{dt} = UA \, \Delta T_{lm} \qquad (3\text{-}13)$$

where:

U = Overall heat transfer coefficient for transfer line flow

A = Total transfer line heat transfer area

ΔT_{lm} = Log mean temperature difference

$$= \frac{(T_w - T_1) - (T_w - T_2)}{\text{Ln}\left(\dfrac{T_w - T_1}{T_w - T_2}\right)} \qquad (3\text{-}14)$$

Note that the exit temperature, T_2, can never reach the wall value. However, a solution can be found for values approaching it.

Find dT_w/dt from previous solution:

$$1/\beta_o \, d\beta/dt = -\alpha e^{-\alpha t} \qquad 3\text{-}15$$

$$= \frac{C_{pg}}{\beta_o} \quad \frac{d\theta}{dt} \tag{3-15}$$

$$= \frac{C_{pg}}{\beta_o (T_{wo} - T_s)} \quad \frac{dT_w}{dt} \tag{3-16}$$

Then, in order to reach the prescribed exit condition:

$$U \geq \frac{(\rho\ VC)_w\, \alpha\, \beta_o}{A\, \Delta T_{lm}\, C_{pg}} \quad (T_{wo} - T_s)\, e^{-\alpha t} \tag{3-17}$$

$$= \frac{\dot{m}}{A} \quad \beta_o\, (T_{wo} - T_s)\, e^{-\alpha t} \tag{3-18}$$

For a 7.62 cm (3-inch) ID, 18.29 m (60-ft) long transfer line:

$$A = \pi DL = 4.38\ m^2\ (47.124\ Ft^2)$$

Tabulation of parameters for the heat transfer relationship shown in equations 3-17 and 3-18 has been made for $\dot{m}$ of 0.45 Kg/m (1 lb/min) and exit overheat temperatures of 0.5, 5.6, and 8.3 K (1, 10, 15R). Reference 3-7 contains these detail listings.

Gas Velocities in Line

Gas velocity in transfer line is simply:

$$v = \frac{\dot{m}}{\rho A}$$

$$= \frac{\dot{m}\, RT}{PA}$$

where

$$A = \frac{\pi D^2}{4}$$

$$= \frac{9\pi}{4}$$

$$= 45.60648\ cm^2\ (7.06858\ in^2)$$

Gas Model for Heat Transfer

Use a turbulent flow heat transfer model for gas-only flow to compare with the required U. The Dittus and Boelter equation is:

$$h = \frac{k}{D}\left[0.023\, Re_D^{0.8}\ Pr^{0.4}\right] \qquad (3\text{-}19)$$

$$Re_D = 4\,\dot{m} / \pi D \mu$$

$$= \frac{4\,(1/60)}{\pi (1/4)\,\mu}$$

$$= 0.0849/\mu$$

The tabulated parameters, evaluated in equation 3-19, are presented in Reference 3-7.

3.1.2 FUNDAMENTAL EXPERIMENT DESIGN DRIVERS. This preliminary experiment definition study phase stressed analyses dealing with the fundamental characteristics which were major experiment design, operational and cost drivers. Figure 3-9 indicates this overall relationship and presents an overview from which some of the more important ones were selected for investigation. The following paragraphs discuss various aspects of the major design drivers - orbiter constraints, experiment operations, and scaling considerations.

3.1.2.1 Orbiter Constraints. The survey of OTV concepts presented in Section 2.0 of this report presented the details of several candidate LH_2 propellant tanks. The preliminary selection for this phase of the study was a large two stage POTV LH_2 tank as shown previously in Figure 2-4. A summary of its features which will be used to establish receiver tank scaling relationships and orbiter resource requirements is as follows:

OTV propellants:	53,061 Kg/stage (117,000 lb) (O_2 and H_2 total)
Propellant fill time:	3 hrs/45,350 Kg (100,000 lbs)
POTV LH_2 receiver tank:	4.215 m (166 inch) diameter, 116 m^3 (4100 ft^3)/stage, 2219-T87 Aluminum alloy construction, with thermodynamic vent 4.5-9 Kg/m (10-20 lb/hr), steer horn vent 45 Kg/hr (~100 lb/hr), MLI insulation, helium pressurant for engine start, autogenous pressurization during engine operation, and no acquisition device.

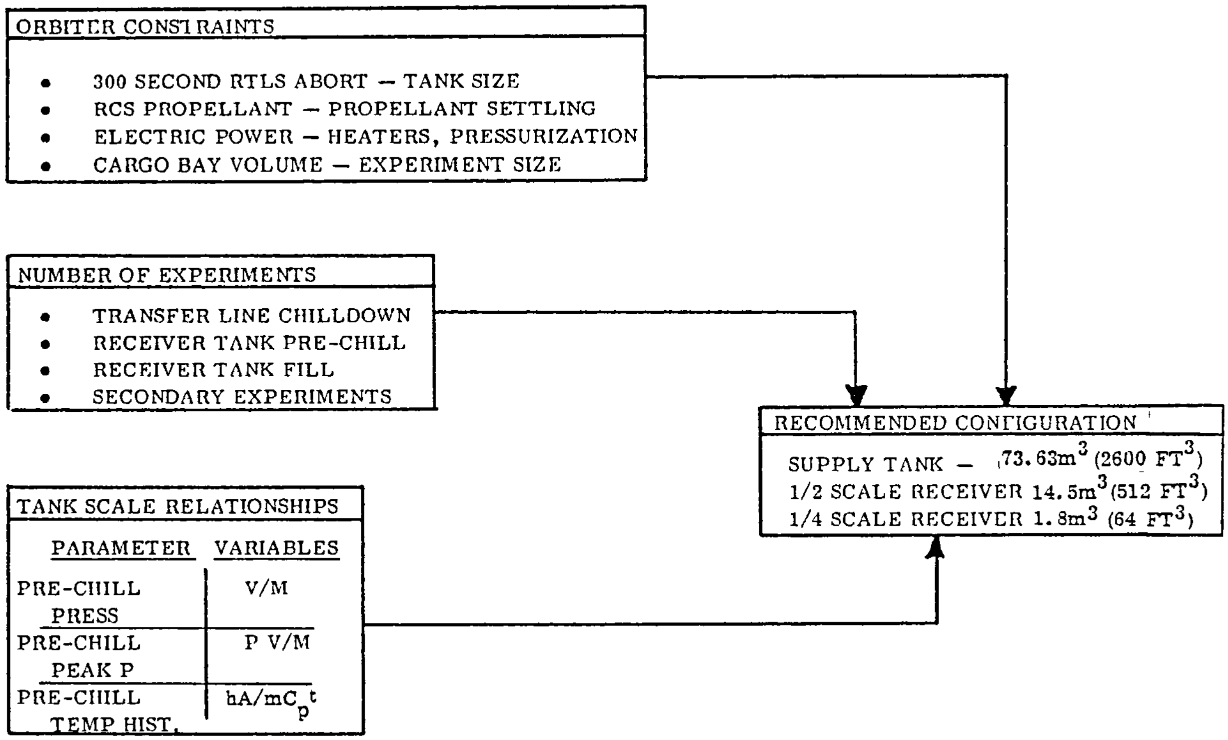


Figure 3-9. Fundamental Design Drivers

Generalized candidate experiment configurations are defined based on the above features.

Several constraints on the experiment have been imposed by conditions relating to orbiter safety, size, and auxiliary power. First of all, it is required that the capability exist to dump all propellants within 300 seconds at a critical point in the launch phase. The most obvious method to provide this capability is to make a sufficient quantity of helium pressurant available to the supply tank. To allow high flow rates a dump line with approximately 12.7 cm (5 inch) diameter must be provided. (See Section 3.1.2.2 for details.)

Fuel available for settling propellants during the conduct of experiments is 1811 Kg (3993 lb). Although additional fuel can be added, it is chargeable to the payload. Electrical power available to the experiments will be approximately 50 kwh based on a 7-day mission. This is a 7 kw average power with peak power limited to 9 kw. Additional 840 kwh fuel cell kits weigh 750-850 kg with volume available outside the payload boundary but weight chargeable to payload. Of course, orbiter cargo volume also presents a constraint. Finally, there is a minimum number of receiver tank fillings which constitute a complete experiment.

3.1.2.2 Experiment Operations

Number and Size of Experiment Tanks

It is apparent that the parameter, PV/M, is important to the early pressure history in tank filling. Preliminary estimates of tank structural mass (see Section 3.3) for various tank sizes, show that the V/M ratio is constant down to approximately 1/2-scale for the POTV receiver tank. It is also apparent from early designs that if 2 tanks scales are selected for the experiment, the orbiter cargo volume constraint will require reducing the largest tank to approximately 1/2-scale. Although the second tank would not have the same V/M ratio, useful information showing the effect of scale would be obtained. There appears to be no good reason to complicate the experiment with more than two receiver tanks.

Options to be considered in the selection of experiment configuration are whether, when, and what quantities of propellant to transfer back from receiver to supply tank. The candidates which appear reasonable are:

1. Single receiver tank with no transfer back
2. Single receiver tank with transfer back
3. Two receiver tanks with transfer back from largest tank
4. Two receiver tanks with no transfer back

Candidate number 1 restricts the size of the receiver tank depending on the supply tank size and the minimum number of experiments (runs). On the positive side, it involves the simplest configuration devoid of an array of lines, valves, and fittings. On the negative side, it restricts the amount of useful data obtainable, making minimum use of the on-orbit time available and the money expended to get there.

Candidate number 2 allows a larger receiver tank to be used and more runs to be made. Data showing the effect of tank scale will not be available, settling burns will have to be made, and extra plumbing and pressurization resources will be needed.

Candidate number 3 is advantageous over candidate number 2 in that the effect of tank scale can be assessed and more experiments can be performed. Additional plumbing will be required over that in candidate number 2 and all the negative comments relating candidate 2 and candidate 1 apply here. However, the additional cost (compared with candidate number 2) in terms of space and complexity does not appear to be severe.

Candidate number 4 will result in the same size large receiver as candidate number 1. The principal disadvantage compared to candidates 2 and 3 is the reduced receiver tank size possible.

The supply tank size has been tentatively fixed at 73.63 m^3 (2600 ft^3). A 95% fill with 138 KN/m^2 (20 psia) LH_2, the tank will contain 4929 Kg (10868 lb) of liquid. It has been established that the abort dump can be accomplished with a 12.7 cm (5-inch) line and 45.4 Kg (100 lb) of 31029 KN/m^2 (4500 psia) helium. Two 101.6 cm (40-inch) diameter bottles would be required for the dump contingency. Each container weighs approximately 136 Kg (300 lb) (empty).

A reasonable sizing of the two receiver tank system appears to be a half-scale and quarter-scale combination. The larger size will provide a V/M very close to the full-scale value. There appears to be no reason to increase the size beyond this point. The quarter-scale tank will show the effect of scale on the data at very modest cost in payload volume and use of experiment resources.

In order to meet the minimum number of experiment (receiver tank fills) requirements, the fluid transferred to the larger receiver tank will have to be transferred back a number of times to the supply tank. For the two-tank configuration, the number of returns is:

$$N_R = \frac{M_R(N_S X_S^3 + N_L X_L^3) - M_S}{M_R X_L^3 (1 - f)}$$

where:

N_R	=	number of returns
M_R	=	mass of propellant residing in a full-scale receiver tank
N_S	=	number of experiments in the small receiver tank
X_S	=	scale factor for the small receiver tank
N_L	=	number of experiments in the large receiver tank
X_L	=	scale factor for the large receiver tank
M_S	=	mass of propellant initially in the supply tank before any experiments are run
f	=	fraction of LH_2 left in the receiver tank after the return is made

If a 5% ullage volume is assumed for both tanks and 138 KN/m^2 (20 psia) saturated liquid is present in both tanks, about 5 returns are required for f = 0.1. Propellant for tank and line chilldown experiments and other sources of boil-off can be obtained by reducing the f-value.

Choosing a single half-scale tank, the number of refills is increased to 8. The reason for this is that the minimum number of runs for the tank is increased from 8 to 12 in the absence of a small tank.

A single-tank system with no return of propellant will require that the receiver tank be reduced to a scale of 0.373. A two-tank system with the smaller tank at quarter-scale and no returns requires an upper limit of 0.379-scale on the large receiver tank.

Propellant Transfer Methods

In Figure 3-10 a schematic of an autogenous pressurization system with two receiver tanks, one capable of transferring propellants back to the supply tank, is shown. Note that a boiler-superheater and possibly a compressor are needed. Helium bottles are required for the abort dump capability. The supply tank should have an acquisition device and a thermodynamic vent to control boil-off. Wall heaters will be required to heat the receiver tank walls up to 200 K (360 R) prior to each experiment. Each receiver needs a dump line to purge tank contents prior to the next fill. Transfer back to the supply tank should be through the same transfer line for simplicity.

A system using the helium on board for the abort dump capability is shown in Figure 3-11. It is identical to the autogenous system except the helium supply provides the pressurization for each transfer.

Another method for transferring propellant is through the use of a pump. Such a system is shown in Figure 3-12, again for a two-tank system with a transfer-back capability for the largest receiver tank. To effect a transfer in either direction, NPSH is required to prevent cavitation. Thus, the suction-side tank must be pressurized using the helium supply during transfer.

Although direct pumping of propellant appears to be attractive, it has some serious drawbacks. First note that all the piping and equipment necessary for helium pressurization will also be required to provide NPSH to the pump to prevent cavitation. An obvious pump choice is the operational Centaur LH_2 boost pump. However, it requires NPSH following engine start from the vehicle acceleration. This pump is no longer available from the manufacturer (future Centaur vehicles must use another system). Although a pump could be developed especially for this experiment, it would not be cost effective. For these reasons, we have chosen to eliminate the pump option from further consideration.

The important question to be answered about helium pressurization method is: "How much pressurant will be needed in addition to that already available for the abort dump?" Calculations were made to determine the amount of 31028 KN/m^2 (4500 psia) 288K (520R) helium required to unload the supply tank at a total pressure of 138 KN/m^2

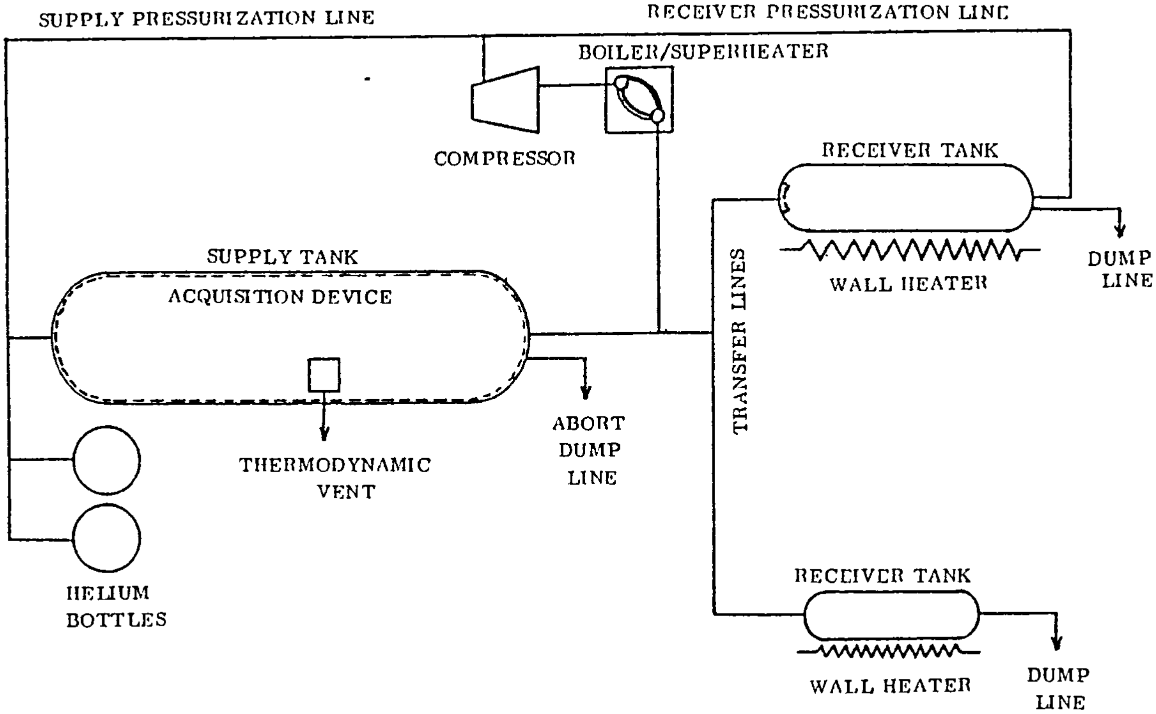


Figure 3-10. Propellant Transfer System with Autogenous Pressurization

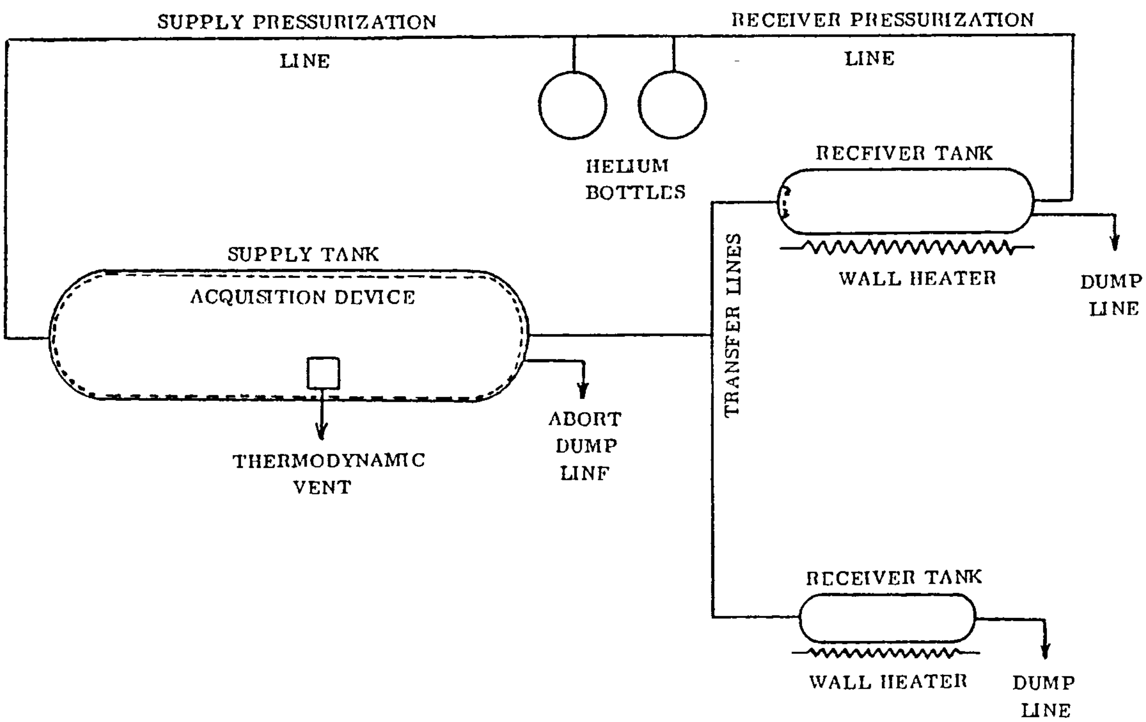


Figure 3-11. Propellant Transfer System with Helium Pressurization

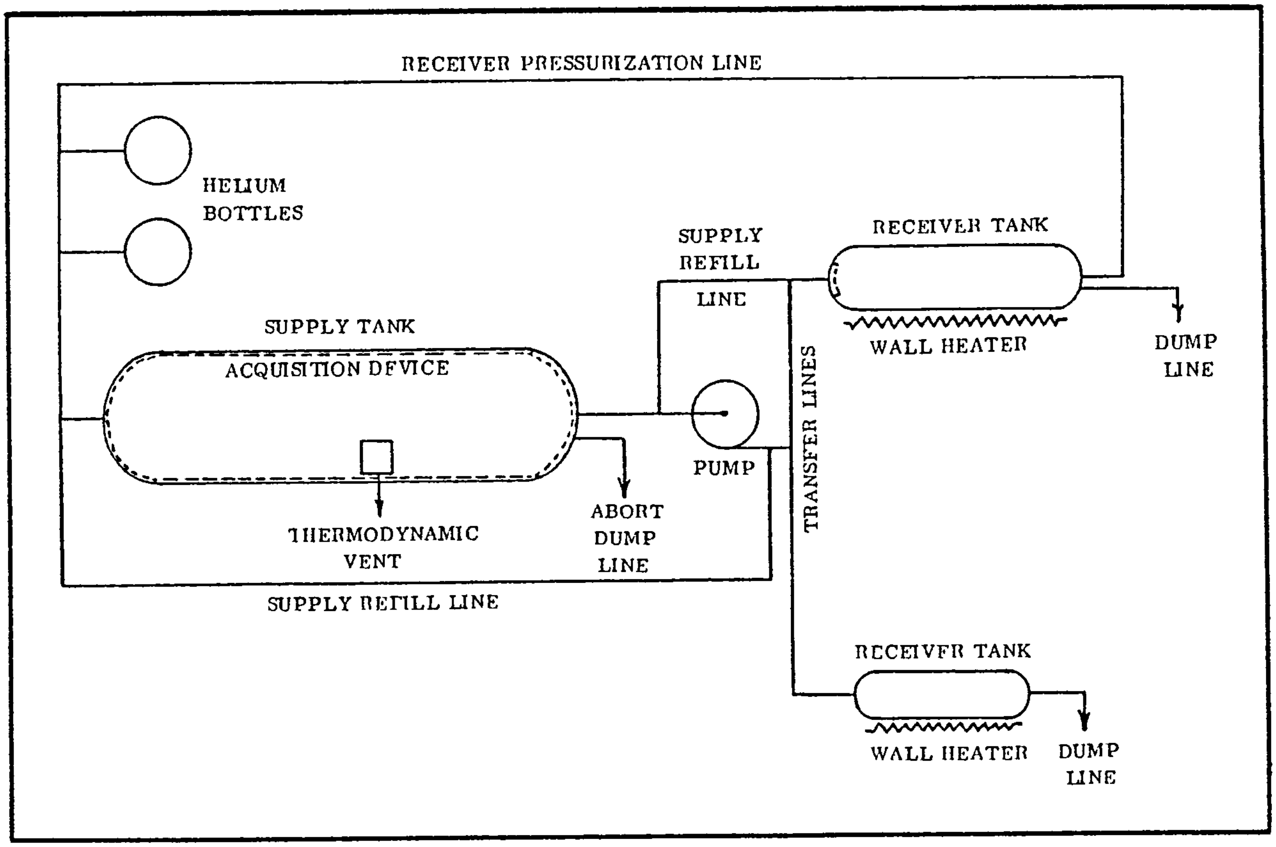


Figure 3-12. Propellant Transfer System with Pump

(20 psia). The results are shown in Figure 3-13. If the ullage volume in the supply tank is allowed to increase to 30% before any refilling is attempted, then the helium required for the refill process can be estimated by taking the difference between the 30% and 10% levels on the plot (10% being the refilled state). This difference is approximately 3 Kg (7 lb) of helium. If the ullage volume is allowed to increase to 50% before refill to 30%, the amount of helium usage is 4.8 Kg (10.5 lb). Although less helium is used in the former case, it may be that the supply tank pressure will be driven too high. Thus, for the two-tank system with five refills, at least 48.3 Kg (106.5 lb) of helium should be tanked. For the single tank system with eight refills, at least 62.6 Kg (138 lb) of helium should be available. In either case, an extra bottle, over the abort dump requirement, is necessary. Obviously if a system with no refills is chosen, no additional helium would be required.

The pressurant supply for autogenous must come from LH_2 boiled and moved into the ullage as vapor. The amount of LH_2 required to unload the supply tank at a pressure of 138 KN/m^2 (20 psia) is shown in Figure 3-14. If the ullage volume is allowed to decay to 50% before return fill is initiated, then 6.3 Kg (14 lb) of pressurant is required for each fill. For the two-tank design, a total of 81.6 Kg (180 lb) of LH_2 must be vaporized. For the single tank design, a total of 100.7 Kg (222 lb) of H_2 vapor is needed.

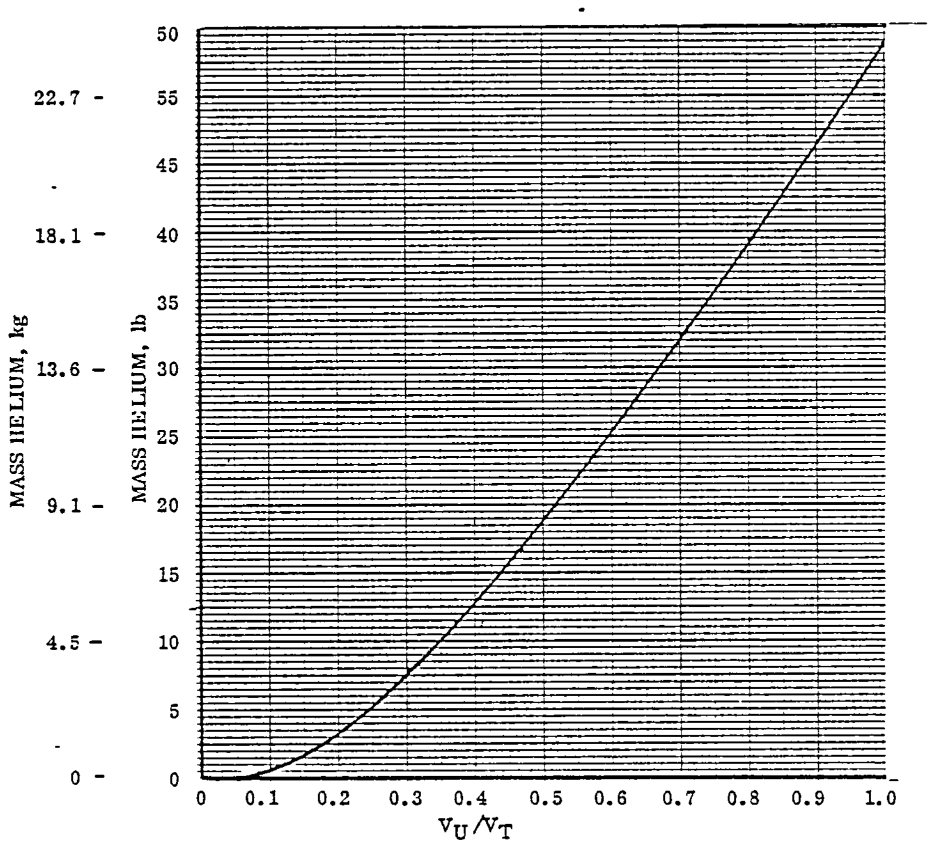


Figure 3-13. Helium Pressurant Required for 73.6 m^3 (2600 ft^3) LH_2 Supply Tank at 138 kN/m^2 (20 psia) Total Pressure

The amount of energy needed to generate the required vapor is simply the product of the mass of LH_2 and the latent heat. For the two-tank system with refills, the required energy is 8.254 kw-hr (28,170 BTU); whereas, for the single-tank system the amount is 10.180 kw-hr (34743 BTU). If a compressor is used, a modest increase in the required energy would be necessary. Very little power would be required to move vapor at low flow rate into a small head. Note that PdV work is small since vapor is merely occupying volume left by liquid at the same pressure.

For any receiver tank system with no refill capability, 49.9 Kg (110 lb) of vapor requires an energy expenditure of 5.043 kw-hr (17215 BTU).

Energy Requirements

Case 1. Helium Pressurization, Single Tank, No Return. For this 0.373-scale tank, a best estimate is that it will weigh about 28.1 Kg (62 lb). The energy required to run three tank pre-chill experiments (cool tank to 200K (360R) is equal to that required to heat the tank back up to 289K (520R) twice. To heat aluminum tank from 200K (360R) to 289K (520R) requires 73.3 KJ/kg (31.5 BTU/lb). Thus 1.144 kw-hr (3906 BTU) is required for this function. To conduct 12 fills, the tank must be heated from 20K (36R)

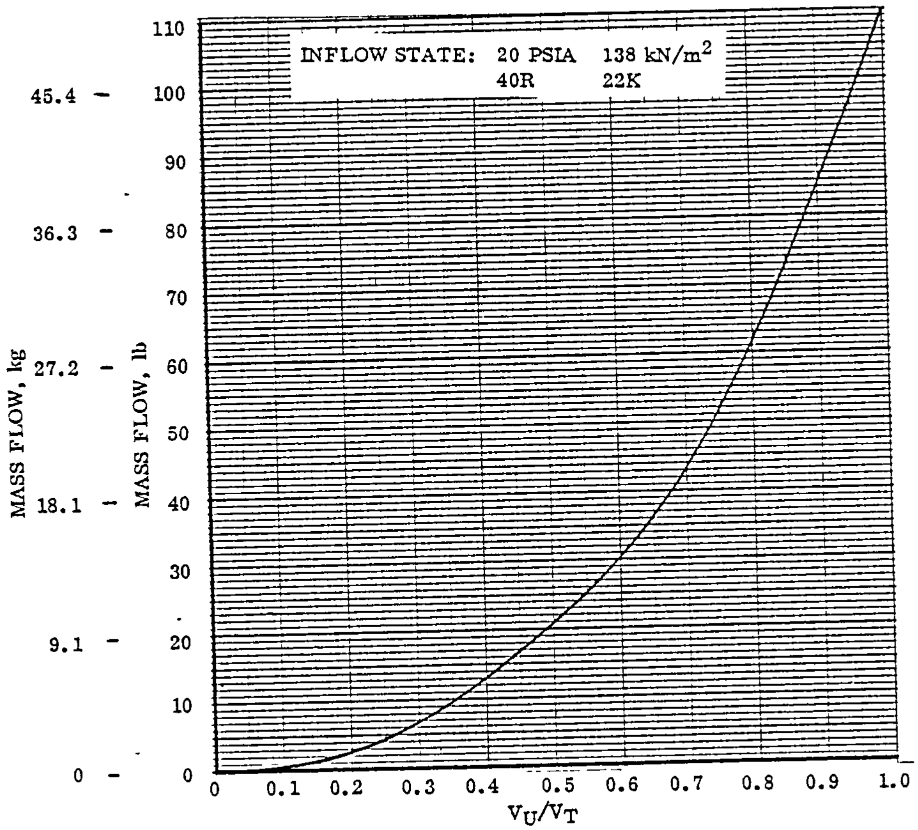


Figure 3-14. Mass Inflow Required to Provide Autogenous Pressurization of 73.6 m^3 (2600 ft^3) Receiver Tank at 138 kN/m^2 (20 psia)

to 200K (360R) eleven times at a rate of 90.7 KJ/Kg (39 BTU/lb). The total for this function is 8.502 kw-hr (29016 BTU). Total energy requred to run the experiments is 9.646 kw-hr (32922 BTU).

Case 2. Helium Pressurization, Single Tank with Return. The half-scale tank will weigh about 55.8 Kg (123 lb). Three pre-chill experiments will require 2.270 Kw-hr (7749 BTU) and the 12 fills will require 15.460 kw-hr (52767 BTU) for a total of 17.731kw-hr (60516 BTU).

Case 3. Helium Pressurization, 2-Tanks, with Return. The values for the 3 pre-chill and 8 fills of the half-scale tank are 2.270 kw-hr (7749 BTU) and 11.283 kw-hr (38510 BTU) respectively. For the quarter-scale tank the demand is 0.738 kw-hr (2520 BTU) and 5.028 kw-hr (17160 BTU) as already stated. The total is 19.320 kw-hr (65939 BTU).

Case 4. Helium Pressurization, 2-Tanks, No Return. The 0.378-scale tank is estimated to weigh 28.6 Kg (63 lb). The energy to run 3 pre-chill experiments is 1.163 kw-hr (3969 BTU). To conduct 8 fills of this tank requires 5.039 kw-hr (17,199 BTU) of reheat energy. The small tank (0.25-scale) weighs about 18.1 Kg

(40 lb). To make 3 pre-chill runs, 0.738 kw-hr (2520 BTU) is required. The 12 fills require reheat energy of 5.028 kw-hr (17,160 BTU). The total for all the experiments is 11.968 kw-hr (40,848 BTU).

The energy requirements for each autogenous system include those of the corresponding helium system above plus that energy required to generate vapor. The totals for these systems and the helium systems are shown in Table 3-1.

Propellant Settling

Using the method described in Reference 3-8, the acceleration required to settle the propellant in the receiver tank prior to transfer back to the supply tank was calculated. An optimum Bond number of 5.1 was selected, giving an acceleration of 1.26×10^{-4} m/sec^2 (4.12×10^{-4} ft/sec^2). The Weber number at this value of Bo is 17.5. Thus, the time required to settle is 710 seconds. The time required to settle varies inversely as the cube of the acceleration. Therefore, the settling time can be adjusted broadly with modest changes in acceleration.

The thrust level required for the 100226 Kg (221,000 lb) orbiter is 1.28 Kg (2.83 lb). Apparently the thrusters must be fired in pairs to avoid a net moment on the vehicle. Firing two of the 11.39 Kg (25-lb) thrusters about 6% of the settling time in short pulses will achieve the desired result. The orbiter propellant consumed in this process (1 settling operation) is about 3.2 Kg (7 lb). Since approximately 1814 Kg (4000 lb) will be available to the experiment, this requirement is very modest.

The method of Reference 3-9 allows an estimate to be made of the residual which will be present in the tank as the transfer line first experiences gas ingestion. At this low value of Bo, the gas ingestion height will be higher than indicated by the reference. The best scenario appears to be to start with a high flow rate until about the 1/4-full point. Then, the flow can be slowed and perhaps the acceleration increased. This will provide fast propellant transfer early in the settling mode when propellant is sure to cover the outlet, followed by procedures which will flatten the liquid surface, lowering the gas ingestion height. To keep the pressure drop in the transfer line under 13.8 KN/m^2 (2 psi), the diameter should be at least 5 cm (2 inches).

3.1.2.3 Scaling Considerations.

Receiver Tank Pre-Chill - It has been concluded in Reference 3-3, Section 6, that V/M and $\dot{m}v^2/V$ are the important parameters which determine receiver tank pressure response during the pre-chill and early fill process. The pre-chill process is the process of introducing liquid into the warm, empty receiver tank, waiting a certain period for significant heat transfer to occur, and venting to ambient pressure before introducing more liquid. The end of the pre-chill process is reached when the tank wall temperature is reduced sufficiently so that the allowable pressure is not exceeded during the fill process which follows. Typically, a number of mass flow-soak-vent cycles will be required to complete the pre-chill phase.

Table 3-1. System Requirements for Various Experiment Designs

(SI UNITS)

System	Scale	Volume, M^3	Tank mass, Kg	LH_2 mass, Kg	Returns	Tank fills	Tank pre-chills	Helium System pressurant, Kg	Helium System energy kw-hr	Auto System pressurant, Kg	Auto System energy, kw-hr
Single tank, no refill	0.373	6.016	28.1	425.9	0	12	3	24.5	9.646	49.9	14 689
Two tanks, no refill	0 379	6 113	28.6	432.7	0	8	3	24.5	11 968	49.9	17.011
	0 25	1.814	18.1	128 3	0	12	3	62.6	17 731	100.7	27.911
Single tank w/refill	0 5	14.514	55.8	1027	8	12	3				
Two tanks, w/refill	0 5	14.514	55.8	1027	5	8	3	48.3	19 320	81.63	27 574
	0 25	1 814	18.1	1283	0	12	3				

NOTES.
1. Supply tank volume is 73.63 M^3, receiver tank (full-scale) is 116.11 M^3.
2. Ullage volumes for calculations assumed to be 5%.
3. Where returns to receiver made, at least 90% LH returned.
4. Supply tank total pressure maintained at 138 KN/M^2 (except during refill).

(ENGLISH UNITS)

System	Scale	Volume, ft^3	Tank mass, lb	LH_2 mass, lb	Returns	Tank fills	Tank pre-chills	Helium System pressurant, lb	Helium System energy kw-hr	Auto System pressurant, lb	Auto System energy, kw-hr
Single tank, no refill	0.373	212 43	62	939	0	12	3	54	9 646	110	14.689
Two tanks, no refill	0 379	215 85	63	954	0	8	3	54	11.968	110	17.011
	0 25	64 06	40	283	0	12	3	138	17.731	222	27.911
Single tank w/refill	0 5	512 50	123	2265	8	12	3				
Two tanks, w/refill	0 5	512 50	123	2265	5	8	3	106.5	19.320	180	27.574
	0 25	64 06	40	283	0	12	3				

NOTES
1. Supply tank volume is 2600 ft^3; receiver tank (full-scale) is 4100 ft^3.
2. Ullage volumes for calculations assumed to be 5%
3. Where returns to receiver made, at least 90% LH_2 returned.
4. Supply tank total pressure maintained at 20 psia (except during refill).

The receiver tank physical values which affect the pre-chill mechanism are shown in Table 3-2. The values are taken from the layouts, 11-15 for the quarter, half, and full-scale tanks (see Section 3.3). Some of the accessories which have contact with the tank, such as the MLI and tank heaters, will demonstrate a significant lag in temperature response compared to those materials which are in intimate contact with the tank fluid. Those materials which have fluid contact are totaled in the column "wetted weight". The response time and effect of the temperature transient from the unwetted weight on the pressure are accounted for in the preliminary experiment definition (see Section 3.2).

If the propellant mass introduced during pre-chill is assumed to vaporize completely and come to equilibrium with the entire tank and accessory mass, a model can be readily constructed and used to estimate the maximum possible tank pressure given an initial tank temperature. This model is developed below and the results are shown in Figure 3-15. The computations are reasonable for a 103-138 KN/m^2 (15-20 psia) saturated liquid supply. It appears from the allowable pressure and the plots, that pre-chill of the full-scale tank would have to be below 158K (285R). For the half and quarter-scale tanks, the pre-chill goal must be below 150K (270R) and 133K (240R), respectively. Since there is uncertainty involved in establishing equilibrium with the unwetted mass, the pre-chill goals will have to be set somewhat lower than these temperatures. The worst-case is that the entire unwetted mass lags at the ambient temperature

Table 3-2. Receiver Tank Parameters Which Affect Pre-Chill (English Units)

Scale	Volume ft^2	Total Weight lb	V/M ft^3/lb	V*/M*	P_{allow} PSID	P*V*/M*	Wetted Weight lb	% Wetted
1.0	4100	2074.0	1.977	1.0	25.0	1.0	1555.1	75.0
0.5	512.5	279.3	1.835	0.928	25.3	0.939	214.8	76.9
0.25	64.06	90.3	0.709	0.358	50.6	0.725	73.6	81.5

(SI Units)

Scale	Volume m^3	Total Weight Kg	V/M m^3/Kg	V*/M*	P_{allow} KN/m^2	P*V*/M*	Wetted Weight Kg	% Wetted
1.0	116.1	940.6	0.1234	1.0	172.4	1.0	705.3	75.0
0.5	14.51	126.7	0.1146	0.928	174.4	0.939	97.4	76.9
0.25	1.82	40.95	0.0444	0.358	348.9	0.725	33.4	81.5

Notes: 1. Wetted weight is that which has intimate contact with fluid during chill process.
2. Terms with superscript * are dimensionless scaled to full-size tank values.

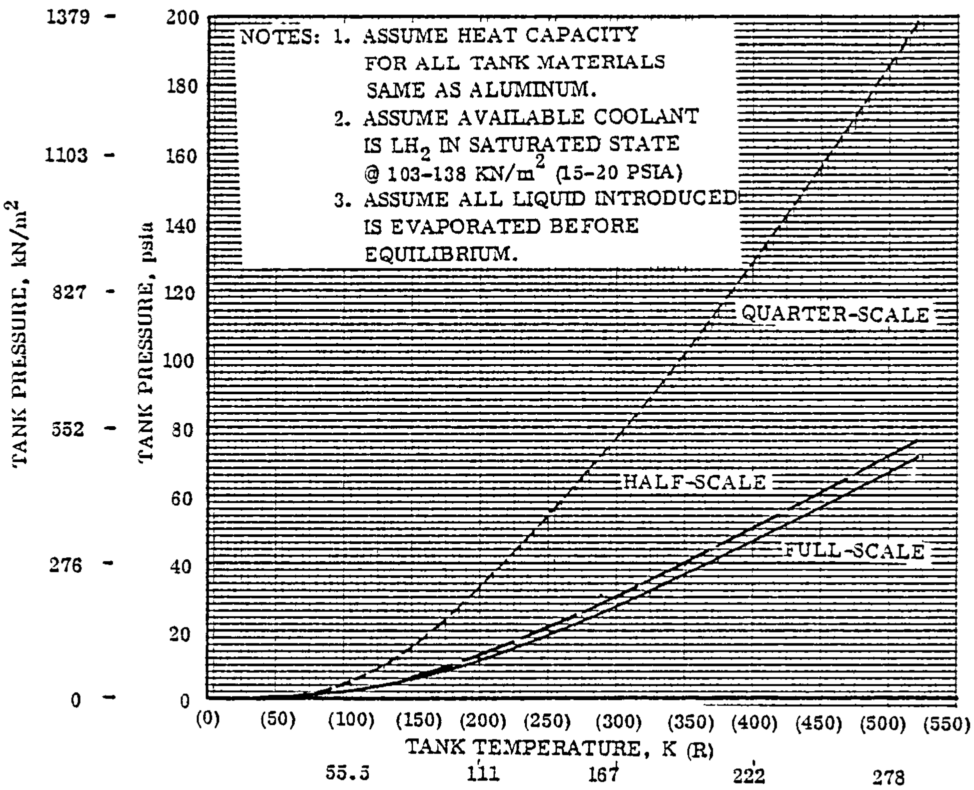


Figure 3-15. Equilibrium Pressure Varies as the Initial Wall Temperature for Pre-Chill of an Empty Receiver Tank

289K (520R) at the time that pre-chill is terminated. The temperature of the tank wall could then increase an amount (over that predicted from the plot):

$$\Delta T = \frac{(MC \Delta T)_{unwetted}}{(MC)_{total}}$$

Using the numbers from Table 3-2, the maximum possible temperature increase due to thermal lag is 32.64K (58.75R) for the full-scale tank, 30.16K 54.29R) for the half-scale, and 24.16K (43.48R) for the quarter-scale. Using the plot, Figure 3-15, this would result in pressures of 248, 220 and 483 KN/m^2 (36, 32, and 70 psia) respectively for the full, half, and quarter-scale tanks during the filling cycle. Obviously, for safety purposes, we would want to pre-chill down to 126K, 120K and 109K (226R, 216R, and 197R) respectively for the full, half, and quarter-scale tanks to avoid any chance of overpressurization.

The minimum mass of propellant required for the pre-chill process as a function of tank wall temperature is calculated below and shown in Figure 3-16. It is assumed that the initial temperature of the tank and accessories is 289K (520R). Note the small amount of propellant required to chill the small tank relative to the full-scale tank. Methods of mass measurement and metering will require special attention for this experiment.

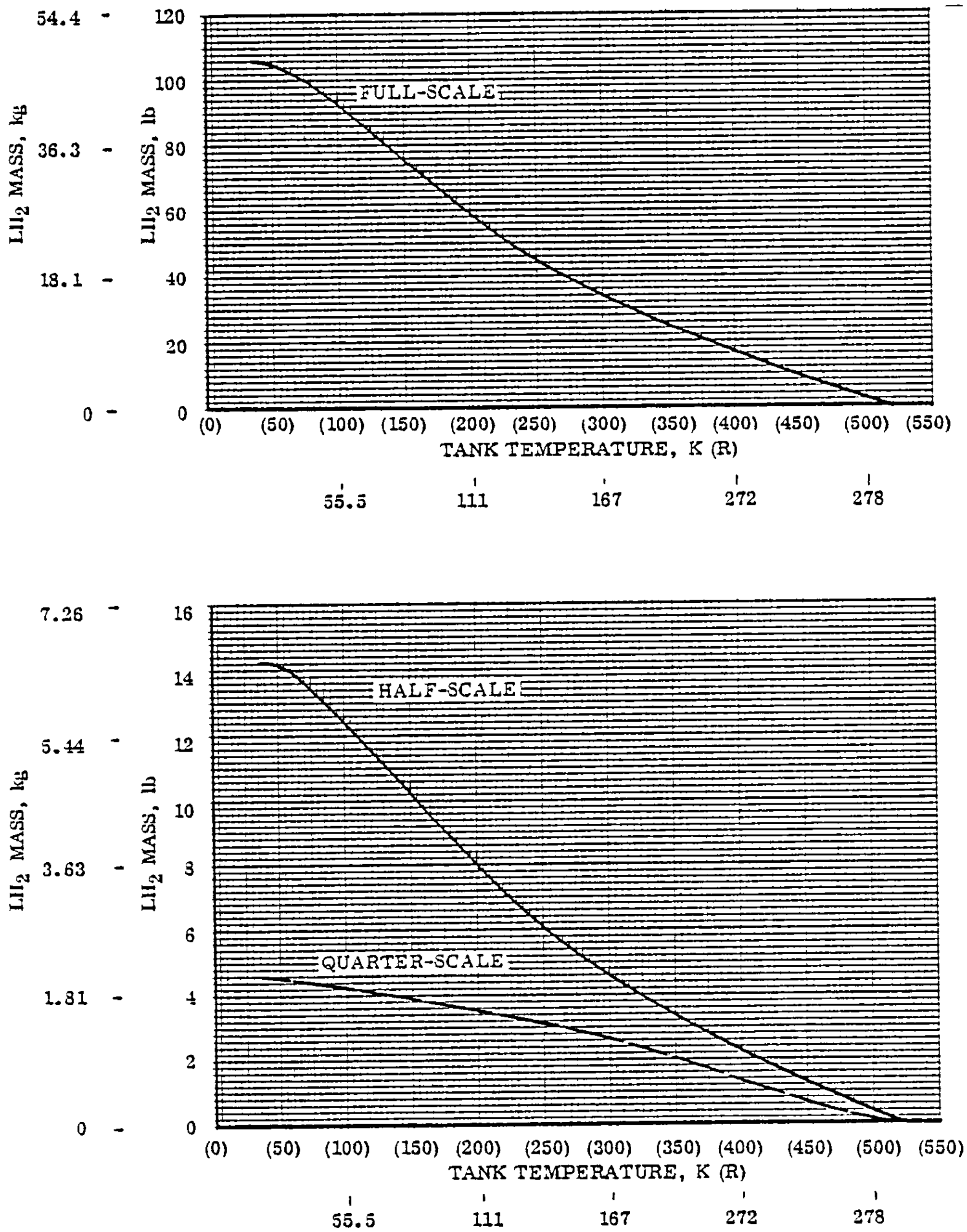


Figure 3-16. Minimum LH_2 Mass Required to Cool Receiver Tank From 289K (520R)

Receiver Tank Equilibrium Pressures During Chill

The thermodynamics of chilling a warm, empty tank with propellant are modeled by:

$$h_e\, m_e + Q = m_f u_g$$

where:

h_e = entrance enthalpy of liquid

m_e = mass of entering liquid

Q = heat added to fluid in tank

m_f = mass of fluid in tank at end of chilldown

u_g = internal energy of vapor in tank at end of chilldown

But the heat added is simply the energy in the tank wall, the acquisition system, and other accessories in contact with the tank wall.

$$Q = MC_T \;\Delta T$$

where: M = total mass of tank & its accessories

C_T = mean heat capacity of the mass

ΔT = chilldown temperature drop

In applying this model, it is assumed that:

1. The final state is an equilibrium state
2. The mass has an effective heat capacity equal to that of aluminum

Since the liquid has an enthalpy equal to:

$$h_e = u_e + \frac{P_e}{\rho_e}$$

where: P_e = supply pressure of liquid

ρ_e = liquid density

u_e = liquid internal energy

then,

$$\frac{m}{M} = \frac{C_T \Delta T}{u_g - h_e}$$

$$= \frac{C_T \Delta T}{u_g - u_{ge} + u_{ge} - u_e - \frac{P_e}{\rho_e}}$$

$$= \frac{C_T \Delta T}{\left(u_{fg} - \frac{P_e}{\rho_e} + u_g - u_{ge}\right)}$$

$$= \frac{\bar{C}_T \Delta T}{\left(u_{fg} - \frac{P_e}{\rho_e}\right) + \bar{C}_v \Delta T}$$

where:

u_{fg} = heat of vaporization at entrance conditions

u_{ge} = internal energy of gas at entrance conditions

$\bar{C}_v$ = constant volume heat capacity of gas in the range ΔT

The perfect gas law is reasonably accurate in the range of states of interest here:

$$P = \frac{m/M}{V/M} \; zRT$$

where: P = internal pressure of tank

v = tank volume

R = 0.082054 liter atms/^{o}K mol (766.4 ft-lb/lb^{o}R for GH_2)

T = tank fluid equilibrium temperature

z = compressibility factor

then:

$$P = \frac{\bar{C}_T \Delta T \; zRT}{V/M \left[u_{fg} - \frac{P_e}{\rho_e} + \bar{C}_v \Delta T\right]}$$

3.2 PRELIMINARY EXPERIMENT CONCEPTS

A preliminary definition of the experiment areas to be considered is shown in Figure 3-17. Data from the last three areas listed are obtained as a result of conducting the other experiments or as a requirement for safety purposes. No additional time or apparatus apart from that required for the other experiments and the mission will be needed. The baseline configuration for this preliminary identification of tests is the two-tank, half/quarter-scale layout with screen acquisition device, zero-g vent, and 22 layers of multilayer insulation (with purge enclosure) on the supply tank. The helium pressurization system is the basic source of pressurant, and the half scale receiver tank contains a start basket and both receiver tanks are covered with 20 layers of multi-layer insulation (no purge system). Each receiver tank and the transfer line have strip heaters on the outside wall for reheat operations. Also, each receiver tank has three sets of nozzle arrays for pre-chill and fill operations, in addition to the main line into the start basket. It is assumed that a boiler would be developed as a source of pressurant for the autogenous pressurization tests if selected and that a zero-g mass gauging device will be available.

Each of the tests has been outlined below giving the objective, method, instrumentation, time, electrical energy, and RCS propellants required.

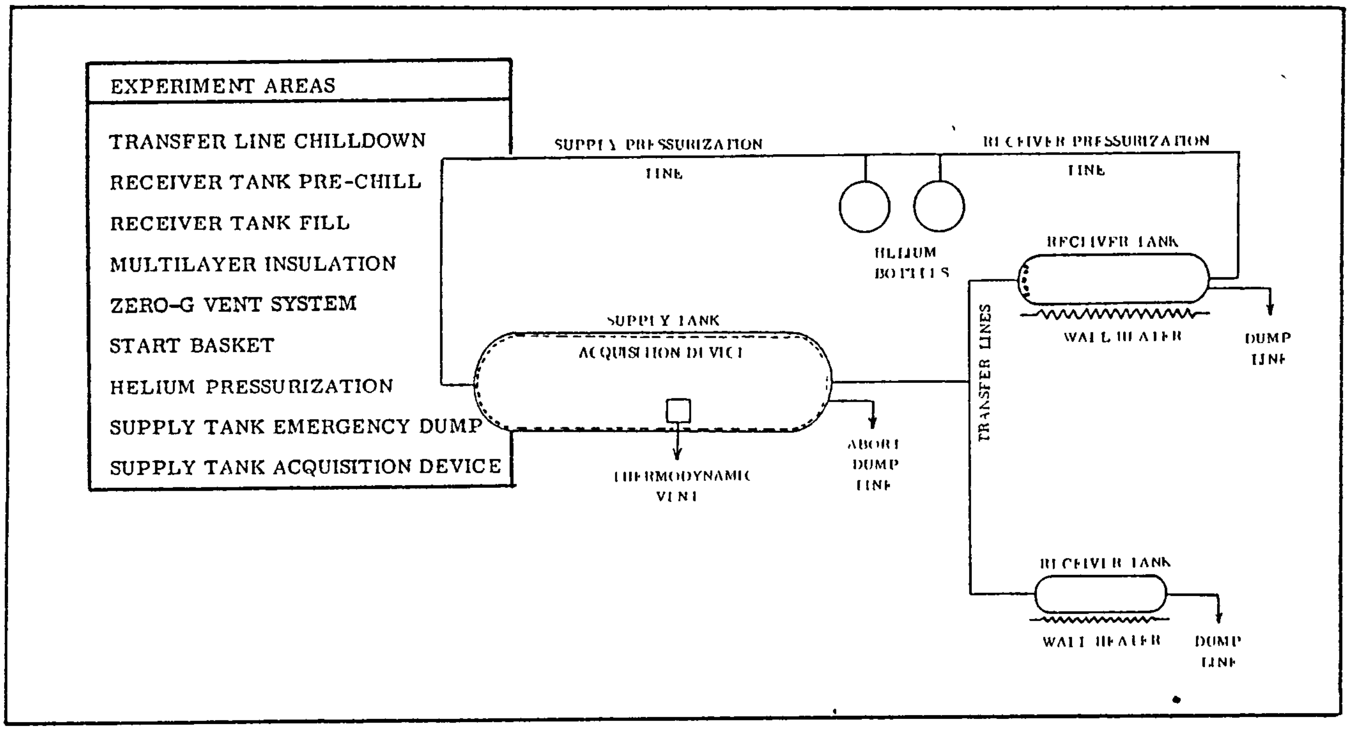


Figure 3-17. Preliminary Definition of Propellant Transfer Experiments

3.2.1 TRANSFER LINE CHILL-DOWN. The objectives of this test are:

1. Determine the relationship between the average line wall temperature transient and the mass flow rate.

2. Determine the severity of pressure transients as a function of mass flow rate.

3. Determine the effectiveness of the zéro-g vent system as a source of coolant for line chill-down.

4. Determine the effect of introducing large quantities of liquid into the line at reduced wall temperatures.

The test method of accomplishing these objectives is to monitor the wall temperature at several locations along the line and the pressure at each end of the line while cooling from 289 K (520 R) to 20 K (36 R). The test line will then be reheated to 520 R and the test repeated at another flow rate. The source of vapor for cooling purposes will be the zero-g vent system sized to deliver 45 Kg/hr (100 lb/hr). A by-pass line will be used for introducing the small quantities of liquid coolant required. At least four mass flow rates per fluid state should be run. Metering of vapor can be accomplished by routing some vapor overboard. Four additional liquid runs should be initiated when the wall has been reheated to 55.6 K (100 R) to determine the feasibility of initial chill to 55.6 K (100 R) using vapor and the remainder using liquid. These runs can be made during tank pre-chill tests. Data will be put into parametric form as follows:

$$\theta = C_1 + C_2 e^{-\tau}$$

where:

$$\theta = (T_w - T_s) / (T_{wo} - T_s)$$

$$\tau = \dot{m} C_{pg} t / (mC)_{tank}$$

Figure 3-18 shows the expected behavior of the data.

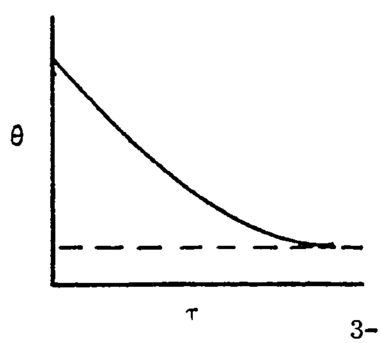


Figure 3-18. Expected Behavior of Parameteric Data

A schematic of the system showing the location of instrumentation is given in Figure 3-19. The "F" refers to the location of flow meters, the "T" to wall-mounted thermocouples, the "P" to pressure transducers, and the "S" to a sight-gauge for assessing quality. The sight gauge would be monitored remotely by a TV camera.

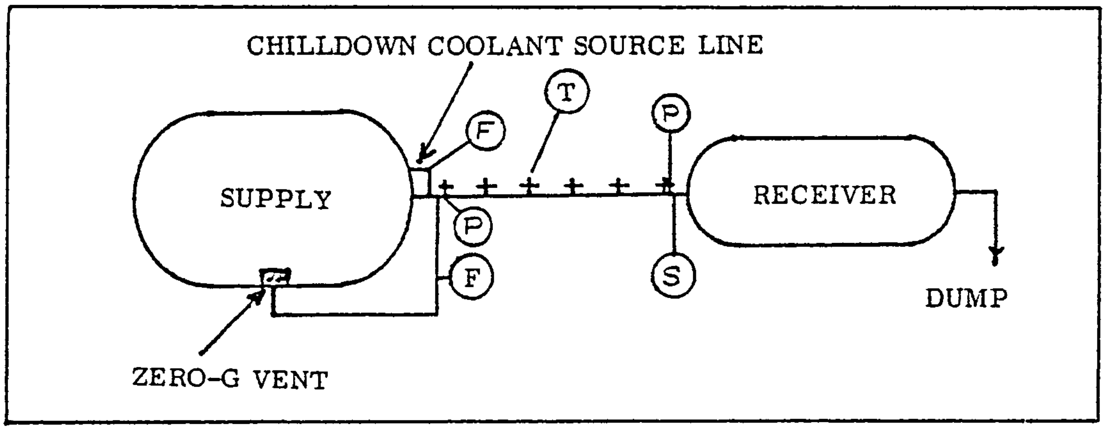


Figure 3-19. Location of Instrumentation for Line Chill-Down

Using a mean flow rate of 0.45 Kg/min (1 lb/min), the time required to chill a line with 6.1 m (20 ft) length from 289K to 20K (520R to 36R) is calculated at approximately 5 minutes for liquid injection and 15 minutes for vapor injection. Assuming 5 kw will be available for reheating the line, the following times, propellants and energy requirements were calculated:

<u>Time Required:</u>

4 Vapor Runs, min:	60
4 Liquid Runs, min:	20
3 Reduced Temp. Runs, min:	9
7 Reheats, 298K (520R), min:	81
3 Reheats, 55.6K (100R), min:	9
Total	179 min

<u>Energy Required:</u>

Reheats:	7.5 KWH

<u>LH_2 Propellant Required:</u>

8 Runs:	36.3 kg (80 lb)

3.2.2 RECEIVER TANK PRE-CHILL. The objective is to determine the relationship between the receiver tank pressure transient and $\dot{m}v^2/V$ for each inlet nozzle type. The parameter, $\dot{m}v^2/V$, has been identified in Reference 3-3 as pertinent to pre-chill and early fill process. The pre-chill process consists of a series of injection, soak, and vent cycles until a "safe" wall temperature is reached; that is, a temperature such that the pressure transient during the fill process will not exceed the allowable limit. In Section 3.1.2.3 it was determined that the pre-chill target temperature was 126 K (226 R) for the full-scale tank, 120 K (216 R) for the half-scale tank, and 109 K (197 R) for the quarter-scale tank.

The test method proposed is to make three runs per nozzle type per tank. Only two nozzles would be selected out of the three available, based on results of the first run. If a nozzle configuration is obviously very poor, no more time would be wasted with it. Each set of three runs would be made using equal time increments for an injection - soak-vent cycle (see Figure 3-20). A fixed mass will be injected each cycle at each flow rate so that the time interval for injection will vary with the flow rate (note dashed lines in figure). As a result, the time to achieve pre-chill, mass required, peak pre-chill pressure for a flow rate, and the average convective coefficient, $h = f(\dot{m}v^2/V)$, will be acquired.

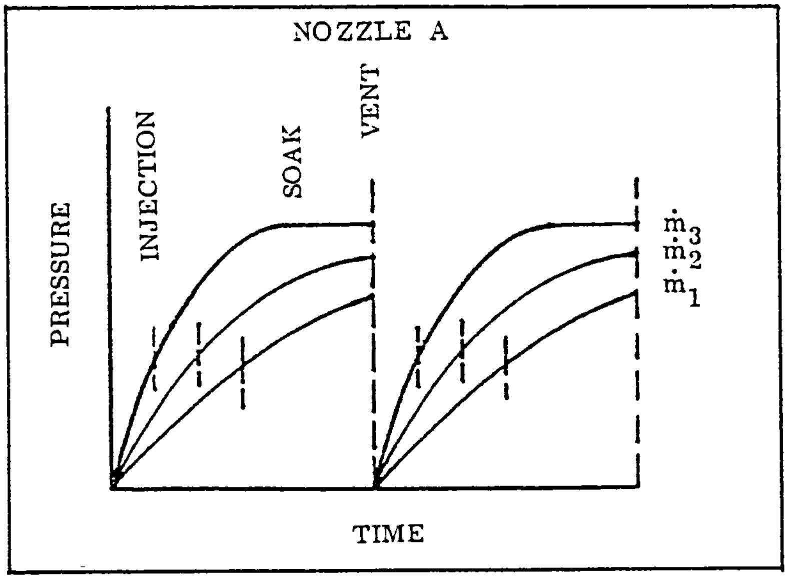


Figure 3-20. Pressure Transient for a Series of 3 Runs on a Single Nozzle

From Reference 3-3, it has been determined that the scaling parameters for the pre-chill operation are:

$$\dot{m}^* = L^* (M^*/V^*)^2$$

$$v^* = (M^*/V^*)^2/L^*$$

$$\tau^* = L^{*2}/(M^*/V^*)$$

where $\dot{m}$, v, τ, L, M, and V are mass flow rate, injection velocity, time, tank scale, tank mass, and tank volume respectively. The * denotes dimensionless quantities based on full-scale tank values. For a representative set of full-scale values the following table is presented:

SCALE	$\dot{m}$, Kg/SEC (LB/SEC)	v, m/sec (FT/SEC)	t, MIN
1.0	0.454 (1.0)	3.35 (11.0)	15.0
0.5	0.263 (0.58)	7.77 (25.5)	3.23
0.25	TBD	TBD	TBD

The quarter-scale tank values are to be determined based on other criteria since scaled values are not realistic for this tank.

The instrumentation required for each receiver is shown in Figure 3-21. A flow meter (F), pressure transducer (P), several wall-mounted temperature sensors (T), and a temperature sensor tree (U) in the ullage will provide the required data.

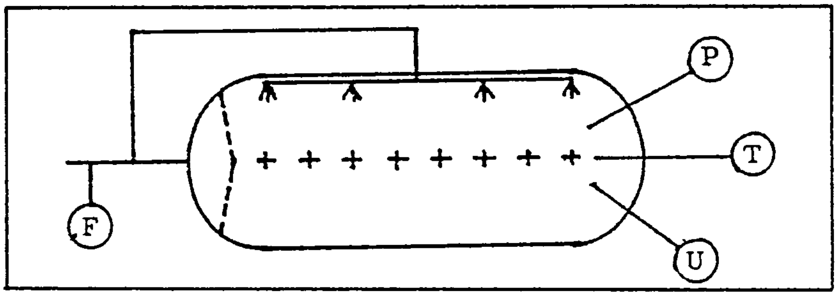


Figure 3-21. Instrumentation Layout for Pre-Chill Tests

The times required for this experiment and the heater energy and propellant necessary are as follows:

Total Time Required:		Energy Required:	
6 Pre-Chills, 1/4-Scale Tank, min:	2	Heaters:	33.2 KWH
6 Pre-Chills, 1/2-Scale Tank, min:	20		
5 Reheats, 1/4-Scale Tank, min:	98	LH_2 Propellant Required:	
5 Reheats, 1/2-Scale Tank, min:	300	12 Pre-Chills:	29.7 Kg (65.4 lb)
Total	420 min (7 hr)		

Pre-chill times for the small receiver may take a few minutes longer than indicated but will not change the total appreciably. The time required for reheat was calculated based on the assumption that 5 kw would be available for that task. The propellant requirements and tank mass were presented in Section 3.1.2.2. If the relatively large reheat time becomes unattractive, it will be necessary to add an energy kit to provide the power to reduce it.

3.2.3 RECEIVER TANK FILL. The objective of this test is to determine the relationship between the receiver tank pressure transient and the parameter $\dot{m}v^2/V$ for each inlet nozzle type. Typical behavior of the pressure transient during a fill scenario is shown in Figure 3-22.

As mixing is improved, the contents of the tank approach thermal equilibrium. Again the pertinent parameter is $\dot{m}v^2/V$ and the quantity of interest is the tank pressure. Our preliminary approach on this experiment is to initiate tests using the quarter-scale receiver tank. A total of twelve runs has been allocated to this task and eight runs to the

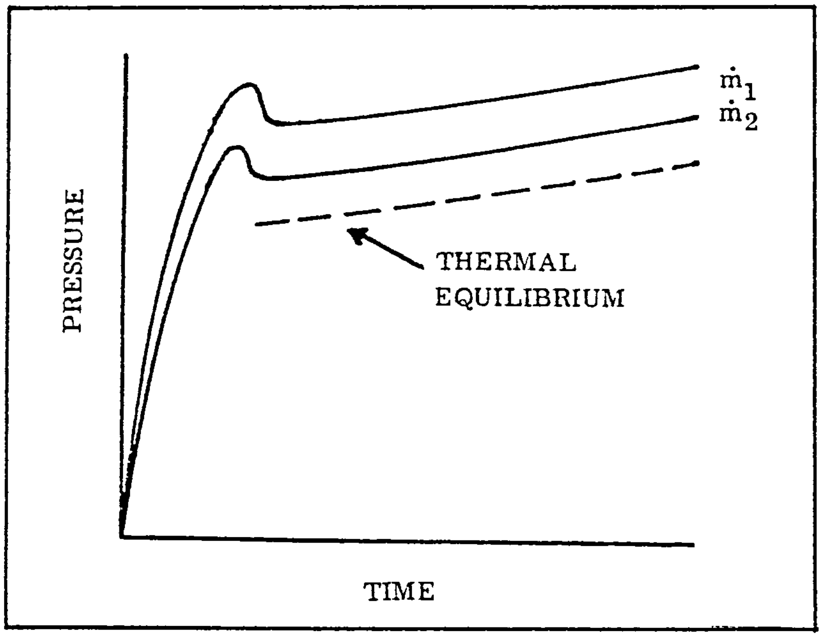


Figure 3-22. Proposed Tank Fill Experiments

half-scale tank. As stated in the pre-chill section, it is now planned to have three nozzle options available in addition to the "no nozzle" option of filling through the main outlet (near the start basket). The first run could be initiated at 75% of the maximum possible flow rate (see Figure 3-23) using "no nozzle" delivery. The tank contents would then be

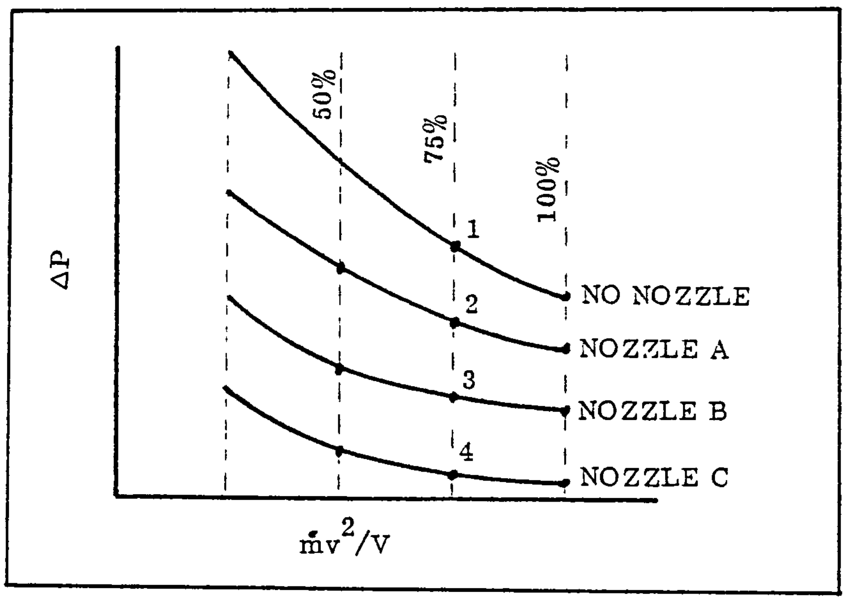


Figure 3-23. Pressure Difference from Equilibrium for Available Nozzle Options in Quarter-Scale Receiver Tank

dumped overboard and the walls reheated to the pre-chill temperature. The next run would be made using another nozzle option at the same $\dot{m}v^2/V$. Subsequent runs would exhaust the nozzle choices at the same parameter value. If the "no nozzle" run Δp is very large, no further runs need be made with this option. If one nozzle is very close to another in performance, the more complicated configuration can be eliminated. In short, decisions can be made based on the initial results as to how the remaining runs will be distributed. After the twelve runs have been made on the small tank, a good choice of nozzles for the eight runs on the large tank can be made. All contents of the small tank will be dumped overboard after each run. The half-scale tank tests will require at least five returns of contents to the supply tank.

The scaling parameters to be used for these tests have been derived in Reference 3-3.

$$\dot{m}^* = L^{*1.63} \qquad v^* = L^{*-0.37} \qquad \tau^* = L^{*1.37}$$

The following are some scaled values for $\dot{m}$, v, and t based on representative full-scale values:

Scale	m, Kg/sec	(lb/sec)	v, m/sec	(ft/sec)	t, min
1.0	0.91	(2.0)	6.71	(22.0)	139.0
0.5	0.295	(0.65)	8.26	(27.1)	53.4
0.25	0.095	(0.21)	11.19	(36.7)	20.7

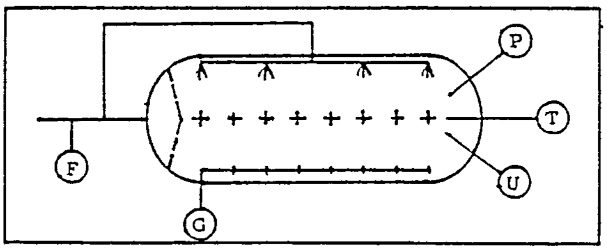


Figure 3-24. Instrumentation for Receiver Tank Fill Tests

The instrumentation required for the fill tests (see Figure 3-24) is essentially the same as that required for the pre-chill tests with an important exception. A mass gauging device (G) will be required to provide a reasonable estimate of the liquid present at any time in the tank.

The times required to conduct the operations in this experiment have been estimated and are shown below with the required RCS propellants (used for transfer back operations) and the reheat energy.

Total Time Required:		Energy Required:	
Pre-Chill Each Tank, hr:	0.06	Heaters	6.3 KWH
12 Fill Runs, 1/4-Scale, hr:	4.14		
8 Fill Runs, 1/2-Scale, hr:	7.12	RCS Propellant Required:	
11 Reheats, 1/4-Scale, hr:	0.64		
7 Reheats, 1/2-Scale, hr:	1.26	5 Settling Thrusts:	20 Kg (44 lb)
12 Dumps, 1/4-Scale, hr:	0.75		
8 Dumps, 1/2-Scale, hr:	1.00		
5 Returns, 1/2-Scale, hr:	1.25		
Total:	16.22 hr		

3.2.4 MULTI-LAYER INSULATION. The objective of this test is to determine the effectiveness of the MLI in controlling the heat load to the supply tank. To make this assessment, the supply tank pressure transient will be recorded during the mission. The heat load profile for the early part of the mission will look similar to that for other shuttle missions which have been investigated. Figure 3-25 shows the typical temperature response expected for the inner and outer layers of the MLI from lift-off until about three hours into the mission. On the ground, convection and conduction keep the heat transfer rate relatively high. About two minutes after lift-off the convection mechanism is shut off and conduction and radiation prevail. Finally, after orbit is attained, the conduction through the MLI is reduced significantly by the purge of helium. At the same time, the cargo bay temperature has been rising from the aerodynamic heating. This phase peaks about one hour into the mission. Given these events, it appears reasonable to assess the supply tank pressure data in the period from 1 to 24 hours into the mission. Based on a preliminary estimate of 403 KJ/hr (382 Btu/hr) incident heat rate, a 13.8-20.7 kN/m^2 (2-3 psia) pressure rise can be expected for a 24-hour period. Since this estimate is based on space heating and shuttle interior will provide a higher load, a larger pressure rise can be expected. Thus, a minimum time period of 8-12 hours would be required to obtain sufficient resolution of the data. Test data would be obtained early while the ullage volume is small. Since automatic control is exercised over the acquisition of data, additional information could be gathered during sleep periods.

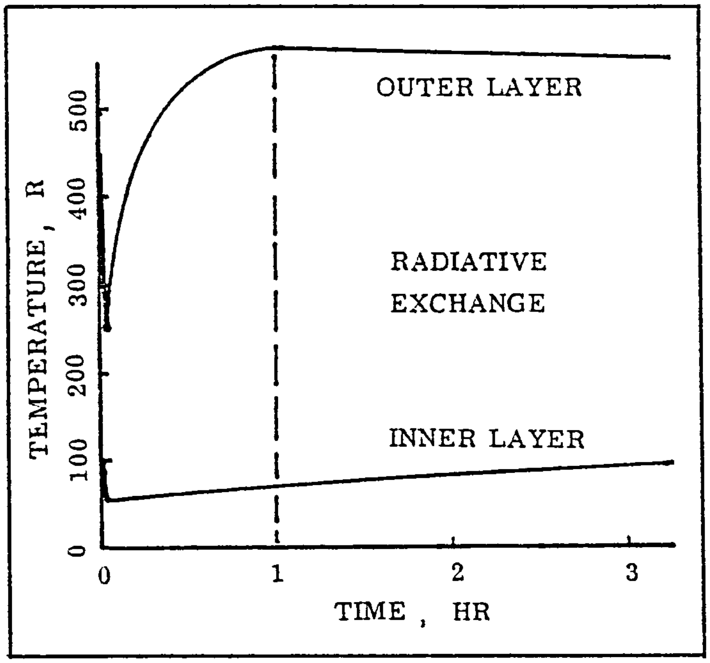


Figure 3-25. Typical MLI Behavior During Early Phase of Mission

A pressure transducer in the supply tank and temperature sensors on the inner and outer layers of the MLI, as well as on all penetrations and supports, will provide all the data required for an energy balance.

3.2.5 START BASKET. The objective of this test is to verify the start basket performance. The start basket in the half-scale receiver will be used as the test apparatus. The test can be conducted during a transfer-back operation. The procedure would be to first pressurize the tank to lower the vapor content of the basket. Then the receiver would be emptied to the 70% fill level, and RCS thrusters employed to move the liquid to the end opposite the basket. This would represent a worst case situation for restart. Then, transfer of propellant would be initiated with forward thrust (see Figure 3-26) at 0.016 g.

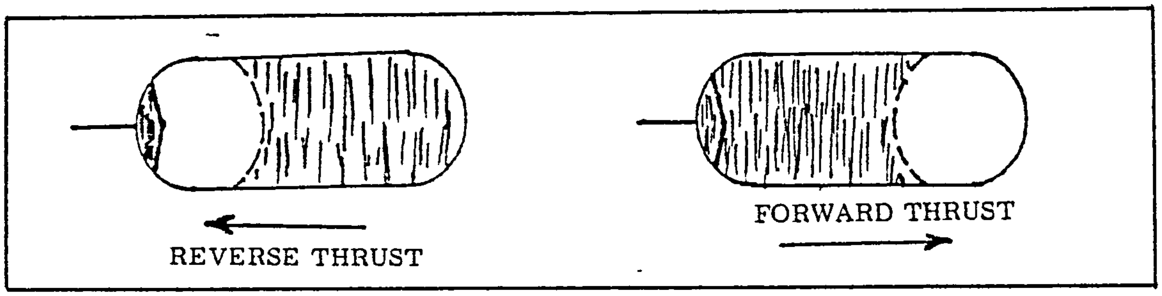


Figure 3-26. Propellant Positioning for Start Basket Test

This thrust level is representative of low-thrust OTV's as presently conceived. About 30 seconds would be sufficient to evaluate the start basket performance. The evaluation would be qualitative - detection of vapor at the receiver tank exit. Thrust would then be reduced to a lower level and transfer continued until the 50% level was reached. At that time, the sequence of events would be repeated. Runs at 70, 50, 30, and 10 percent levels are recommended.

The only instrumentation required for this test is apparatus to assess quality at the receiver tank exit. This instrument will already be required for the line chill-down tests. The time required to conduct the test is simply that required to empty the tank (15 minutes) plus that required for four reverse thrust operations at ten minutes each. The RCS propellant requirements for this test were determined to be 657 Kg (1448 lb) based on using four RCS engines at 395 Kg (870 lb) thrust each, and specific impulse of 290 sec for 30 seconds at each tank level.

3.2.6 AUTOGENOUS PRESSURIZATION. The objective of this test is to determine the extent of ullage collapse (from condensation) due to introduction of hot LH_2 vapor. Although it may require development of a gas generator to conduct this test, it is possible that sufficient vapor near 345 KN/m^2 (50 psi) might be generated in the small receiver tank. As stated earlier, a minimum of 6.3 Kg (14 lb) of pressurant is required for a single transfer. If all the energy of vaporization comes from the power supply, about 0.4 kwh is required. No additional instrumentation other than that associated with monitoring gas generator performance will be required. No additional time is required since the operation replaces a helium pressurized transfer.

3.2.7 AUXILIARY EQUIPMENT TESTS. These tests consist of evaluations of the performance of equipment used in the previous tests or that related to mission abort. No additional time, power, or RCS propellant will be required.

1. Helium Pressurization System - Data taken during fill and return tests provide basis for evaluation of this system.

2. Zero-g Vent System - Initial venting of the supply tank, prior to initiation of transfer experiments, will provide an opportunity to assess the performance of the vent package. One objective will be to gather sufficient data to determine the ability of the system to meet venting requirements on orbit. Another objective will be to determine mixer capability to maintain supply tank equilibrium during inactive periods (periods without outflow).

   Instrumentation will be provided on the vent package such that data on vent fluid state and flow rate, mixer performance, and heat exchanger hot-side pressure drop and temperature can be obtained. In addition, temperature and pressure sensors on the vent line will be useful.

3. Supply Tank Emergency Dump System - The final contents of the supply tank will be dumped through the emergency dump line providing data on the time to unload a given mass of propellant. A flow meter and a quality gauge will be required on the dump line. Such a test would require only a few seconds.

4. Supply Tank Screen Acquisition Device - The performance of the screen acquisition device in the supply tank will be assessed during the off-loading of the final contents of the tank. Since the purpose of the device is to minimize tank residuals, assessment of performance will depend on the use of the mass gauging device, probably during the final dump operation. In addition to the mass gauging device, flowmeter, temperature and pressure sensors on the dump line will aid in this performance assessment.

Experiment Time Schedule - A preliminary time schedule for the entire set of experiments is shown in Figure 3-27.

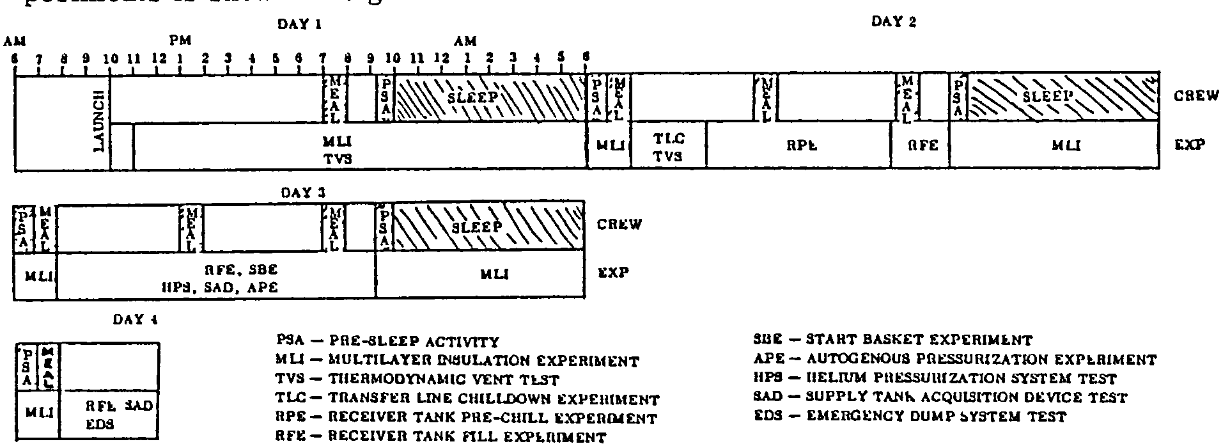


Figure 3-27. A Possible Time Schedule for the Experiment.

3.3 PRELIMINARY EXPERIMENT DESIGNS

This section documents the design evolution of the propellant transfer experiment. These preliminary designs were the basis of the detail conceptual designs of Section 4.1 and the program plans of Section 5. Some of the preliminary design concepts presented were dropped as candidates; however, they are presented to provide an overview of the total design evolution. The results of this design effort as well as the previous experiment definitions formed the basis for the NASA approval to proceed with the selected designs presented in Section 4.0.

3.3.1 EXPERIMENT SIZING AND ARRANGEMENTS. The initial preliminary design activity was keyed to determine the maximum scale receiver tank that could be accommodated within the Shuttle cargo bay. In addition the designs also considered the probable OTV orientations during propellant tanking to determine if any adverse design problems existed because of this operational consideration. Subsequent design studies eliminated the articulating receiver tank configurations as being unnecessary from the propellant transfer standpoint.

Figures 3-28, -29 and -30 (Layouts 4, 5 and 6) were developed to determine the approximate size of the experimental LH_2 tank installed in the Shuttle payload bay and to present orientation options for conducting the experiment. Layout 4 shows an experiment tank module, a LH_2 supply tank, and interconnecting plumbing installed in the Shuttle payload bay. The tank module is a 3/4 scale model of the full size LH_2 tank for the POTV discussed in Section 2.0. The tank is suspended inside a truss cage using the same support system described for the full size tank. The truss cage in turn interfaces with the Shuttle payload support journals at stations X_o 766.13 and X_o 935.27. The experiment tank is equipped with fill, vent, and insulation systems similar to those for the full size tank. No acquisition system is included in this design; however, conceptual designs described later in Section 4.1 do contain the capability to return propellant to the supply tank via an acquisition device. The vent systems are connected to the Shuttle LH_2 flight vent circuit.

The LH_2 supply tank is a 427 cm (164 in) dia. cylinder with two spherical bulkheads. The tank is suspended inside a vacuum shell equipped with two girth rings which in turn interface with the Shuttle payload support journals. The tank features an insulation system, a pressurization system, an acquisition system; and plumbing which connects to the Shuttle payload service interfaces.

Similar to the full-scale article the transfer line between supply tank and experiment incorporates swivel joints, flex joints, a disconnect valve, and insulation. The line is connected to the experiment before launch, therefore the RMS is not used to manipulate the transfer line when in orbit. In addition to propellant transfer data, the Layout 4 arrangement offers a means for checking out major transfer line components such as swivel joints and disconnect valve systems.

In Figure 3-29 (Layout 5) the experiment truss cage incorporates a means for rotating the experiment 1.57 RAD (90^o) from the stowed position. The truss cage also features an external disconnect panel and a latch system which attaches to a truss yoke when at the 1.57 RAD (90^o) position. A nonpropulsive steer horn vent system has also been added at the forward end (see View A-A). The transfer line is a model of the full-scale article including the disconnect valve capturing and latching systems. The transfer line is

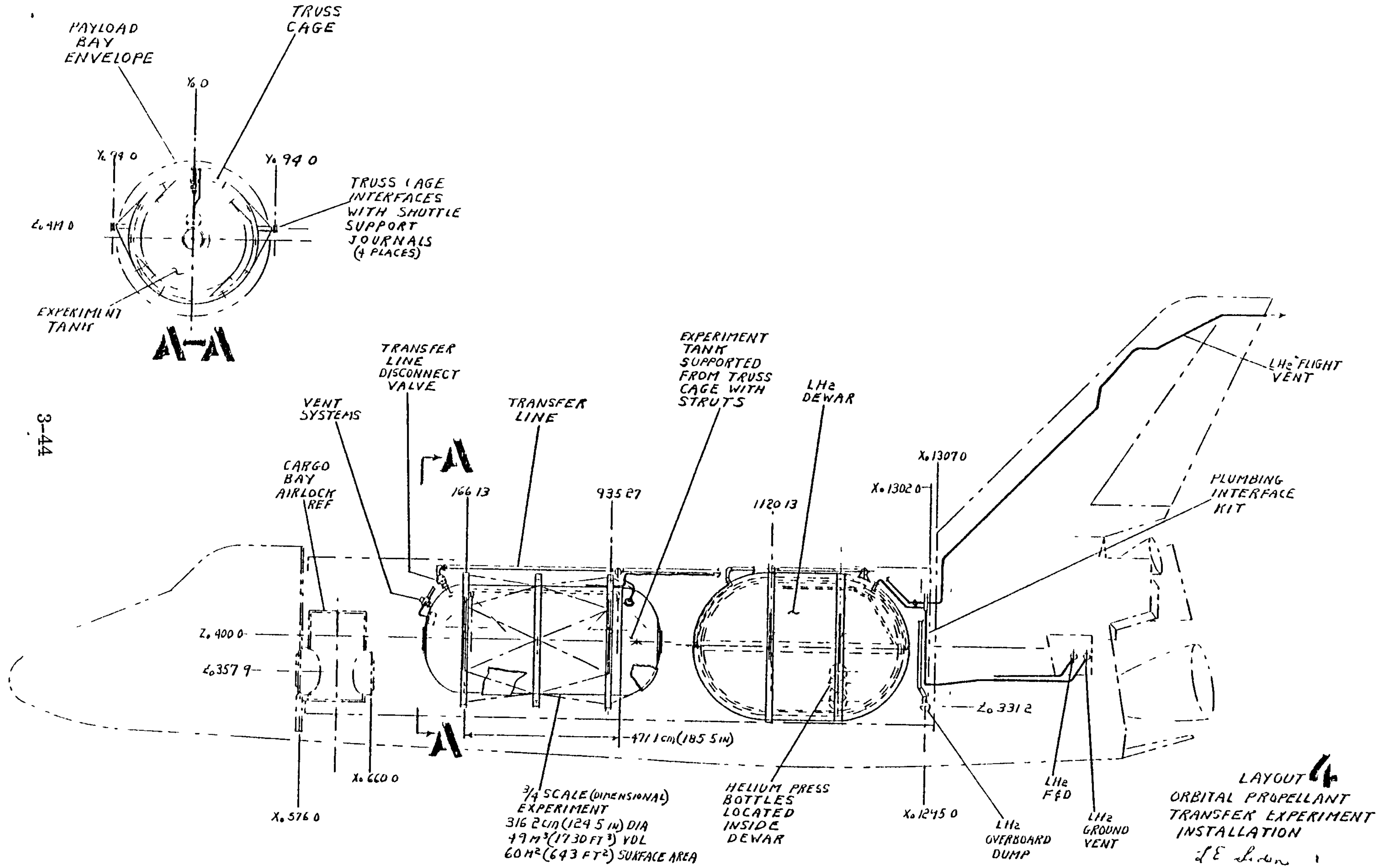


Figure 3-28. Preliminary Maximum Scale POTV Hydrogen Tank Layout

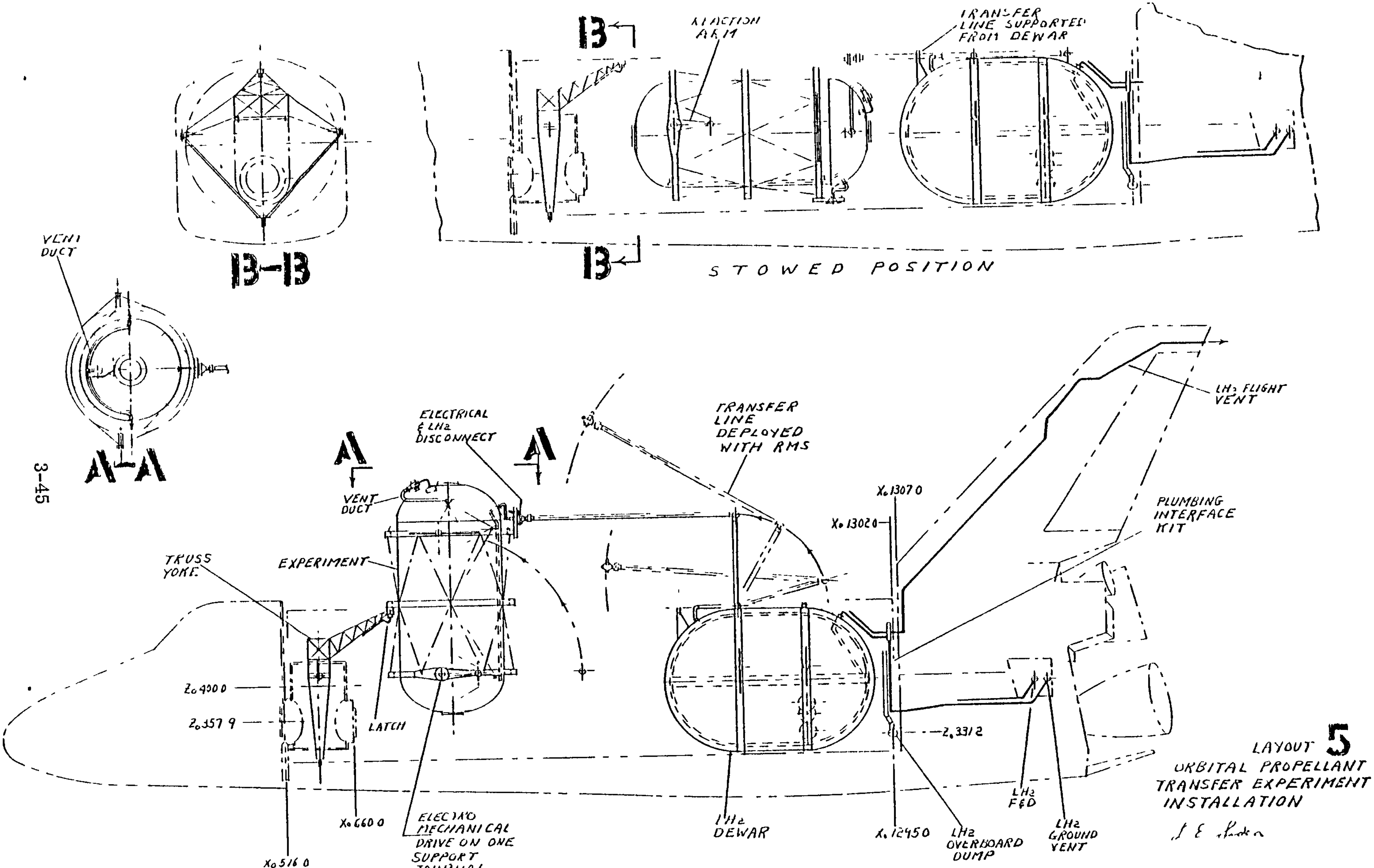


Figure 3-29. Articulating Receiver Tank Installation.

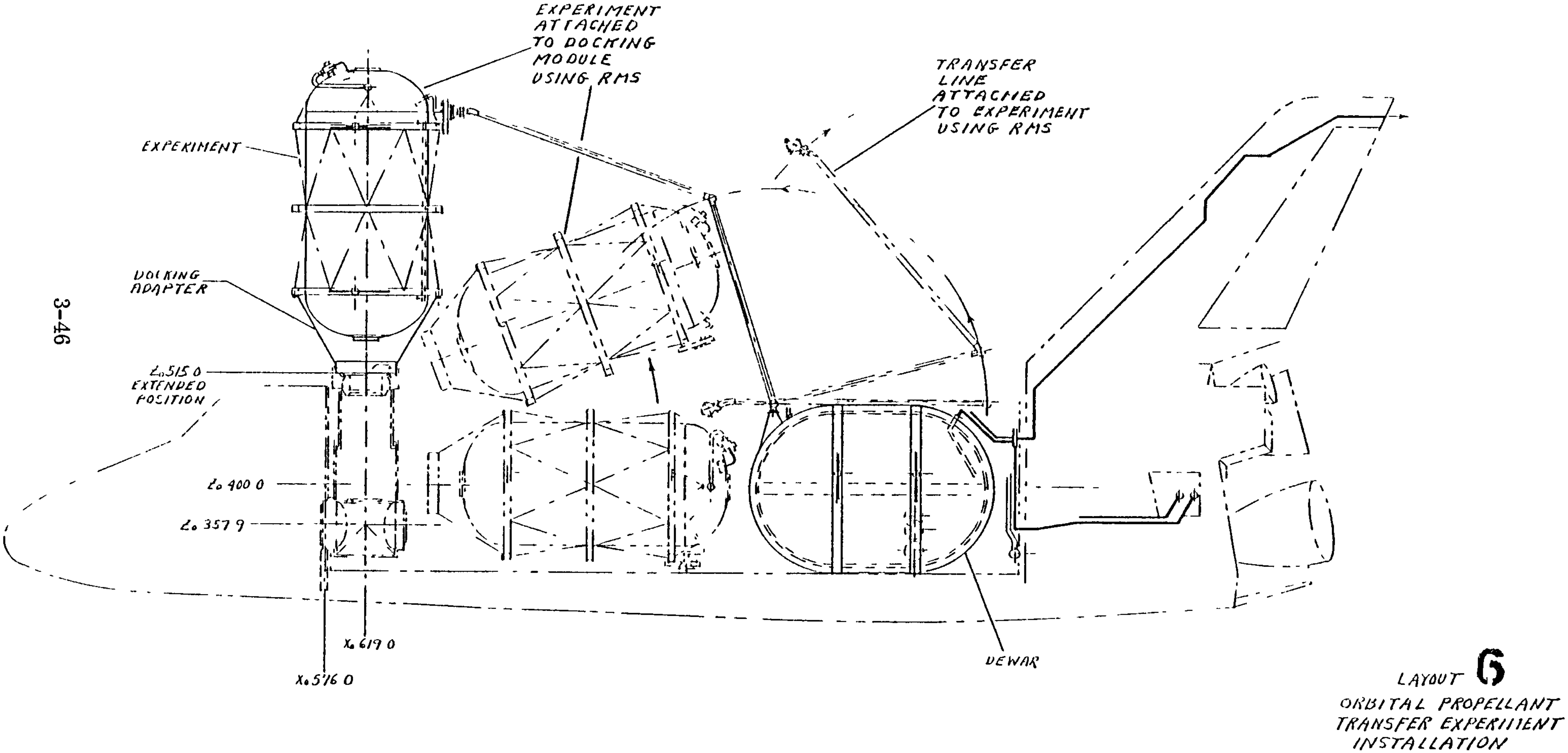


Figure 3-30. Receiver Tank/Docking Adapter Configuration

not connected to the experiment before launch, therefore the RMS is required to position the transfer line disconnect valve to the experiment disconnect panel. In addition to propellant transfer data, the approach provides opportunities for checking out the transfer line and system dynamics when exposed to realistic operating modes.

In Figure 3-30 (Layout 6) the experiment truss cage is equipped with a docking adapter and provisions for latching and unlatching from the Shuttle payload support journals. Prior to propellant transfer, the experiment is attached to the Shuttle docking module using the RMS. The RMS is also used to position the transfer line disconnect valve to the experiment disconnect panel. Compared to Layout 5, this arrangement more closely represents the actual conditions encountered with a full-scale OTV docked to the Shuttle.

3.3.2 PRELIMINARY EXPERIMENT INSTALLATION CONCEPTS. The major intent of this installation exercise shown in Figure 3-31 (Layout 7) was to define the approximate size limits of a receiver tank, a supply tank, and associated plumbing, and electrical systems. (See Section 4.1 for the final selected designs.)

At the forward end of the payload bay, a 1.2m (4-ft) EVA zone is provided. At the aft end an additional 1m (3 ft) is required for items such as abort dump, pressurization systems, ground vent, ground fill & drain, and electrical systems. The maximum length available for the experiment concept is approximately 16.2m (53 ft). The receiver tank shown is a 3/4 scale model of the LH_2 tank for the target OTV that is being considered in the mission model. The tank example is suspended inside a truss cage which in turn interfaces with the Shuttle support journals using an arrangement similar to that shown in Detail "A" on the layout. As a first cut conceptual design it was assumed that the remaining space (after receiver installation) in the payload bay was occupied by a dewar supply tank. The resulting dewar volume is 102m^3 (3600 ft^3) which is slightly more than twice the volume for the 3/4 scale receiver tank.

The example concept shown assumes that both tanks will include acquisition systems. The receiver tank will also include hardware for selecting several types of filling modes. The filling may be accomplished with simultaneous sprays at the forward and aft ends versus a single spray injection at the aft end. Plumbing systems are required for propellant transfer, abort dump, vents, fill and drain, and pressurization. Layout 7 shows general locations for these systems. The propellant transfer line is a static line and will include thermal masses and bends for simulating the joints and flow paths of actual OTV tanks. The abort dump requirement is a prime driver in the experiment plumbing system due to its large size, vacuum jacketing, and valve redundancy. A possible plumbing arrangement for this abort capability is shown in View C-C of the layout. Both tanks require vents, therefore the vent plumbing will traverse the full length of the installation and interface with the Shuttle at X_o 1302. Fill and drain plumbing is associated with the supply tank and therefore will be located primarily in the aft region between the dewar and X_o 1302.

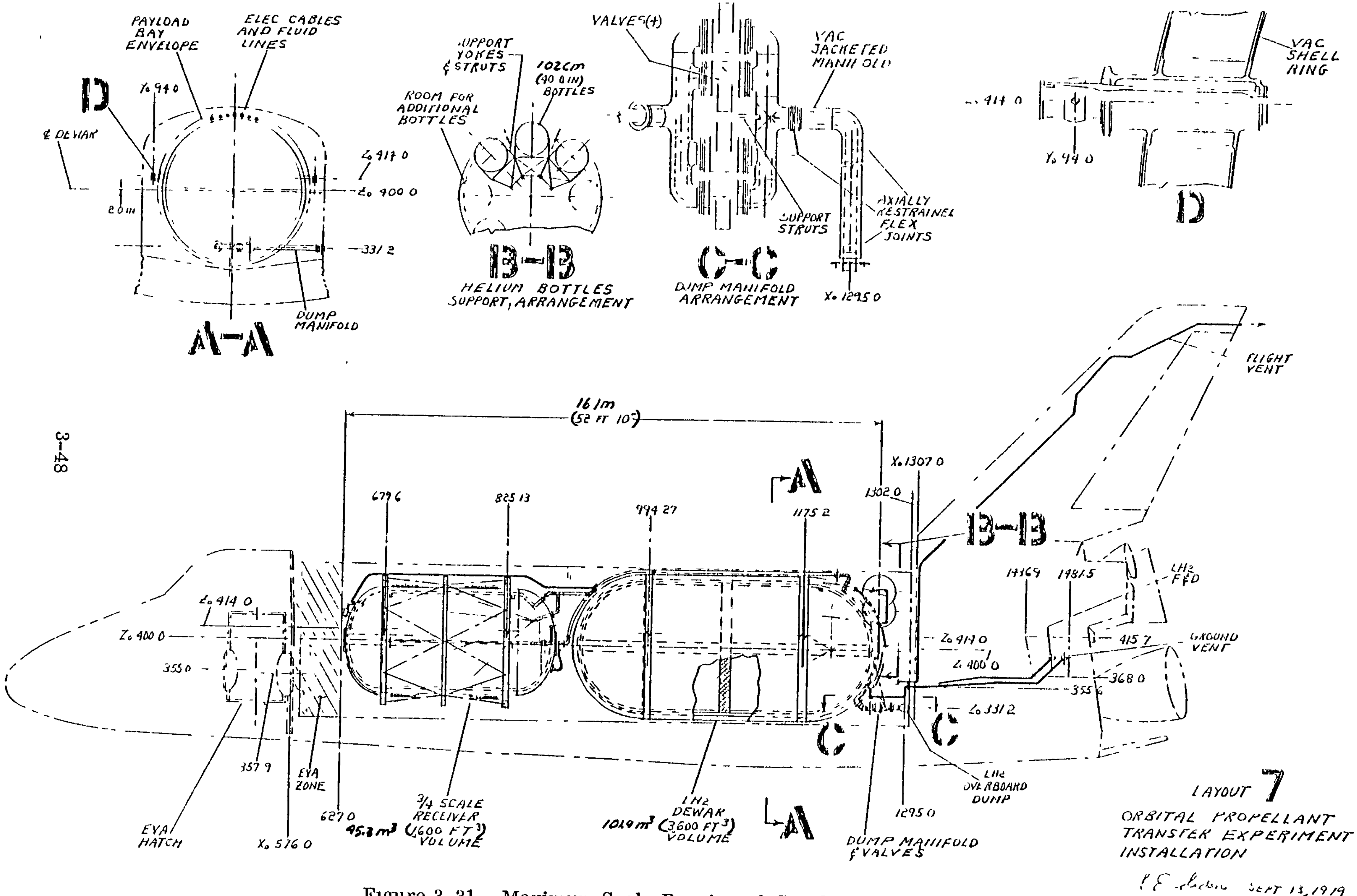


Figure 3-31. Maximum Scale Receiver & Supply Tank Instrumentation.

Several helium storage bottles, control valves, regulators, etc. are required for the abort pressurization system. The interconnecting plumbing for these systems will be located aft near the storage bottles and is typical of that shown in View B-B. A small portion of the plumbing will also extend forward to the receiver. Instrumentation wiring will be located over the full length, width and depth of the installation envelope. The main trunks of the harnesses will typically be located at the top side as shown in View A-A. Equipment for data and controls will be supported off the dewar forward bulkhead or the receiver tank truss cage.

The pertinent thermodynamics, fluid dynamics, and scaling considerations have been studied and were summarized previously in Section 3.1.2. A preliminary experiment design approach that reflects these analyses is shown in Figure 3-32 (Layout #9). This includes a 73.6m^3 (2600 ft^3) LH_2 supply tank with two experimental receiver tanks. The supply tank is located approximately 1m (3 ft) forward of X_o 1302.0 to allow room for plumbing and electrical systems including an abort dump system. Both receiver tanks are supported from a skirt section which is part of the supply tank assembly. The overall length of the total installation is 12.2m (40 ft) which leaves a net 3.8m (12.5 ft) for additional payload space. A 1.2m (4.0 ft) EVA zone is assumed at the forward end.

Unlike the first cut design concept discussed previously (see Figure 3-31), the supply tank is not a dewar. The basic tank shell is a cylinder equipped with two hemispherical bulkheads. The tank is suspended inside a cylindrical body structure which in turn interfaces with the Shuttle support journals. The forward end of the body structure features an adapter which interfaces with the experiments. This adapter is equipped with flat closure panels which serve as purge enclosures (see View B-B). The aft end of the body structure has a fiberglass bulkhead which also serves as a purge enclosure. The tank is enveloped with MLI and a purge system.

The two experimental receiver tanks are 1/2 and 1/4 scale models of an OTV LH_2 tank. Each tank is a 2219-T87 aluminum alloy cylinder with two elliptical bulkheads (a/b = 1.38). The tanks are suspended inside body structures which in turn are attached to the support adapter.

3.3.3 PRELIMINARY TANK & INTEGRATED SYSTEM CONCEPTS. A half-scale receiver tank and a weight estimate is shown in Figure 3-33 (Layout #11). The basic shell is a 2219-T87 aluminum cylinder equipped with two ellipsoidal bulkheads (a/b = 1.38). The tank is equipped with a multi-layer insulation (MLI) system, outside wall heaters, and acquisition system, and internal fill manifolds. Also included is wall penetration hardware for electrical, plumbing and access.

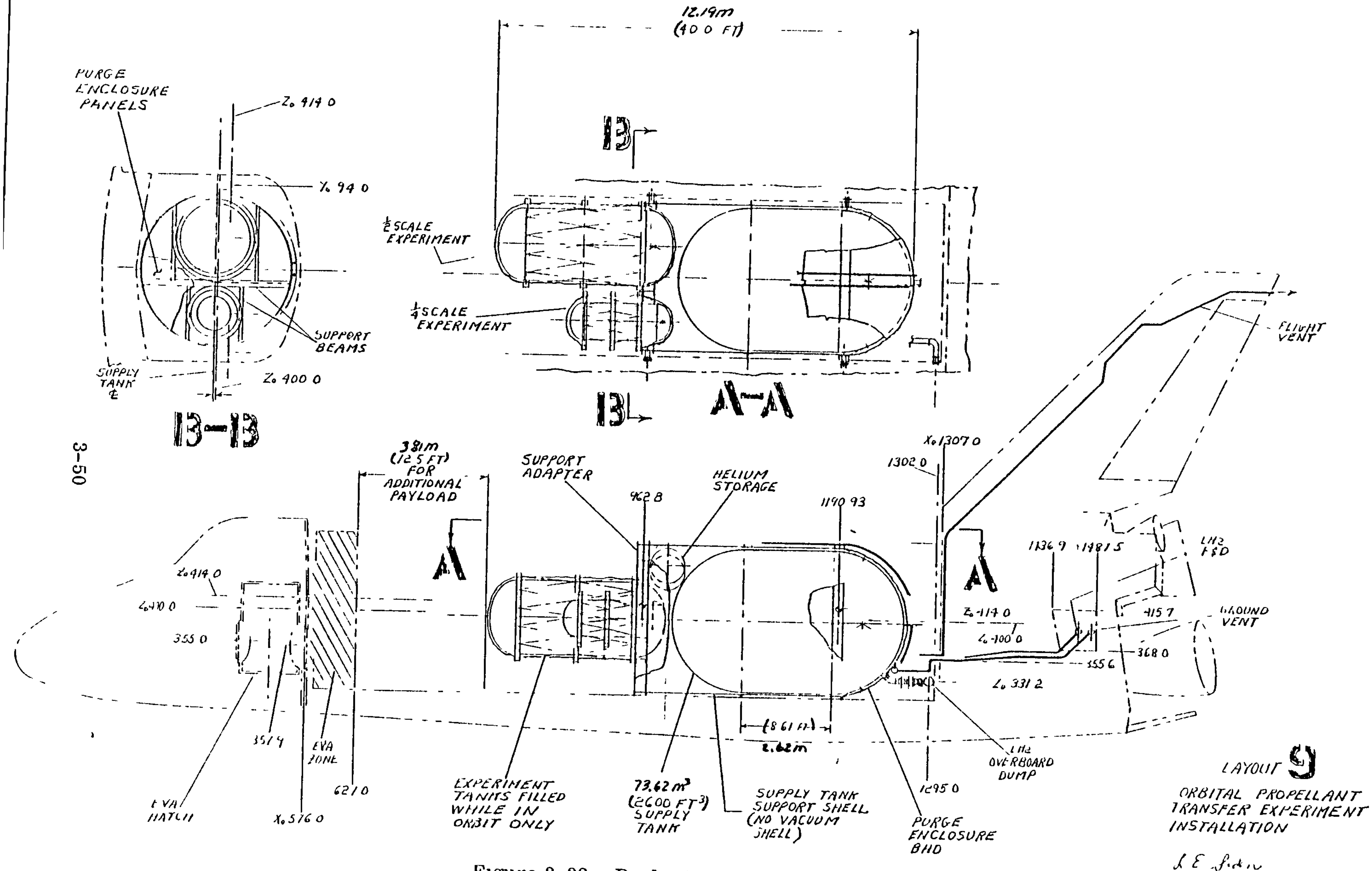
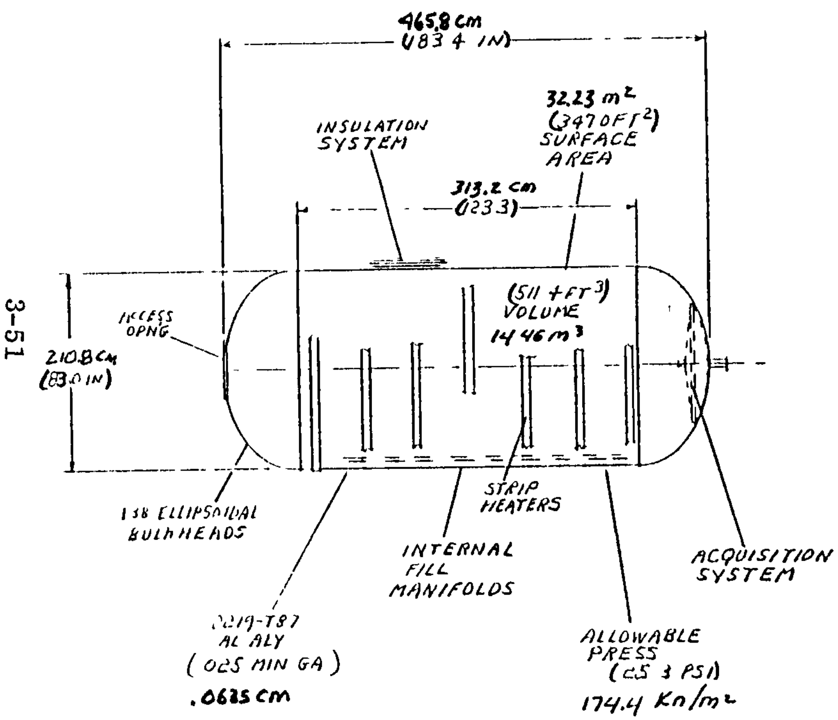


Figure 3-32. Preliminary Experiment Installation.



ITEM (NO SCALE)	WT Kg (lb)
TWO ELECTRICAL RECEPTACLE	.54 (1.2)
ELECTRICAL HEATERS	2.72 (6.0)
(.123#/FT²) 20 LAYERS NO PURGE .6Kg/m²	21.3 (47.0)
ACQUISITION SYSTEM	13.6 (30.0)
15% CONTINGENCIES	16.5 (36.4)
TOTAL	126.7 (279.3)

ITEM (NO SCALE)	WT Kg (lb)
(15# FOR WELD ZONES 6.8Kg) TANK SHELL INC'L WELD LANDS	63.5 (140.0)
TANK WALL PENETRATION FTGS AND SUPPORTS	.91 (2.0)
(24.0) FD 61.cm ACCESS OPNG RING	2.72 (6.0)
ACCESS DOOR COVER	.91 (2.0)
CRES BOLTS SEALS BOLTS, SEALS & SUPPORT LUGS FOR INTERNAL MANIFOLDS	.91 (2.0)
INTERNAL MANIFOLDS & FTGS.	2.2 (4.8)
TWO ELECTRICAL BOSSES	.54 (1.2)
TWO ELECTRICAL FTG RETAINER RING	.31 (.68)

LAYOUT II

ORBITAL REFILL EXPERIMENT

1/2 SCALE RECIEVER TANK

J E Sidon

OCT 18, 1979

Figure 3-33. Half-Scale Receiver Tank.

The basic shell is all welded construction with chem-milled weld zones on both the bulkheads and the cylindrical shell. The thickness at these weld zones is twice the basic shell gage. The 0.064 cm (0.025 in) basic wall gage is considered minimum relative to manufacturing and handling.

The entire surface of the tank is covered with MLI applied in gore and cap sections. Since the tank is dry before and during ascent no purge system is used. Dry nitrogen gas in the shuttle payload bay is considered adequate for preconditioning.

The wall heaters are circumferential strip types equally spaced along the length of the cylindrical section. The heaters are bonded to the outside surface of the tank wall with the electrical leads packaged into a single cable which penetrates the MLI at one point.

The acquisition system is a capillary type device located inside the aft bulkhead. The device is basically a shallow dish equipped with a conical lid, an internal channel assembly and an outlet. The material is aluminum alloy. Typical wall construction consists of a capillary screen attached to a perforated sheet.

It is planned to equip the tank with two internal spray manifolds and a single nozzle. This provides testing flexibility since different filling modes can be selected. The spray manifolds are straight tube sections located inside the tank and running the full length of the cylindrical section. Each of these tubes have tee fittings equipped with spray nozzle fittings. Additional details including the single spray nozzle are shown in Figure 3-34 (Layout #11A). Tank wall penetration fittings are required for the electrical, plumbing, and access opening. These fittings are boss type rings welded into the shell. A brief description of these parts is shown in the weight breakdown chart.

Layout #11A shows how the half-scale model receiver tank is supported and also some additional details of the fill and acquisition systems. The tank is suspended inside a cylindrical truss cage using low conductive struts. Four pairs of struts arranged in a "V" pattern are used to attach the aft bulkhead to the truss cage box ring. The center line of these struts is directed tangentially into the bulkhead wall. The forward bulkhead is attached to the truss cage with four tangential low conductive drag links per Detail "B" on the layout. The complete assembly (tank and cage) is mounted from the supply tank adapter. The aft box ring on the truss cage interfaces with adapter beams. An enclosure bulkhead is provided at the aft end which separates the supply tank purge from the receiver tank assembly.

A quarter-scale receiver tank is shown in Figure 3-35 (Layout #12). Except for size, the tank is the same as that shown for the half scale in Layout #11 and 11A including the support methods. A weight breakdown is also shown in the layout.

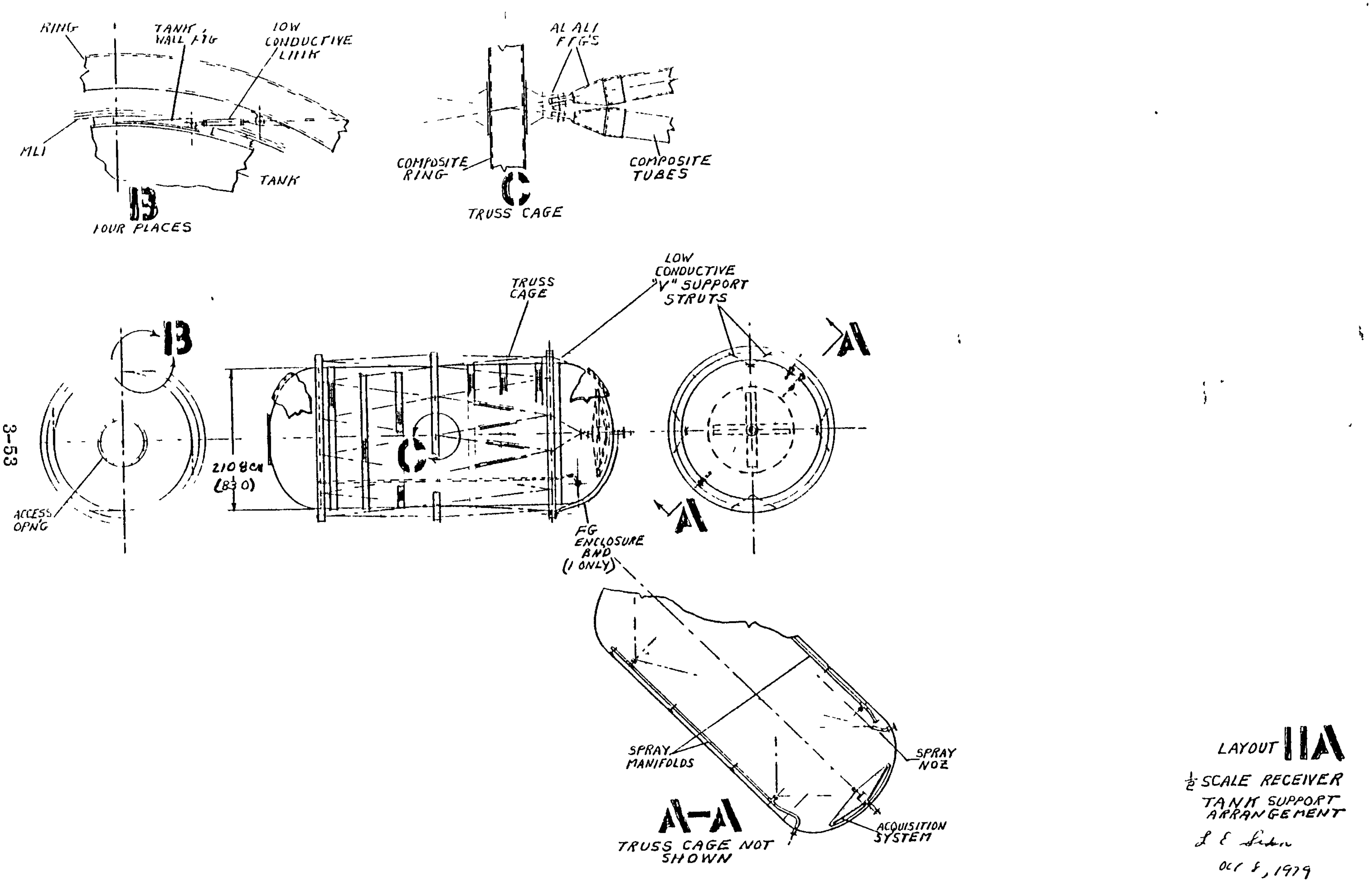
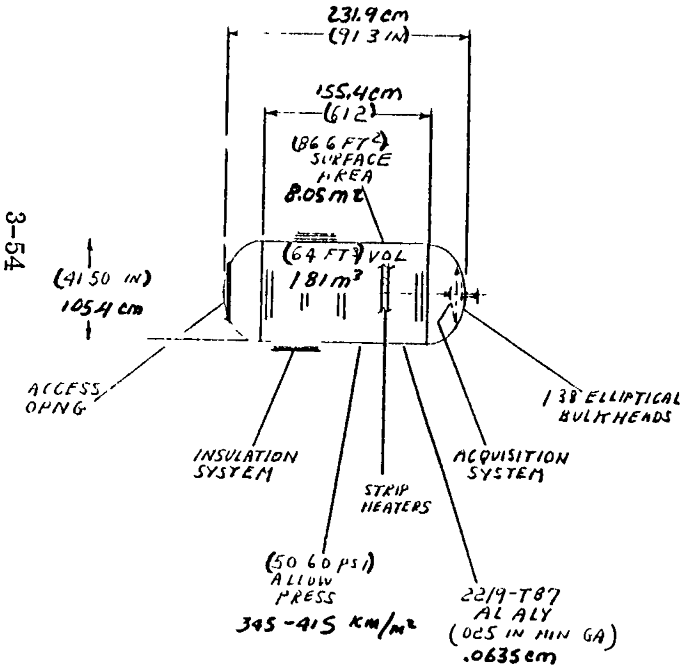


Figure 3-34. Half-Scale Receiver Tank Support Arrangement.



ITEM (NO SCALE)	WT Kg (lb)
ELECTRICAL RECEPTACLE (TWO)	.27 (.6)
ELECTRICAL HEATERS	1.04 (2.3)
INSULATION 20 LAYERS (123#/FT³) NO PURGE .6 Kg/m²	4.9 (10.7)
ACQUISITION SYSTEM	7.0 (15.4)
15% CONTINGENCIES	5.4 (11.8)
TOTAL 41.0	(90.3)

ITEM (NO SCALE)	WT Kg (lb)
TANK SHELL INC'L WELD LANDS	16.3 (36.0)
TANK WALL PENETRATION FTGS AND SUPPORTS	.59 (1.3)
ACCESS OPNG RING (24.0) ID 61 cm	2.72 (6.0)
ACCESS DOOR COVER	.91 (2.0)
CRES BOLTS, SEALS, LUGS — BOLTS, SEALS & SUPPORT LUGS FOR INTERNAL MANIFOLDS	.68 (1.5)
INTERNAL MANIFOLDS & FTGS	.82 (1.8)
ELECTRICAL BOSSES (ONE)	.27 (.60)
ELECTRICAL FTG RETAINER RING (ONE)	.15 (.34)

LAYOUT 12

ORBITAL REFILL EXPERIMENT.
1/4 SCALE RECEIVER TANK
L.E. Siden
OCT 18, 1979

Figure 3-35. Quarter-Scale Receiver Tank.

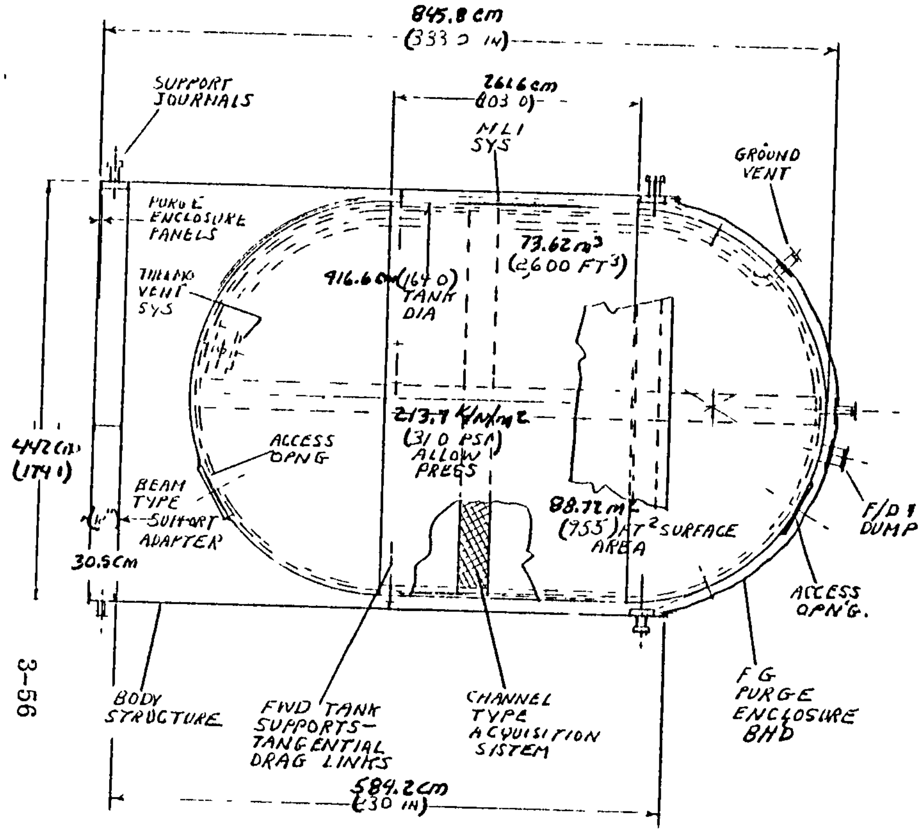
Figure 3-36 (Layout #13) gives a description and a weight breakdown for the supply tank and body structure. The tank is a 416.6 cm (164.0 in) dia. cylinder equipped with hemispherical bulkheads. The tank material is 2219-T87 aluminum alloy. The accessories include a channel type capillary acquisition system; thermo vent/ internal plumbing for ground and flight vent; F/D and dump outlet fitting; a MLI system, access openings, and electrical penetrations. A basic parts breakdown is shown in the weights chart. The tank is supported from an outer body structure which in turn interfaces with the shuttle support journals. The tank support system is the same as that described for the half-scale receiver tank. The body structure is a 442 cm (174 in) dia. cylinder equipped with a support adapter at the forward end and a purge enclosure bulkhead at the aft end. Each end of the structure has box rings equipped with support trunnions. The support adapter at the forward end has cross beams which interface with the receiver tank truss cages. These beams are covered with flat panels in the areas between the truss cages which complete the purge enclosure.

The overall system installation and a weight breakdown is shown in Figure 3-37 (Layout #14), Sheets 1 and 2. The purpose for Layout #14 is to show the general arrangements and basic plumbing routes. No attempt is made to show all circuits.

The complete assembly including supply tank, body structure and receiver tanks is positioned in the shuttle so that the aft end is approximately 102 cm (40.0 in) from station X_o 1302.0. The purpose for this location is to allow room at the aft end for the abort dump manifold and other systems associated with fill, drain, vent and electrical. Most of the lines are routed along the top of the body structure as shown in views A-A and B-B. The transfer line has three straight sections coupled with swivel joints for simulating the operational fill line. At the forward end, the receiver tanks are interconnected with plumbing and valves so that different transfer modes can be selected. The helium storage bottles with controls and plumbing are supported from the supply tank body structure at the forward end.

The abort dump manifold is a prime driver in the plumbing system due to the quad valve system, vacuum jacketing and large size. An arrangement is shown in view C-C. The manifold is supported from the supply tank body structure with a strut system. A duct section with three axially restrained flex joints routes from the manifold to the shuttle overboard interface fitting at station X_o 1295.0. A weight breakdown showing the basic parts is shown in Sheet 2 of Layout 14.

To provide baseline data for scaling analyses presented in Section 3.1.2.1, a design and weight estimate for a full-size LH_2 tank was made and is shown in Figure 3-38 (Layout #15). Except for size, the basic tank construction and support systems are the same as those described for the half-and quarter-scale receivers. Unlike the scale receivers which provide experiment flexibility, only a single loading system is used in the full-scale tank. For estimating purposes, one spray manifold is shown. The MLI also includes a purge system which was not used on the scale receivers.



ITEM (NO SCALE)	WT Kg (lb)
PURGE ENCLOSURE BHD (AFT)	45.4 (100.0)
PURGE ENCLOSURE (FWD) FG	40.82 (90.0)
SUPPORT ADAPTER	68.0 (150.0)
BODY STRUCTURE (PLUS RING & JOURNALS)	498.9 (1100.0)
THERMO VENT SYS.	54.4 (120.0)
15% CONTINGENCIES	212.7 (469.0)
TOTAL 1630	(3594.0)

ITEM (NO SCALE)	WT Kg (lb)
TANK (2219-T87 AL ALY t=.060, 27% ADDED FOR WELD LANDS)	475.3 (1048.0)
ACQUISITION SYS	127.9 (282.0)
INTERNAL PLUMBING	27.2 (60.0)
	13.6 (30.0)
ACCESS OPNG RINGS (2)	5.4 (12.0)
ACCESS DOOR COVER (2)	2.72 (6.0)
BOLTS, SEALS & BRACKETS	2.27 (5.0)
ELECTRICAL PENETRATION FTGS	1.81 (4.0)
20 LAYERS TANK INSULATION	53.5 (118.0)

LAYOUT 13
ORBITAL REFILL EXPERIMENT.
LH_2 SUPPLY TANK
S. E. Siden
OCT 19, 1979

Figure 3-36. LH_2 Supply Tank.

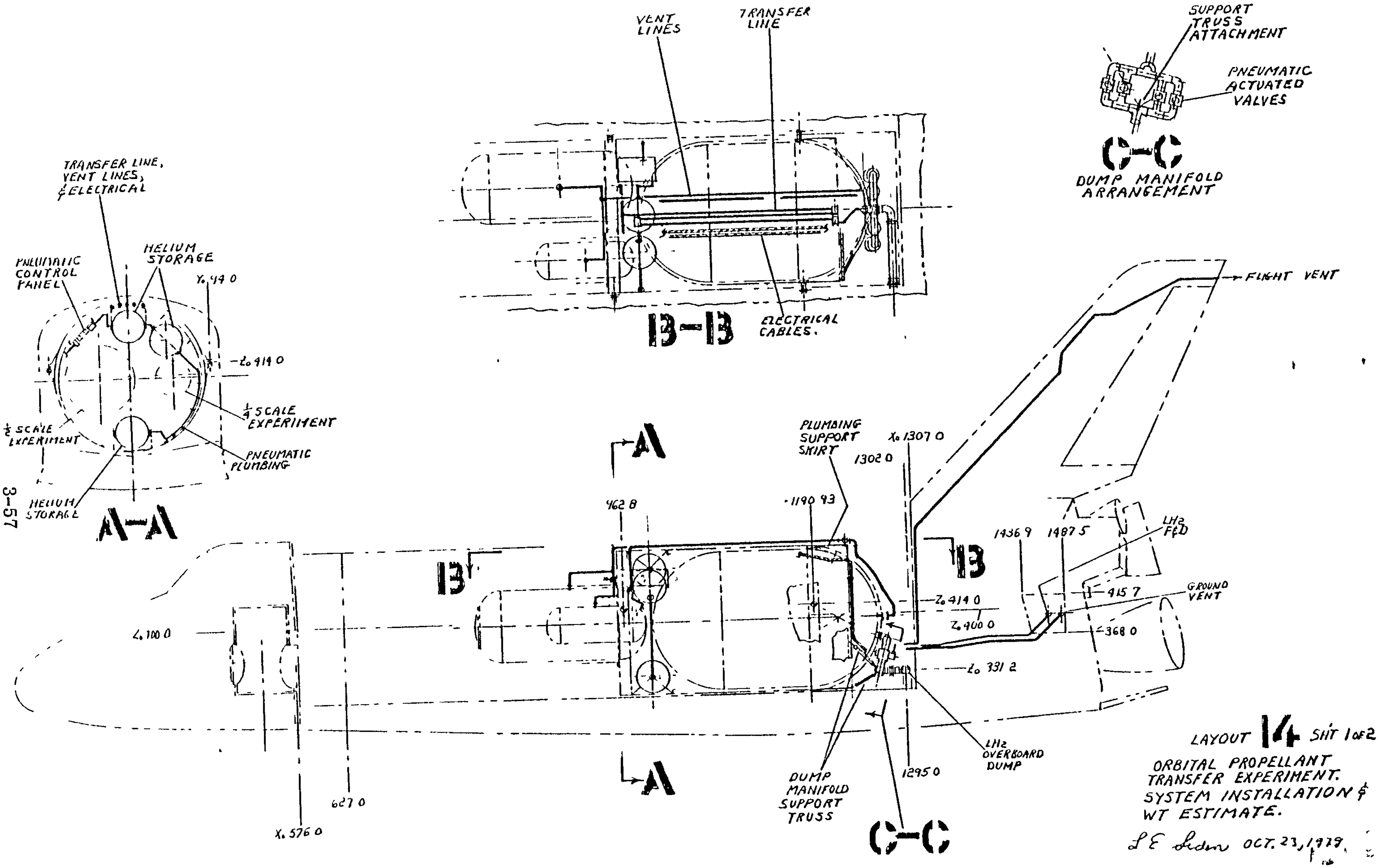
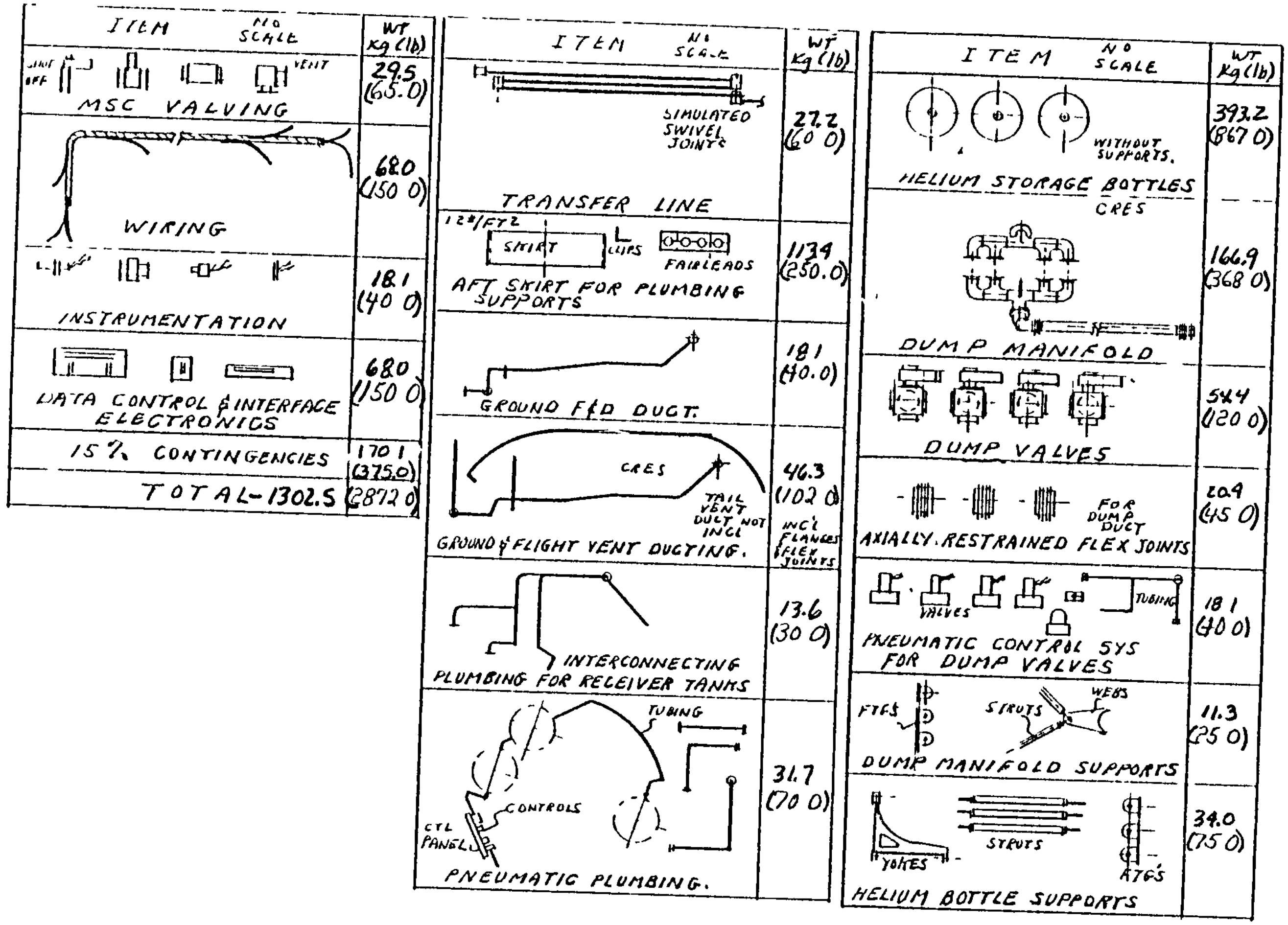


Figure 3-37. Preliminary System Installation & Weight Estimate.



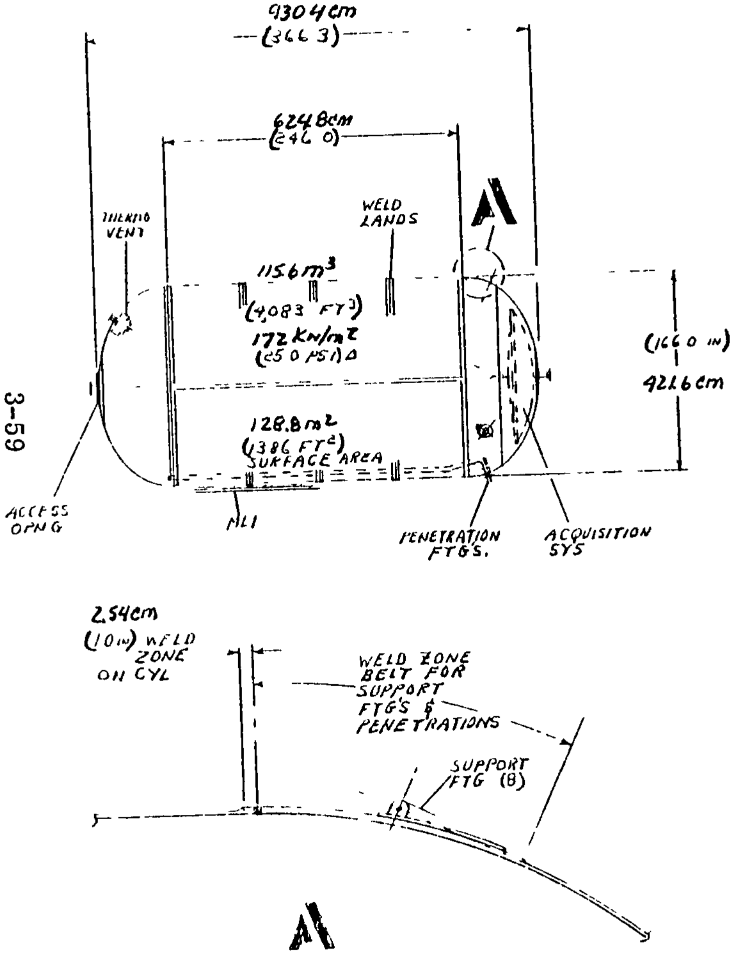
ITEM (NO SCALE)	WT kg (lb)
MSC VALVING	29.5 (65.0)
WIRING	68.0 (150.0)
INSTRUMENTATION	18.1 (40.0)
DATA CONTROL & INTERFACE ELECTRONICS	68.0 (150.0)
15% CONTINGENCIES	170.1 (375.0)
TOTAL - 1302.5	(2872.0)

ITEM (NO SCALE)	WT kg (lb)
TRANSFER LINE (SIMULATED SWIVEL JOINTS)	27.2 (60.0)
AFT SKIRT FOR PLUMBING SUPPORTS (12#/FT2, SKIRT, CLIPS, FAIRLEADS)	113.4 (250.0)
GROUND FLD DUCT	18.1 (40.0)
GROUND & FLIGHT VENT DUCTING (CRES; TAIL VENT DUCT NOT INCL)	46.3 (102.0) INC'L FLANGES & FLEX JOINTS
INTERCONNECTING PLUMBING FOR RECEIVER TANKS	13.6 (30.0)
PNEUMATIC PLUMBING (TUBING, CONTROLS, CTL PANEL)	31.7 (70.0)

ITEM (NO SCALE)	WT kg (lb)
HELIUM STORAGE BOTTLES (WITHOUT SUPPORTS)	393.2 (867.0)
CRES	---
DUMP MANIFOLD	166.9 (368.0)
DUMP VALVES	54.4 (120.0)
AXIALLY RESTRAINED FLEX JOINTS (FOR DUMP DUCT)	20.4 (45.0)
PNEUMATIC CONTROL SYS FOR DUMP VALVES (VALVES, TUBING)	18.1 (40.0)
DUMP MANIFOLD SUPPORTS (FTGS, STRUTS, WEBS)	11.3 (25.0)
HELIUM BOTTLE SUPPORTS (YOKES, STRUTS, FTGS)	34.0 (75.0)

LAYOUT 14 SHT 2 OF 2
ORBITAL PROPELLANT TRANSFER EXPERIMENT SYSTEM INSTALLATION & WT. ESTIMATE.
L E Siden OCT 23, 1979

Figure 3-37. Preliminary System Installation & Weight Estimate (Continued)



ITEM (NO SCALE)	WT kg (lb)
ELECTRICAL BOSSES (TWO)	.54 (1.2)
ELECTRICAL FTG RETAINER RING (TWO)	.32 (.70)
ELECTRICAL RECEPTACLE (TWO)	.54 (1.2)
20 LAYERS 1.6 kg/m² (.323 #/FT²) INSULATION & PURGE SYS	203.2 (448.0)
ACQUISITION SYSTEM	112.0 (247.0)
15% CONTINGENCIES	122.7 (270.5)
TOTAL- 940.6	(2074.0)

EXCLUDES PURGE ENCLOSURE & CTL'S

SEE LAYOUT FOR DETAILED BREAK DOWN

ITEM (NO SCALE)	WT kg (lb)
2219-T87 AL ALY BASIC TANK SHELL	452.6 (998.0)
BHD. WELD ZONES	27.8 (61.3)
CYLINDER WELD LANDS	10.8 (23.8)
(24.0) I.D 61 cm ACCESS OPNG RING	3.2 (7.0)
ACCESS DOOR COVER	1.4 (3.0)
BOLTS, SEALS, SUPPORT FTGS FOR MANIFOLDS.	1.8 (4.0)
2" x .030 AL ALY INTERNAL SPRAY MANIFOLD & FTGS	2.4 (5.2)
TANK WALL PENETRATION FTG'S & SUPPORTS	1.4 (3.0)

LAYOUT 15

ORBITAL REFILL EXPERIMENT.
DETAIL WT. ESTIMATE FOR A FULL
SIZE LH2 TANK.
OTV Wp = 120,000
MR = 6.1

Figure 3-38. Baseline OTV LH_2 Tank

4

SELECTED EXPERIMENT CONCEPTUAL DESIGNS (TASK III)

The preliminary experiment definition presented in Section 3 included as a final checkpoint a design review by NASA which established the direction of this subsequent conceptual design task. The intent of this conceptual design task is to present a level of experiment concept detail sufficient to provide a credible basis for the program planning tasks that follow.

The experiment conceptual design has three major task elements. Section 4.1 provides the detail configurations, layouts, and physical descriptions of the experiment hardware design; Section 4.2 describes the pre-flight procedures of ground applications and design features required to implement the Shuttle safety criteria; and Section 4.3 details the typical experiments, instrumentation, and flow schematics for a series of proposed propellant transfer experiments in orbit.

4.1 EXPERIMENT DESIGN LAYOUTS/CONFIGURATIONS

The designs presented provide a level of detail necessary to: 1) establish feasibility of the experiment concept; 2) provide sufficient detail for defining costs; and 3) to provide a basis for defining the development, testing, and manufacturing schedule. It was not the intent of this study to develop a final detail design of the experiment. The subsequent program plan for implementation of this experiment would include the formalized phase B, C & D activities where the detail design would be an element of the overall program development.

Table 4-1 is a listing of the experiment tankage and support systems that have been conceptually designed. Also indicated in the table are the report sections in which the details of the particular designs are presented.

Table 4-1. Experiment Tankage and Support Systems

Design Element	Section
Supply Tank	4.1.1
Supply Tank Insulation and Purge Systems	4.1.2
1/2 Scale Receiver Tank	4.1.3
1/2 Scale Receiver Tank Insulation System	4.1.4
1/2 Scale Receiver Tank Acquisition Device	4.1.5
1/4 Scale Receiver Tank System	4.1.6
Supply and Receiver Tank Support Structure	4.1.7
Complete Experiment Module Assembly	4.1.8
Experiment Module Shuttle Installation	4.1.9
C.G. of Experiment/Shuttle During Landing	4.1.10

4.1.1 SUPPLY TANK DESIGN. In Figure 4-1 (Layout #19) a design for a 72.80 m^3 (2600 ft^3) supply tank is presented. There are three sheets to Layout #19. The general arrangement, supports, and details for the acquisition system are described on Sheet 1. Additional details for the acquisition system, bubbler manifold, and access openings are given on Sheet 2. Also included on Sheet 3 is a detailed parts list (with weights) showing the basic parts and assembly. The tank is a 421.6 cm (166.0 in) dia cylinder equipped with two ellipsoidal bulkheads (a/b = 1.38); an acquisition system, and a helium bubbler manifold. The material is 2219-T87 aluminum alloy, except for the acquisition system which is 304 L corrosion resistant steel (CRES). Tank accessories include two access openings, forward and aft support fittings, and tank wall penetration fittings. These penetration fittings are for fill, drain, vents, abort dump, pressurization, and electrical.

4.1.1.1 Forward and Aft Bulkheads. A single piece spun formed bulkhead with chem-milled weld lands is assumed. Compared to gore construction, the single piece approach saves approximately 46 meters (150 ft) of welding and 10 kg (22 lb) using 0.79 radian (45°) gores. GD/C has constructed a 221 cm (87.0 in) diameter ellipsoidal tank with single piece hot spun bulkheads. The diameter was limited to the available stock sheet size. For this analysis, it is assumed that larger stock sizes and forming equipment will be available. The aft bulkhead has a wide weld zone (55 cm) at the girth area. The purpose for this zone is for attaching the eight support fittings (Detail "B") and the penetration fittings for electrical and helium pressurization. Any additional penetration fittings would be located in this zone. At the aft end of the bulkhead, two additional weld lands are provided for the acquisition system outlet fitting and the access door ring. The aft bulkhead access opening consists of a ring (containing thread inserts) and a cover. The cover is equipped with two penetration fittings, one for ground fill and drain, and the second for abort dump. The cover also has a pull-thru plate for abort dump (see H-H on Sheet 2 of Layout). The purpose for the off-center location of the access opening is to permit access to the tank with the acquisition system installed. Also, abort dump modes require the outlet to be offset from the tank center line which in turn depends upon the Shuttle attitude during the dump mode. The location shown, therefore, serves a two-fold purpose; access and abort dump. Eighteen support fittings are required for the bubbler manifold; these fittings are located and welded to the aft bulkhead in the support zone previously described.

The aft bulkhead is welded to the cylindrical section at the tangent line (see "T" on Sheet 1). To minimize internal tooling, a lip is machined on the bulkhead which in turn engages with the I.D. of the cylindrical section. This lip provides alignment plus backup for the butt welding process. Internal tooling should be kept to a minimum because the acquisition channels are in place when the bulkheads are installed. These channels (which are surfaced with fine screen) are close (1.27 cm) to the tank wall and have previously been cleaned and checked out, therefore, activities inside the tank should be at an absolute minimum at this assembly level.

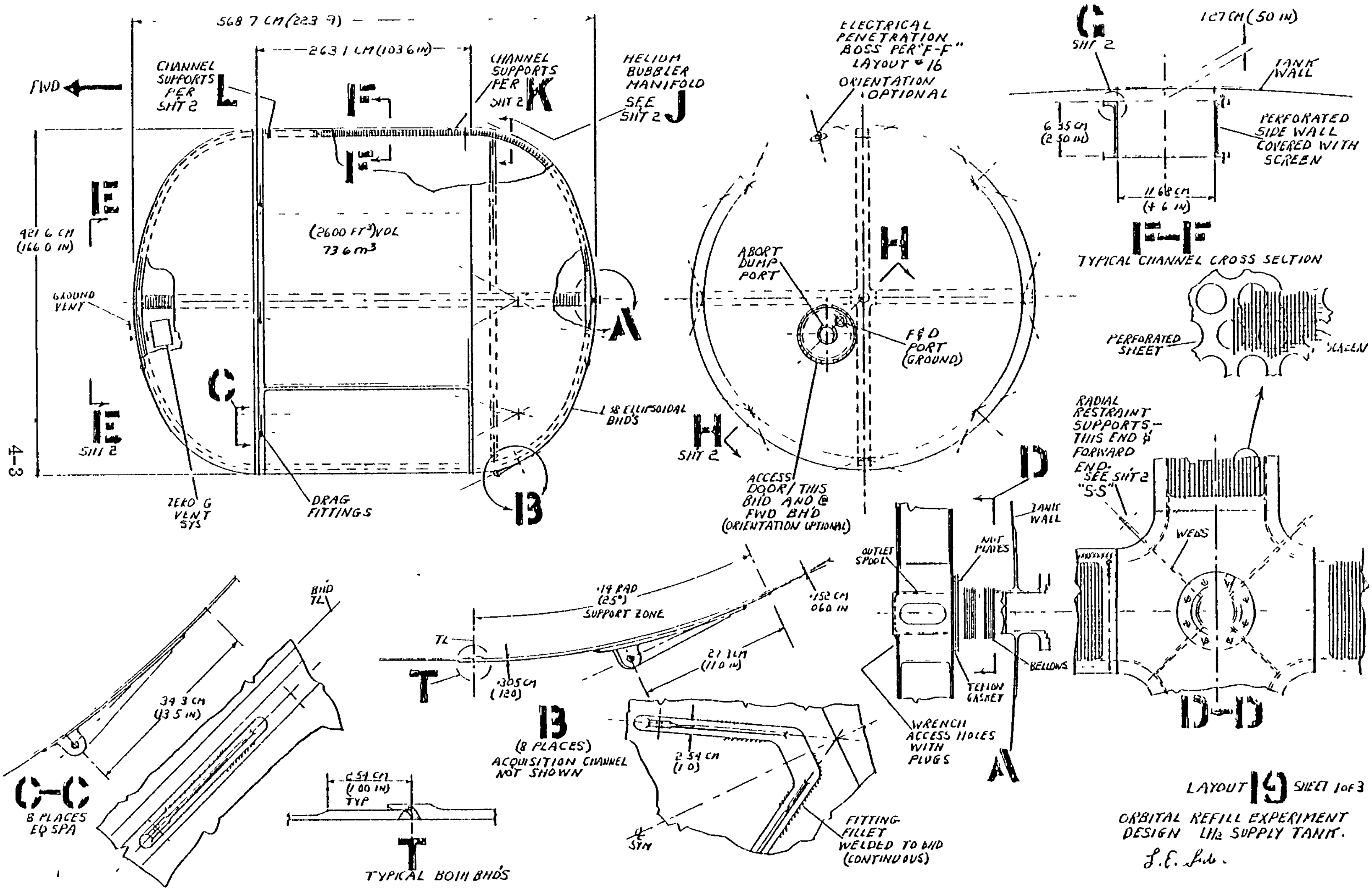


Figure 4-1. Supply Tank

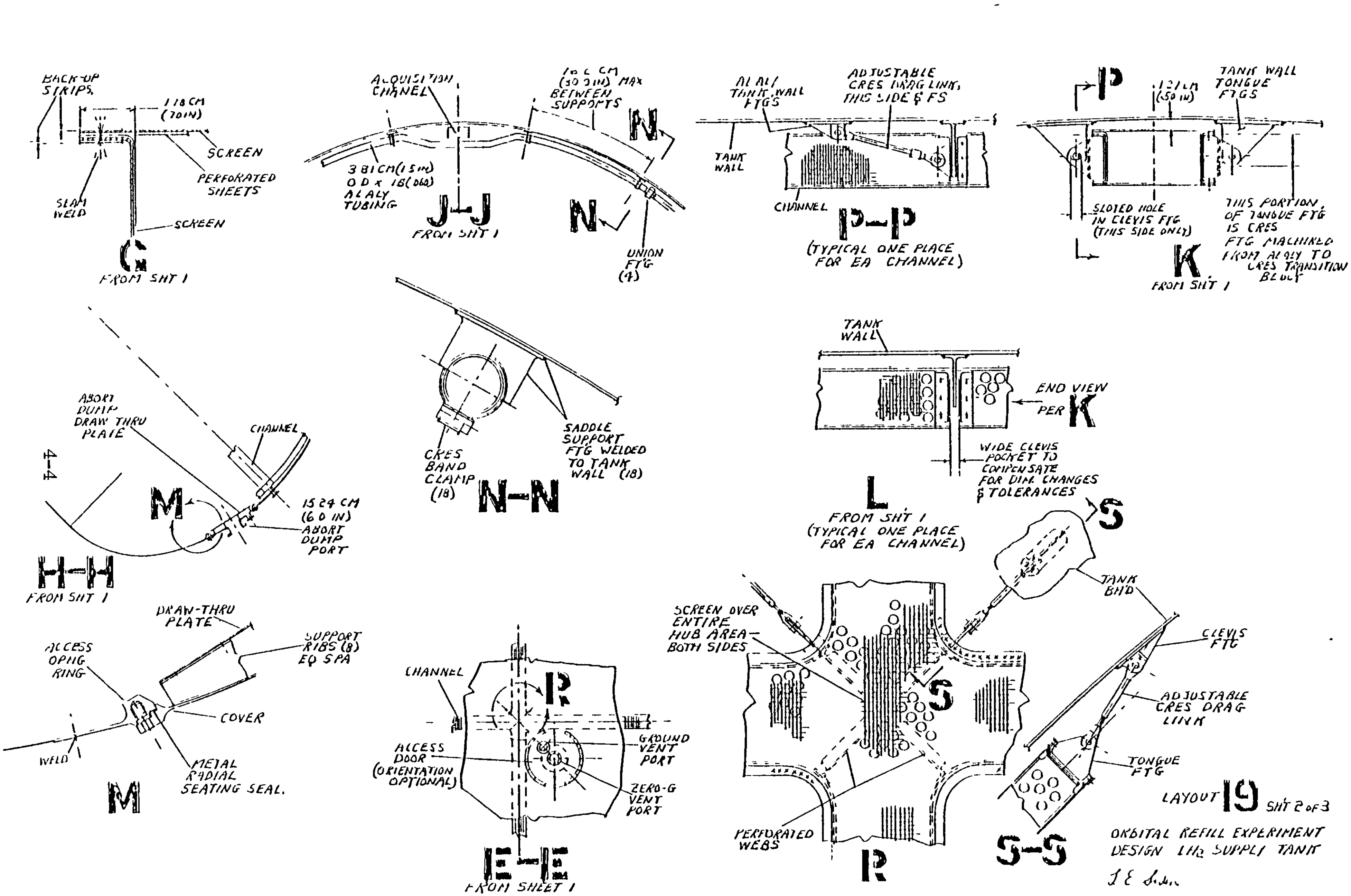
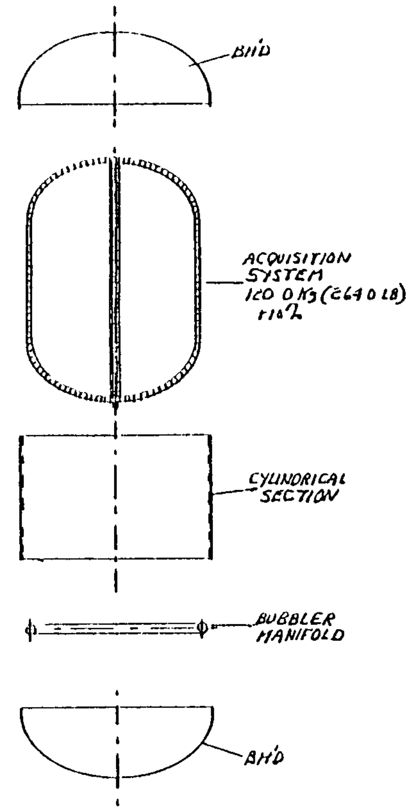


Figure 4-1. Supply Tank (Continued)



ITEM (NO SCALE)	WT Kg (LBS)
BACK-UP STRIPS	14 6 (32 0)
CHANNEL SUPPORT FITTINGS	2 2 (1 8)
TANK WALL FTG'S FOR CHANNEL SUPPORT	1 3 (2 8)
CHANNEL SUPPORT FITTINGS @ POLES	.50 (1 1)
CHANNEL WEBS/POLES	.45 (1.0)
CHANNEL OUTLET HUB	.4 (.80)
CRES DRAG LINKS	.8 (1 8)
10% CONTINGENCIES	55 3 (121 6)
TOTAL	607 9 (1337 3)

ITEM (NO SCALE)	WT Kg (LBS)
ABORT DUMP PULL THRU PLATE	2 1 (1 5)
BUBBLER MANIFOLD	6 8 (15 0)
BUBBLER MANIFOLD ACCESSORIES	1 8 (4 0)
TANK SUPPORT FITTINGS/AFT	2 6 (5 6)
TANK SUPPORT FITTINGS/FWD	1 5 (3 2)
ELEC PENETRATION BOSS	1 4 (3 0)
ELEC RECEPTACLE RETAINER	1 0 (2 2)
ELEC RECEPTACLE	.8 (1 8)
CHANNEL SCREENS/SIDES	21 6 (47 6)
CHANNEL SCREENS/EDGES	14 1 (31 0)
CHANNEL PERFORATED SHEETS	43 2 (95 0)
CHANNEL EDGE STRIPS	21 0 (46.0)

ITEM (NO SCALE)	WT Kg (LBS)	
BULKHEADS	194 3 (427 4)	SINGLE PC SPUN BHDS
CYLINDRICAL SECTION	147 4 (324 2)	
BH'D WELD ZONES	36 4 (80 0)	INCL ZONES FOR FTGS
CYLINDRICAL SECTION WELD ZONES	6 8 (15 0)	
ACCESS DOOR	12.5 (27 5)	FOR TWO
ACCESS DOOR RING	12 0 (26 4)	FOR TWO
ACCESS DOOR SEALS & BOLTS	2 7 (6.00)	
PENETRATION FITTINGS	2 2 (4 9)	
OUTLET BELLOWS ASSY	.50 (1 1)	

LAYOUT 19 SHT 3 OF 3

ORBITAL REFILL EXPERIMENT
DESIGN LH2 SUPPLY TANK

J E Sidon

Figure 4-1. Supply Tank (Continued)

The forward bulkhead is the same as the aft bulkhead, except the weld zone at the girth is narrow (2.84 cm) and the access opening contains penetration fittings for the ground and zero-g vents. Similar to the aft bulkhead, the access door is located off-center to permit access with the acquisition system in place.

4.1.1.2 Cylindrical Section. The 263.1 cm (103.6 in) length cylindrical section has weld zones at each end for attaching the bulkheads plus two longitudinal weld zones. The forward end of the cylinder has a 5.08 cm (2.00 in) weld zone for accommodating eight external tangental support fittings (see "C-C"). Also, 16 local weld zones near the aft end and 8 near the forward end are required to mount the acquisition support fittings. Each end of the cylinder is chamfered at the inside edge for engaging with the alignment lip on the bulkheads.

4.1.1.3 Acquisition System. The acquisition system is basically two rectangular tubes formed into rings which follow the contour of the tank and are spaced to form 90° quadrants (see end view in Sheet 1). The four walls of each tube consist of perforated sheets covered with capillary screens. The material is 304 L CRES, including the screen. A typical cross section is shown in views "F-F" on Sheet 1 and view "G" on Sheet 2. The two rings are interconnected at the aft end per view "D-D" and at the forward end per view "R". The internal flow paths of both rings are interconnected at both ends. The aft end contains an outlet which is routed thru the tank wall.

4.1.1.4 Acquisition System Support. Manufacturing tolerances exist between the acquisition assembly and the tank. Also, dimensional changes occur between the tank walls and the acquisition assembly during temperature and pressure cycles. To compensate for these dimensional changes, the acquisition assembly is suspended inside the tank using a system of pinned connections and drag links. The aft end of each channel ring is supported with two tongue fittings attached to the tank wall and two clevis fittings attached to the channel (see "K" on Sheet 2 of Layout). One of the clevis fittings is slotted to compensate for tolerances. Each of these clevis fittings are also attached to the tank wall with a drag link. The total aft support for each channel therefore provides radial, lateral and axial restraint. To reduce heat transfer into the channels the drag link material is CRES and the tongue fittings transist from aluminum to CRES (see note on Detail "K"). Additional heat path resistance can be obtained using fiberglass drag links and Teflon inserts in the tongue fittings. The forward support on each channel is similar to the aft support, except no drag links are used (see "L" on Sheet 2). Also, the clevis fittings attached to the channel have wide slots to accommodate forward and aft tolerances and dimensional changes. This forward support, therefore, provides radial and lateral restraint only.

The acquisition channels are interconnected at the forward and aft ends forming poles. The system is supported in the radial direction only at each pole using CRES drag links spaced at 90° (see "D-D" and "R"). The aft pole has an outlet equipped with a bellows for absorbing axial and radial movements. The bellows is 304 L CRES and the outlet fitting which penetrates the tank wall is a 304 L CRES to 2219-T87 aluminum transition fitting (see "A" on sheet 1).

4.1.1.5 Bubbler Manifold. The bubbler manifold is a 3.81 cm (1.5 in) diameter aluminum alloy tube formed into a circle having four offset bends, and is supported from the tank wall with 18 fittings as shown in view "N-N". The purpose for these offset bends is to provide clearance from the acquisition channels (see "J"). The manifold has a series of holes equally spaced at the forward side thru which helium gas is ejected. Helium gas is supplied thru a tank wall penetration fitting which is connected to the manifold (inside the tank) with a tubular flex loop. Four union fittings are provided so that the manifold can be inserted thru the access opening in 90^o sections.

4.1.1.6 Assembly. Prior to final assembly, the acquisition system is cleaned, inspected, tested, and protective covers placed over the screened surfaces. The total assembly is positioned inside the tank cylindrical section and the support fittings interconnected and adjusted. The forward bulkhead is next engaged with the cylindrical section and clearances between the acquisition channel and the bulkhead are checked. The forward bulkhead is then welded to the cylinder and the two forward drag link supports installed.

The aft bulkhead is next engaged with the cylinder, clearances and fits checked, and the girth weld made. Using a gasket and 8 bolts, the acquisition outlet spool is connected to the tank penetration fitting and the two drag links (shown in "D-D") are then installed and adjusted. The zero-g vent system, the bubbler manifold and instrumentation wiring is installed next and checked out. The assembly is completed by removing the protective covers on the channels, installing the access door covers, and leak-checking. All access cover seals will provide double tolerant failure designs to satisfy hazard analysis requirements.

4.1.2 SUPPLY TANK INSULATION SYSTEM. An insulation system for the LH_2 supply tank is shown in Figure 4-2 (Layout #20). Included is a tank mounted helium purge system and a detailed parts list with weights.

The insulation is multi-layer radiation shields called MLI applied over the entire surface of the tank. These shields are separated with flocking which provides purging and venting paths between the layers. This method was developed by GD/C and given the name "Superfloc."

Blanket assemblies in gore and circular cap configurations are applied to the tank in two layers. A system of tubing mounted on the tank wall delivers gaseous helium between each layer. Foam blocks located between these tubes and bonded to the tank wall provide a uniform surface for mounting the MLI blankets.

4.1.2.1 MLI Blanket Construction. Two circular cap blankets and twelve gore blankets make up one blanket layer. Two layers are used. The gore blankets run continuously between the cap blankets and incorporate cutouts for clearing the tank support fittings. A typical blanket cross section is thirteen double aluminized Kapton core sheets sandwiched between two scrim reinforced face sheets. The face sheets are also aluminized. The

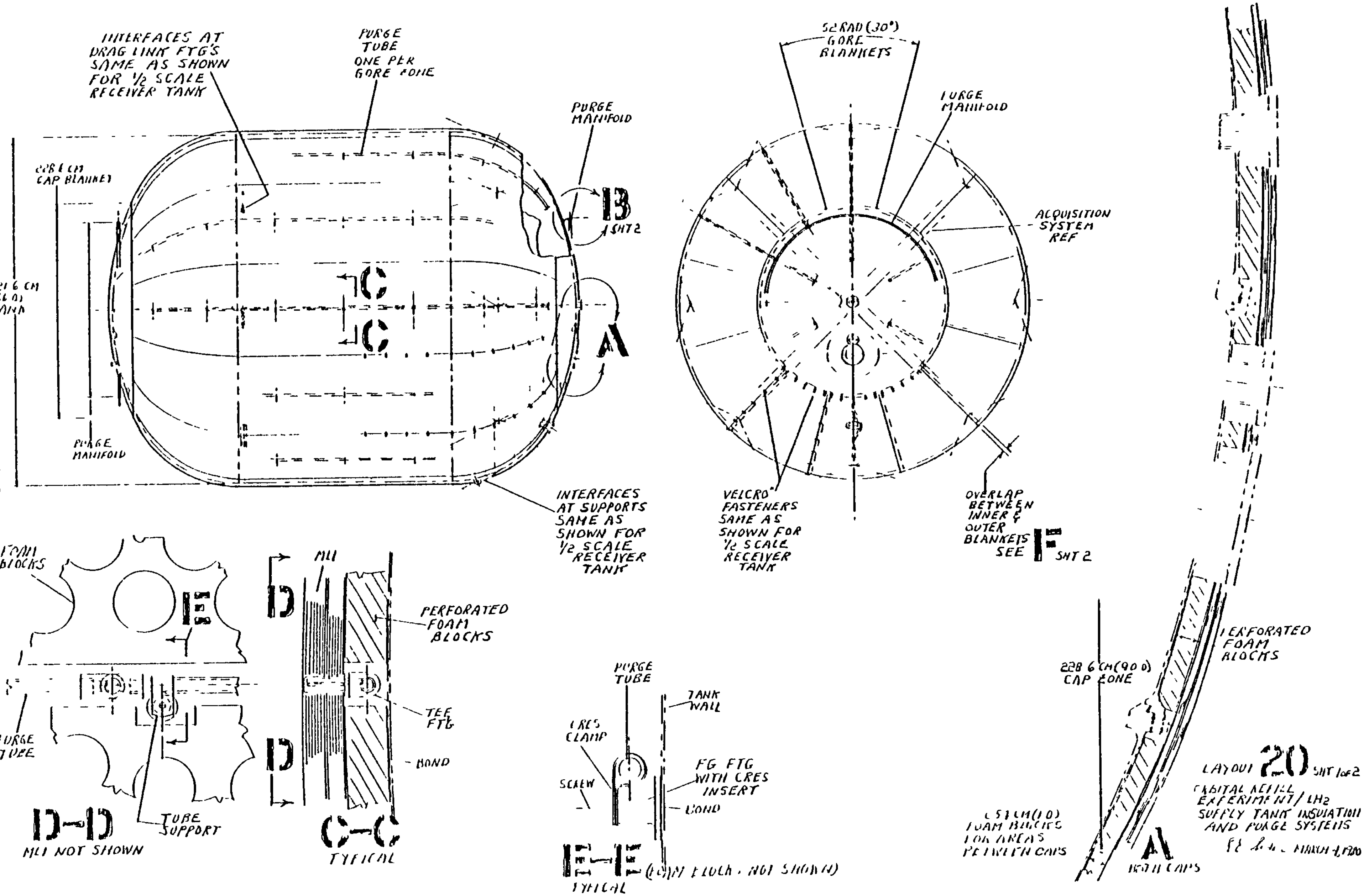
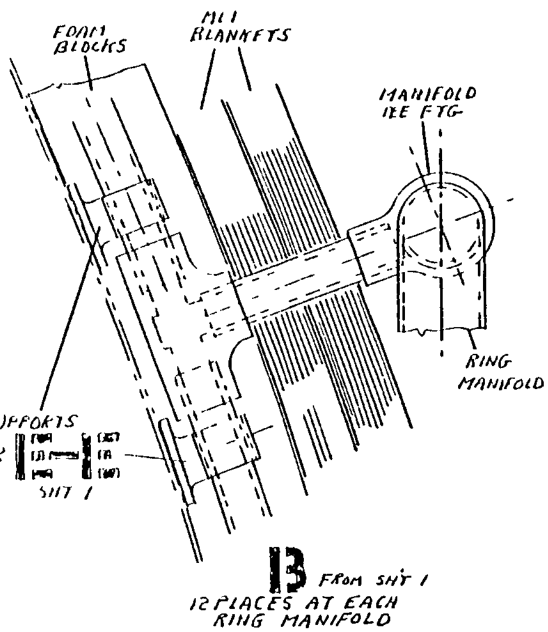
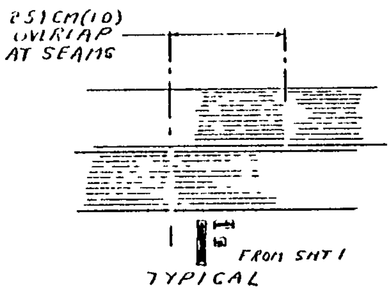


Figure 4-2. Supply Tank Insulation





ITEM (NO SCALE)		WT KG (LBS)
PERFORATED FOAM BLOCKS (810 FT² TANK AREA)	2#/FT³; % OPEN AREA; 2 54 (1 0)	31 6 (81 0)
BONDING AGENT FOR BLOCKS	20GA; 026#	17 8 (39 1)
CAP BLANKET FACE SHEETS (TWO PER BLANKET)	1 MIL; 46 FT²; 9 REQD; 228 6 (90 0) DIA; DOUBLE ALUMINIZED SCRIM REINF KAPTON; 0182#/FT²	3 1 (6 7)
CAP BLANKET CORE SHEETS (13 SHEETS PER BLANKET)	52 REQD; 1/4 MIL; DOUBLE ALUMINIZED KAPTON; 004986#/FT²	2 2 (4 8)
GORE BLANKET FACE SHEETS	48 REQD; 64 8 FT² EA; 0182#/FT²; 1 MIL	25 7 (56 6)
GORE BLANKET CORE SHEETS	312 REQD; 001986#/FT²; 1/4 MIL	18 3 (40 3)
INTERPLY BONDING SPACERS (14 PER SPOT BOND)	43,120 REQD; 1 27 (50); 08 CM (03) FIBERGLASS	9 1 (20 0)
VELCRO TAPE SET	3080 REQD; 04#/in³; 2 54 CM; 1 21 CM; NYLON; HOOK; PILE; T̄ = 030 EA PART	1 7 (3 70)
BONDING AGENT/BLANKET CONSTRUCTION		1 4 (3 0)
MSC TAPE STRIPS & BOOTS		9 (2 0)
10% CONTINGENCIES		13 1 (28 7)
TOTAL		113 3 (315 2)

BLANKETS 62 3 (137 1#)

ITEM (NO SCALE)		WT KG (LBS)
PURGE TUBING SUPPORT FTGS	FIBERGLASS; CRES INSERT; 236 REQD; 95 CM (375); 15 (06); (50); 191 (75)	1.09 (2 4)
PURGE TUBE SUPPORT CLAMPS	051 (020) CRES; 236 REQD	1 09 (2 4)
PURGE TUBE SUPPORT SCREWS	CRES; 95 (375); 46 (18) DIA; 236 REQD	.45 (1 0)
PURGE TEE FITTINGS	PPO; 037#/in³; 150 REQD; 1 52 (60); 1 91 (75); 254 (10)	1 36 (3 0)
PURGE PINS	PPO; 150 REQD; 3 49 (1 375); 15 CM; (06) WALL	25 (54)
RING MANIFOLD TEE FTG'S	PPO; 24 REQD; (2 0); 2 54 (1 0); 254 (10) WALL; 1/8 BRANCH	27 (60)
RING MANIFOLD TEES	PPO; TWO REQD; 3/4 BRANCH	03 (07)
DISTRIBUTION TUBING	75 (115) x 15 (06) PPO; (1000 in); 10,160 CM	4 8 (10 5)
	191 (75) x 15 (06) PPO; (510 0); 12 15 CM	1 2 (2 7)
BONDING MATERIAL	051 (020) GA	05 (10)

PURGE DISTRIBUTION 10 6 KG (23 3#)

LAYOUT 20 SHT 2 of 2

ORBITAL REFILL EXPERIMENT — LH2 SUPPLY TANK INSULATION AND PURGE SYSTEM

MARCH 6, 1980

Figure 4-2. Supply Tank Insulation (Continued) core sheets are interconnected to the face sheets with interlayer spot bonds located at the perimeter of each blanket. A typical spot bond consists of adhesive coated fiberglass buttons inserted between each layer and the total local area bonded. Also bonded to the face sheets at these areas are "Velcro" tape fasteners described in 4.1.4.2 (Gore Blankets) for the 1/2 scale receiver tank. Each blanket is constructed over molds which match the tank contour.

4.1.2.2 Purge System. The purge system is basically twelve PPO tubes running the full length of the tank and interconnected at each end with a ring manifold (see B). Each tube supplies gaseous helium to one inner and one outer gore blanket. The tubes also extend into the cap blanket areas. Gaseous helium is injected between the blanket layers with a series of purge pins attached to the fittings located in the tubes (see "C-C" on layout).

The tubes are attached to the tank wall with fiberglass fittings, CRES clamps and screws. The fittings, which incorporate self-locking thread inserts, are bonded to the tank wall. A typical arrangement is shown in "E-E" on the layout.

Perforated foam blocks are located between the tubes and bonded to the tank wall. The purpose for these blocks is to provide a uniform base for mounting the MLI blankets. At the cap areas, the thickness of the blocks is increased due to the jump in the tank profile at the access door rings (see Detail "A").

4.1.2.3 MLI Installation. The first blanket layer installation starts by positioning the two cap blankets on the bulkheads. The gore blankets are positioned next and attached to the cap blankets with the "Velcro" fasteners. The gore blankets are also interconnected at the gore lines with "Velcro" fasteners. The second blanket layer is installed in the same manner as the first layer. The butt joints between blankets are staggered 2.54 cm (1.0 in) as shown in "F-F" on the layout. The MLI installation is completed by applying shield accessories at the support fittings as described later (Section 4.1.3.3) for the half-scale receiver tank.

Referring to Detail "A" on the layout, the MLI blankets have cutouts for the tank outlets. The cutout diameters in the outer blankets are greater than the cutouts for the inner blankets. The purpose for this is to provide staggered butt joint arrangement with the MLI on the plumbing lines.

4.1.3 HALF-SCALE RECEIVER TANK DESIGN. A design for the half-scale receiver tank is shown in Figure 4-3 (Layout #16). The tank is basically a cylinder with two ellipsoidal bulkheads equipped with accessories for in-orbit filling and venting; fill, drain and vent for ground testing; and an acquisition system. Also included are provisions for routing instrumentation wiring through the tank wall and external support fittings. The material is 2219-T87 aluminum alloy. Layout #16 also includes a parts list and weight breakdown.

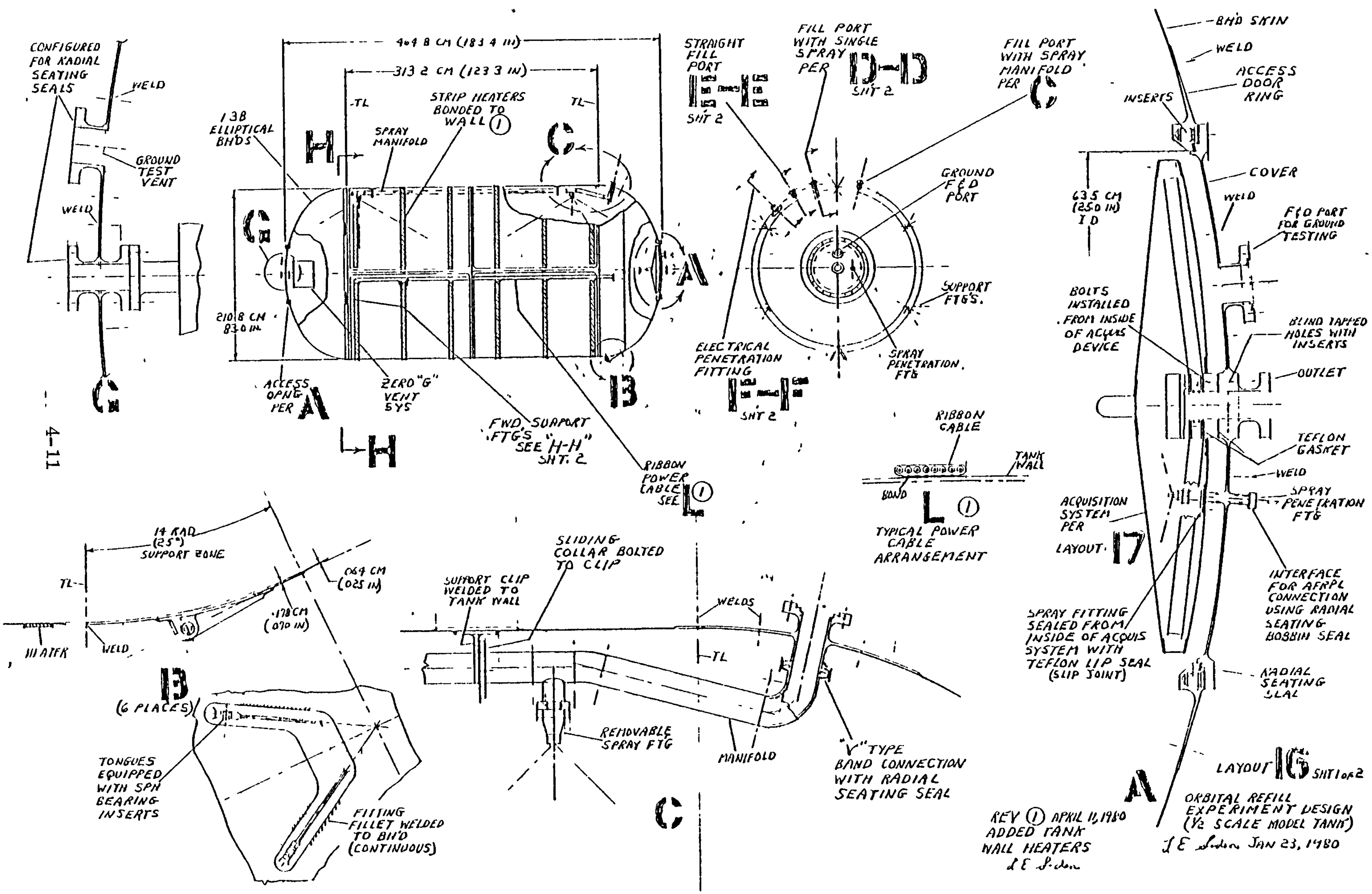
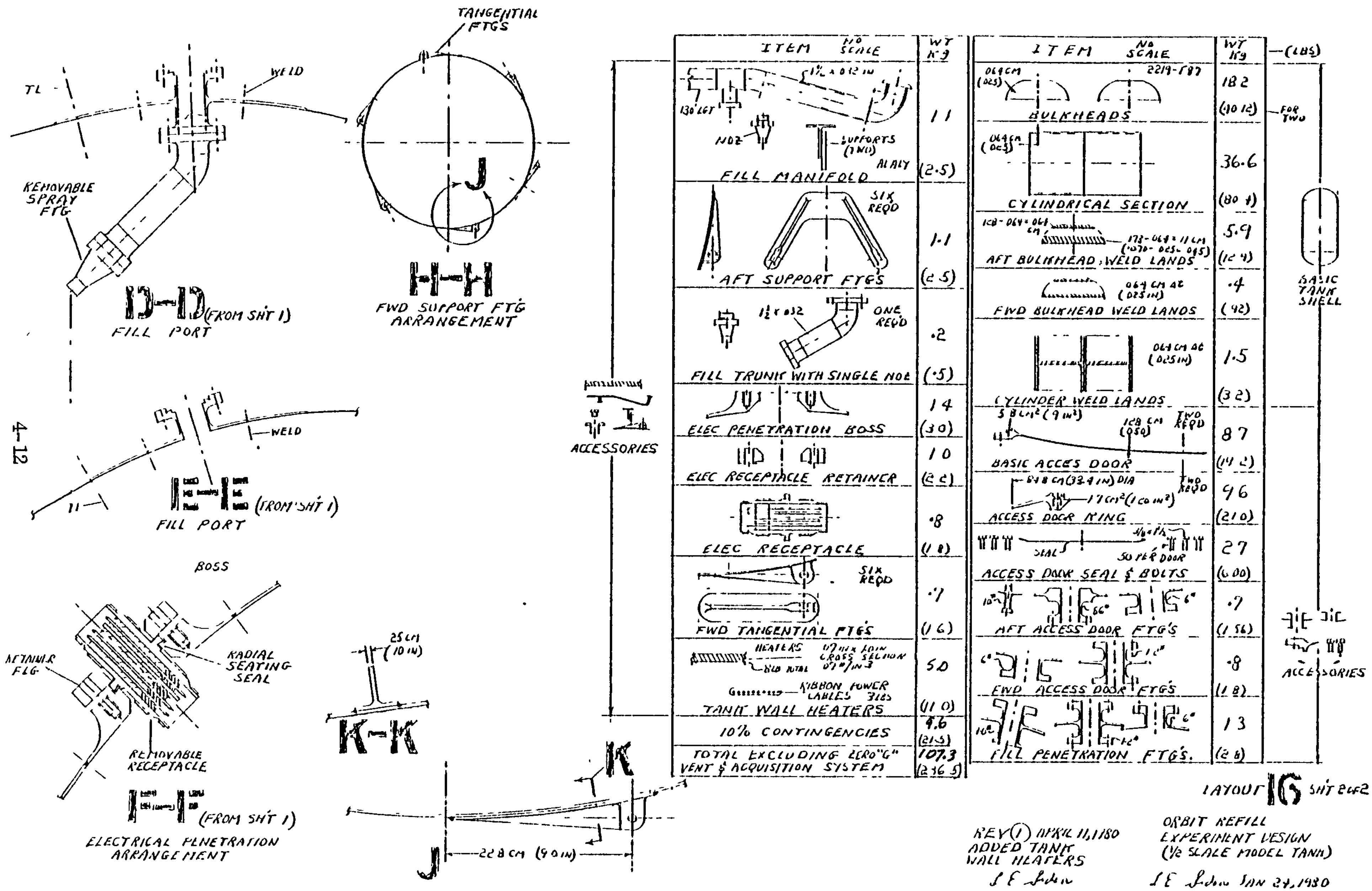


Figure 4-3. Half-Scale Receiver Tank



ITEM (NO SCALE)	WT KG (LBS)	ITEM (NO SCALE)	WT KG (LBS)
FILL MANIFOLD	1.1 (2.5)	BULKHEADS	18.2 (40.12) FOR TWO
AFT SUPPORT FTGS	1.1 (2.5)	CYLINDRICAL SECTION	36.6 (80.4)
FILL TRUNK WITH SINGLE NOZ	.2 (.5)	AFT BULKHEAD WELD LANDS	5.9 (12.4)
ELEC PENETRATION BOSS	1.4 (3.0)	FWD BULKHEAD WELD LANDS	.4 (.92)
ELEC RECEPTACLE RETAINER	1.0 (2.2)	CYLINDER WELD LANDS	1.5 (3.2)
ELEC RECEPTACLE	.8 (1.8)	BASIC ACCESS DOOR	8.7 (19.2)
FWD TANGENTIAL FTGS	.7 (1.6)	ACCESS DOOR RING	9.6 (21.0)
TANK WALL HEATERS	5.0 (11.0)	ACCESS DOOR SEAL & BOLTS	2.7 (6.00)
10% CONTINGENCIES	9.6 (21.5)	AFT ACCESS DOOR FTGS	.7 (1.56)
TOTAL EXCLUDING ZERO "G" VENT & ACQUISITION SYSTEM	107.3 (236.5)	FWD ACCESS DOOR FTGS	.8 (1.8)
		FILL PENETRATION FTGS.	1.3 (2.8)

Figure 4-3. Half-Scale Receiver Tank (Continued)

4.1.3.1 Cylindrical Section. The cylindrical section is 210.8 cm (83 in) diameter x 313.2 cm (123.3 in) length and is constructed from two rolled sheets. These two rolled sheets are welded together with one circumferential weld and one longitudinal weld. The perimeter of both sheets have one-inch wide weld zones. The thickness of these weld zones is twice the basic tank gage. Additional local weld pads are located along the length of the cylinder to accommodate miscellaneous clips for supporting wiring and tubular manifolds.

4.1.3.2 Bulkheads. Both bulkheads are ellipsoidal having a radius to height ratio equal to 1.38. The construction is single piece spin formed with chem-milled weld zones. Each bulkhead has circular cutouts at the top for a 63.5 cm (25 in) I.D. access opening. The aft bulkhead has a wide weld zone at the girth area for accommodating support brackets and several fluid penetration fittings. The forward bulkhead has a narrow weld zone at the girth for attaching the cylinder and six tangential support brackets.

4.1.3.3 Accessories. The accessories are six aft support fittings, six forward support fittings, two access door rings, two access door cover assemblies, one spray manifold, one spray tube, a fill port and one electrical penetration assembly. The aft support fittings are described in detail "B" on the layout. These fittings are "V" shaped and contoured to fit the shape of the bulkhead at the girth zone. Two upstanding webs with end holes provide the interfaces for attaching support struts. These holes are equipped with spherical bearings to compensate for angular misalignments. The fittings are positioned on the bulkhead such that the line of action from the support struts is directed tangentially into the center of the bulkhead wall. Attachment is made with a continuous fillet weld.

The forward support fittings are single web machined types contoured to match the tank diameter (see Section H-H on the Layout). The hole at one end of each fitting is for attaching drag support links. The fittings are equally spaced along the bulkhead girth weld zone and secured with a continuous fillet weld.

A cross section of the access door rings is shown in Detail "A" of the layout. The rings are machined to fit the bulkhead contour and for receiving a metal radial seating seal. Blind tapped holes equipped with inserts provide the fastening means for the covers. Both rings are attached to the bulkheads with continuous butt welds.

The access door cover assemblies are basically circular panels equipped with a ring at the perimeter and penetration fittings near or at the center. The circular panel portion is contoured to match the bulkhead profile and the perimeter ring is machined to match the bulkhead ring. The aft access door cover has a flanged boss at the center which interfaces with the outlet on the acquisition system and a flanged port (positioned off center) for ground fill/drain. Also included is a fitting for injecting fluid to the interior of the acquisition device. The forward access door has two flanged fittings. One is for ground vent and the second is for the zero-g vent system.

The spray manifold arrangement is shown in detail "C" of the layout. The manifold is a tube equipped with two tees and two elbows. Both tees are machined to receive threaded spray fittings. The manifold is supported from the inside of the tank wall with collar type fittings which provide radial restraint only. The manifold passes through the aft bulkhead wall using a flanged penetration fitting which is located in the girth weld zone. The manifold is attached to this penetration fitting inside the tank with a "V" band joint using a "cono seal."

A second method of injecting LH_2 in the tank is using a single spray tube equipped with a removal spray nozzle. An arrangement is shown in view "D-D" on Sheet 2 of the layout. This tube is attached to a flanged penetration fitting located in the aft bulkhead girth weld zone.

A third method of LH_2 injection is a straight port with no spray nozzle which is shown in view "E-E" on Sheet 2 of the layout. The port has an external flange only and is welded into the bulkhead at the girth weld zone.

Electrical penetration provisions are also provided through the aft bulkhead girth weld zone as shown in view "F-F" on Sheet 2 of the layout. This arrangement uses a penetration boss, a metal radial seating seal, a receptacle, and a retainer flange. The boss (which is welded into the bulkhead) contains blind tapped holes equipped with inserts and a cavity for receiving the seal and receptacle. The receptacle is attached to the boss with the retainer flange.

An additional accessory is the acquisition device which is mounted on the aft access door. This permits bench checkouts and testing before installation. Acquisition device and access cover are installed as a module. The acquisition device is described in Section 4.1.5 of this report. The zero-g vent system shown at the forward bulkhead is also supported from the access cover.

4.1.3.4 Location of Penetration Fittings. Referring to Layout #16, the end view of the tank shows most of the penetration fittings located to one side of the tank centerline. The purpose of this is accessibility. When installed in the shuttle, these fittings and the interconnecting plumbing, valves and electrical harnesses will face the payload doors. This location will permit easy access for checkout, and servicing.

4.1.3.5 Wall Strip Heaters. The heaters are located between the tank weld lands and are arranged in six circumferential bands along the length of the cylindrical section.

Protrusions from the tank surface should be kept to a minimum because the multilayer insulation (MLI) is mounted on the tank wall. Excessive protrusions cause local compression of the MLI blankets causing contact between layers and prohibits a uniform fit over the tank surface. To minimize these conditions, flat ribbon-type power cables are used for heaters. A typical arrangement is shown in detail "L" in the layout. The power cables are routed along the length of the cylinder and are bonded to the tank wall. Most of the cables are positioned between the weld lands to minimize protrusions. Some areas are unavoidable where the cable crosses a circumferential weld but these areas are small.

4.1.3.6 Weights. A detailed parts list with weights is shown on Sheet 2 of Layout #16. The list is divided in two sections. The first section is for the basic tank shell without accessories. The first two entries are for the total shell using the basic gage. The remaining entries are for the weld zones.

The second section of the parts list is for the accessories. This section contains both removable and non-removable parts. The total tank weight including 10% contingencies is 107.3 Kg (236.5 lb).

4.1.4 HALF-SCALE RECEIVER TANK INSULATION SYSTEM. An insulation system for the half-scale receiver tank is shown in Figure 4-4 (Layout #18). The insulation techniques shown were developed by GD/C under NASA Contracts NAS8-27419 and NAS8-31778 for MSFC and under GD/C funded IRAD studies. The insulation is basically a multi-ply radiation shield assembly called "Superfloc" (a GD/C development). Layout #18 describes the basic lay-up, the major penetrations for supports and plumbing; and includes a parts list with weights.

The insulation is applied in two layers. Each of these layers consists of two cap blankets and eight gore blankets. The purpose for two layers is to permit overlaps at the seams. The blankets are interconnected using "Velcro" fastener tape sections. These fasteners operate mechanically by having the hook section of one part interlock with the pile section of the mating half.

The installation does not include a purge system since ground testing will be done in a vacuum chamber and the receiver tank will be dry during ascent. Also, after the in-orbit testing, the LH_2 in the tank is expelled overboard or transferred back into the supply tank for additional testing.

4.1.4.1 Cap Blankets. Each end of the receiver tank has an access opening with a door. Each door is equipped with a ring flange which in turn fastens to the tank with approximately 50 bolts. These flanges and bolts protrude significantly above the tank contour. If an insulation blanket is installed over this area, these protrusions will locally compress the blanket causing contact between the layers. To prevent this, closed cell foam blocks are bonded to the doors and the adjacent tank surfaces to form a uniform base for mounting the cap blankets. A description is shown in detail "A" of Layout #18.

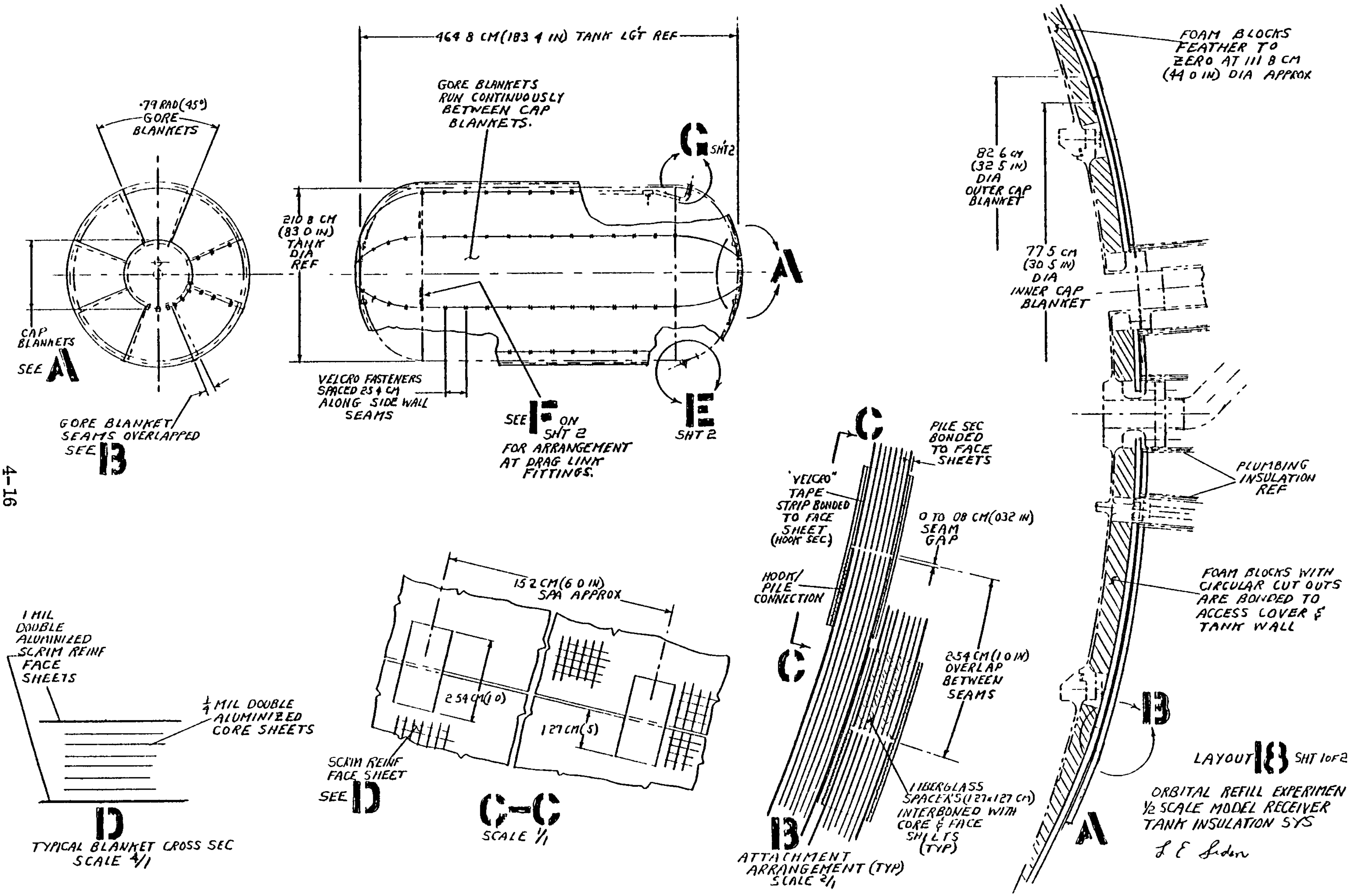
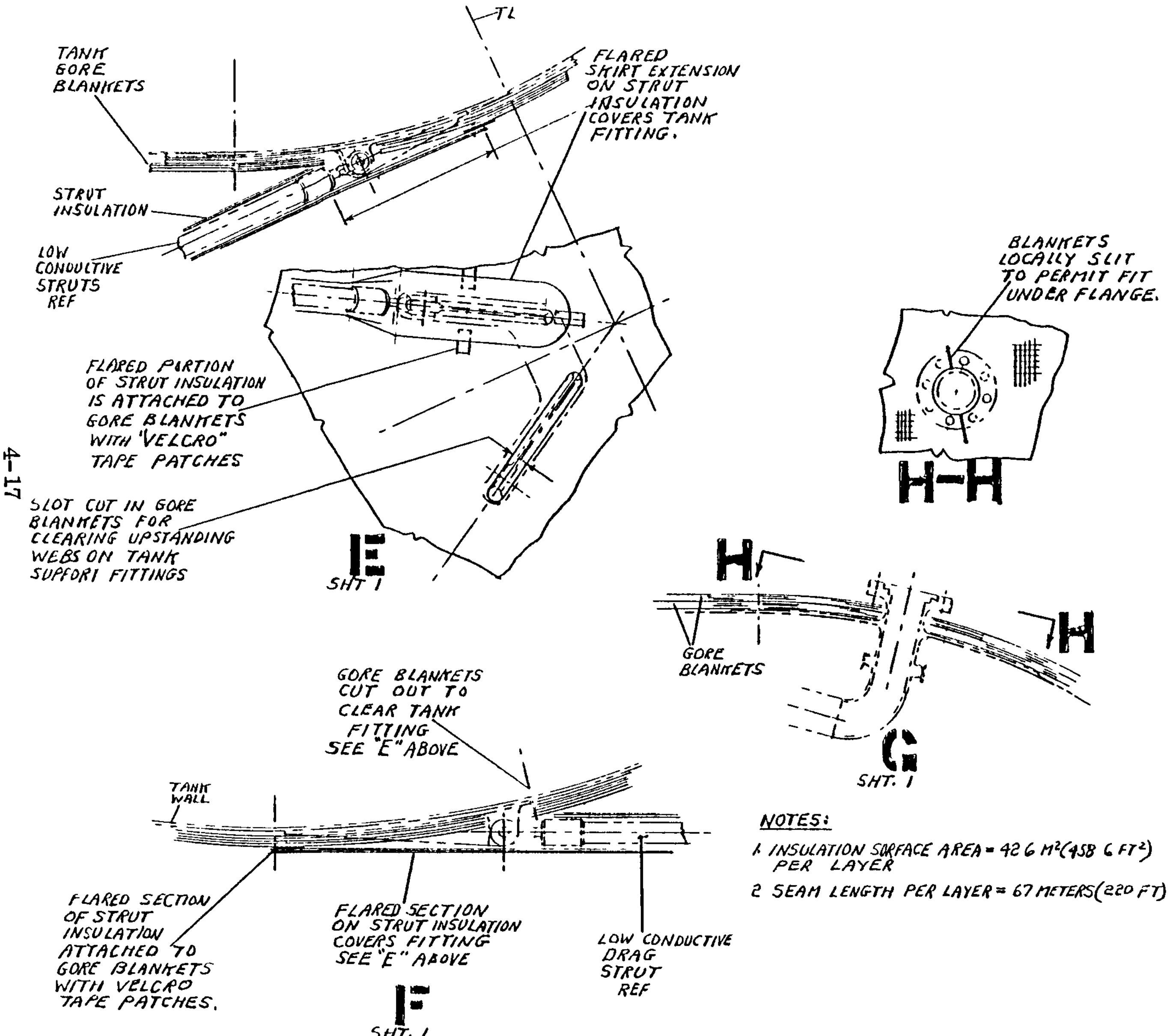


Figure 4-4. Half-Scale Receiver Tank Insulation



NOTES:

1. INSULATION SURFACE AREA = 42.6 M²(458.6 FT²) PER LAYER
2. SEAM LENGTH PER LAYER = 67 METERS (220 FT)

ITEM (NO SCALE)	WT KG (LBS)
FOAM CAP BLOCKS	1.82 (4.0) INCLUDES BONDING AGENT
CAP BLANKETS	.52 (1.15)
GORE BLANKETS	15.3 (33.6)
INTERPLY BONDING SPACERS	1.30 (2.86)
VELCRO TAPE SET	.72 (1.58)
STRUT INSULATION BOOTS	.23 (.50)
BONDING AGENTS	.45 (1.0)
10% CONTINGENCIES	2.0 (4.5)
TOTAL	22.36 (49.2)

LAYOUT 18 SHT 2 OF 2
ORBITAL REFILL EXPERIMENT.
½ SCALE MODEL RECEIVER TANK INSULATION

J.E. [signature]

Figure 4-4. Half-Scale Receiver Tank Insulation (Continued)

The circular cap blankets are prefabricated over molds that match the contour of the mounting surface. A typical cross section is six core sheets sandwiched between two scrim reinforced face sheets. The material is mylar, aluminized on both sides. GD/C has constructed blankets in both mylar and kapton. Kapton is used for high temperature applications. Each of the core sheets is separated by dacron flocks spaced in a triangular pattern on 0.95 cm (3/8 in) centers which provides venting paths between layers.

The two face sheets and six core sheets are interconnected at the perimeter with twenty-four 1.27 cm square interlayer spot bonds. Fiberglass spacers are inserted between each layer and interbonded. This prevents shifting of the core sheets relative to the face sheets and provides hard points for attaching the gore blankets. Loads are primarily passed through the two face sheets. Referring to detail "B", a "Velcro" tape strip is bonded to the inboard face sheet at each spot bond. The pile section of the tape strips extends radially beyond the perimeter for attaching the gore blankets. Circular cutouts are provided near the center of the blanket for clearing the tank bosses. These cutouts may be slit as shown in View "H-H" for fitting the blanket under the flanges.

4.1.4.2 Gore Blankets. Eight 0.79 rad (45°) gore blankets (per layer) cover the tank side wall and a portion of the bulkheads. These gore blankets run continuously between the cap blankets and are interconnected at the gore lines with "Velcro" tape fasteners. Similar to the cap blankets, these gore blankets are prefabricated over molds that match the tank contour. The layers are interconnected at the perimeter with interlayer spot bonds which also serve as hard points for the "Velcro" fasteners. Cutouts are provided at both ends for clearing the tank support fittings (see details "E" & "F") and the inlet boss (see Detail "G").

4.1.4.3 Tank Supports. To reduce heat leaks, the tank supports are low conductive struts wrapped with "superfloc" insulation. The insulation extends past one end of the strut which serves as a cover for the tank support fittings (details E &F). These struts are thin wall fiberglass tubes equipped with adjustable corrosion resistant steel (CRES) end fittings and internal radiation discs. GD/C has constructed and tested this type of strut.

4.1.4.4 Interfaces with Plumbing. Plumbing lines leading from the tank will be wrapped with insulation blankets. Referring to detail "A", the plumbing line insulation interfaces with the first blanket layer on the tank with a simple butt joint. The second blanket layer on the tank also interfaces with the plumbing insulation using a simple butt joint. Aluminized mylar self-adhesive tape strips are applied to the outside face sheets of each joint to hold the joint in position. This technique simplifies fabrication and assembly and has been found satisfactory under tests. The insulation on the plumbing lines is shown at a diameter for slipping over the flanged connection. This is accomplished by bonding thin fiberglass collars to the lines over which the insulation is wrapped. More insulation details will be shown later for the plumbing systems.

4.1.4.5 Assembly. After bonding the foam blocks to each end, the forward cap blankets are positioned at the forward end and the tank suspended in the vertical position from the flange vent boss located at the center of the forward access door. The eight gore blankets making up the first layer are positioned and attached to the inner cap blanket. The outer cap blanket is simply folded back during this operation. The first layer cap blanket is next held in position at the aft bulkhead and attached to the gore blankets with "Velcro" fasteners.

The first layer is completed after checking for fits around the cutouts and applying the fasteners at the gore lines. The second blanket layer is applied in the same way as the first layer except the seams and the gore lines are offset from the first layer seams. The installation is completed by attaching the low conductive struts to the tank fittings, applying the strut insulation, and attaching the flared end of the strut insulation to the gore blanket face sheet. The struts are held in position by a temporary external fixture.

4.1.5 HALF-SCALE RECEIVER TANK ACQUISITION DEVICE. A capillary-type acquisition device is described in Figure 4-5 (Layout #17) for the half-scale model receiver tank. The device is designed to be supported from the tank access door as shown in Figure 4-4 (Layout #18). A parts list, weights, and an assembly sequence is shown on Sheet 2 of Layout #17. The material is 304 L corrosion resistant steel (CRES).

Referring to the assembly sequence, the device consists of a bottom section, an internal channel, a support tube and a lid assembly. The parts are interconnected and sealed using Teflon gaskets, CRES screws, and nut plates.

4.1.5.1 Bottom Assembly. The bottom assembly consists of a perimeter ring, a center hub, a perforated sheet, a screen and two backup rings (see Detail "B"). The perforated sheet, screen and backup rings are continuously seam-welded to the perimeter ring and hub. The screen is located on the outboard side and is spotweld at approximately 15.24 cm (6.0 in) centers to the perforated sheet over the entire area. The purpose for the perforated sheet is to provide support for the screen and to provide a structural tie between the perimeter ring and hub. The inside face of one leg on the perimeter ring is equipped with 48 floating-type nut plates for attaching the lid assembly. During transfer into the receiver tank, a separate circuit is provided for injecting LH_2 inside the acquisition device. Section "C-C" on the layout shows an arrangement for receiving a probe which is mounted from the tank access door. A "KEL-F" lip seal is held between a backup ring and the bottom wall. The arrangement compensates for axial and angular movements during chilldown. Another approach is to increase the annulus gap between device and the tank access opening ring sufficiently to allow the use of a tubular flex loop. This flex loop would be routed to a fitting located in the lid assembly.

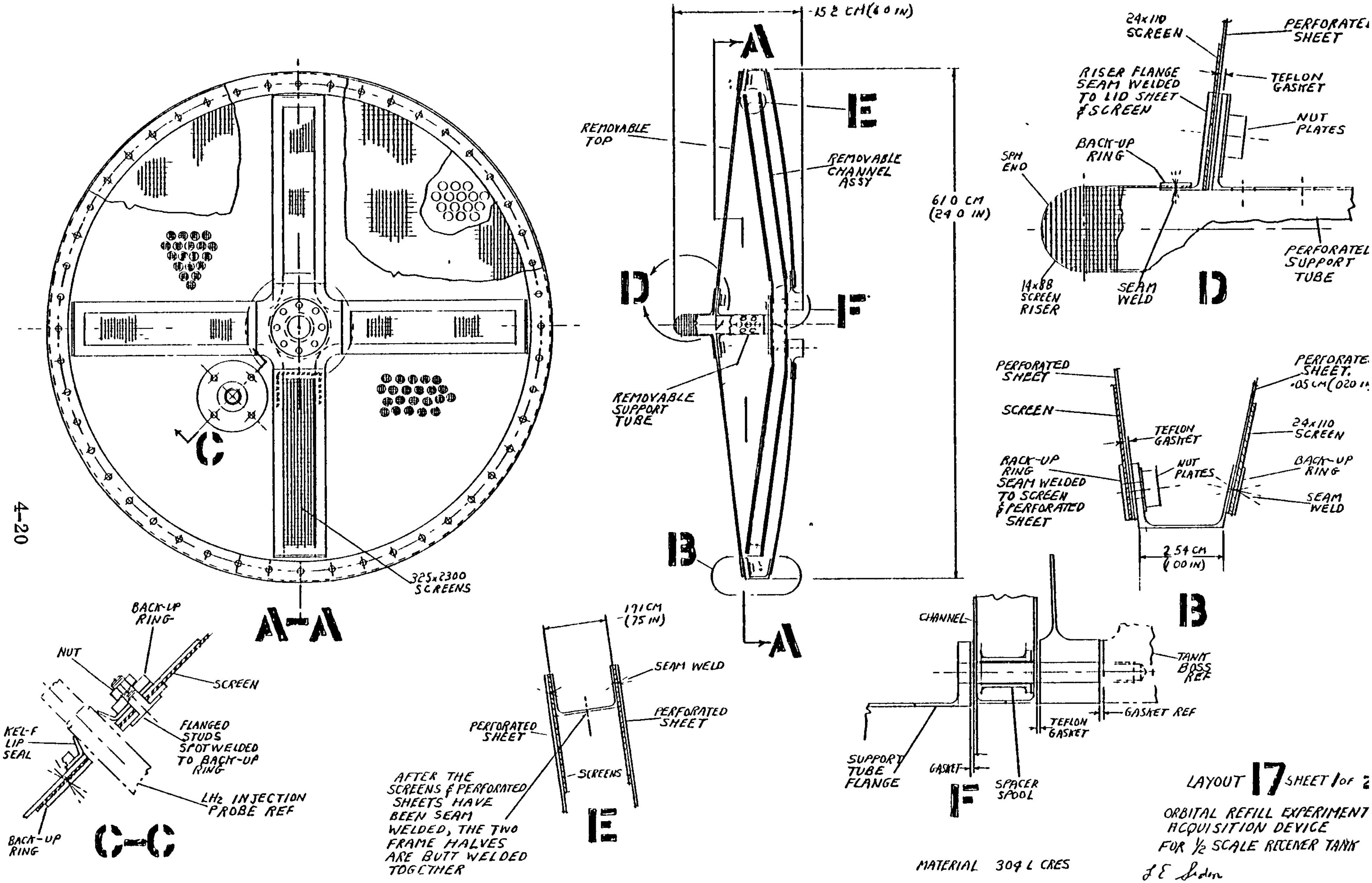


Figure 4-5. Half-Scale Receiver Tank Acquisition Device

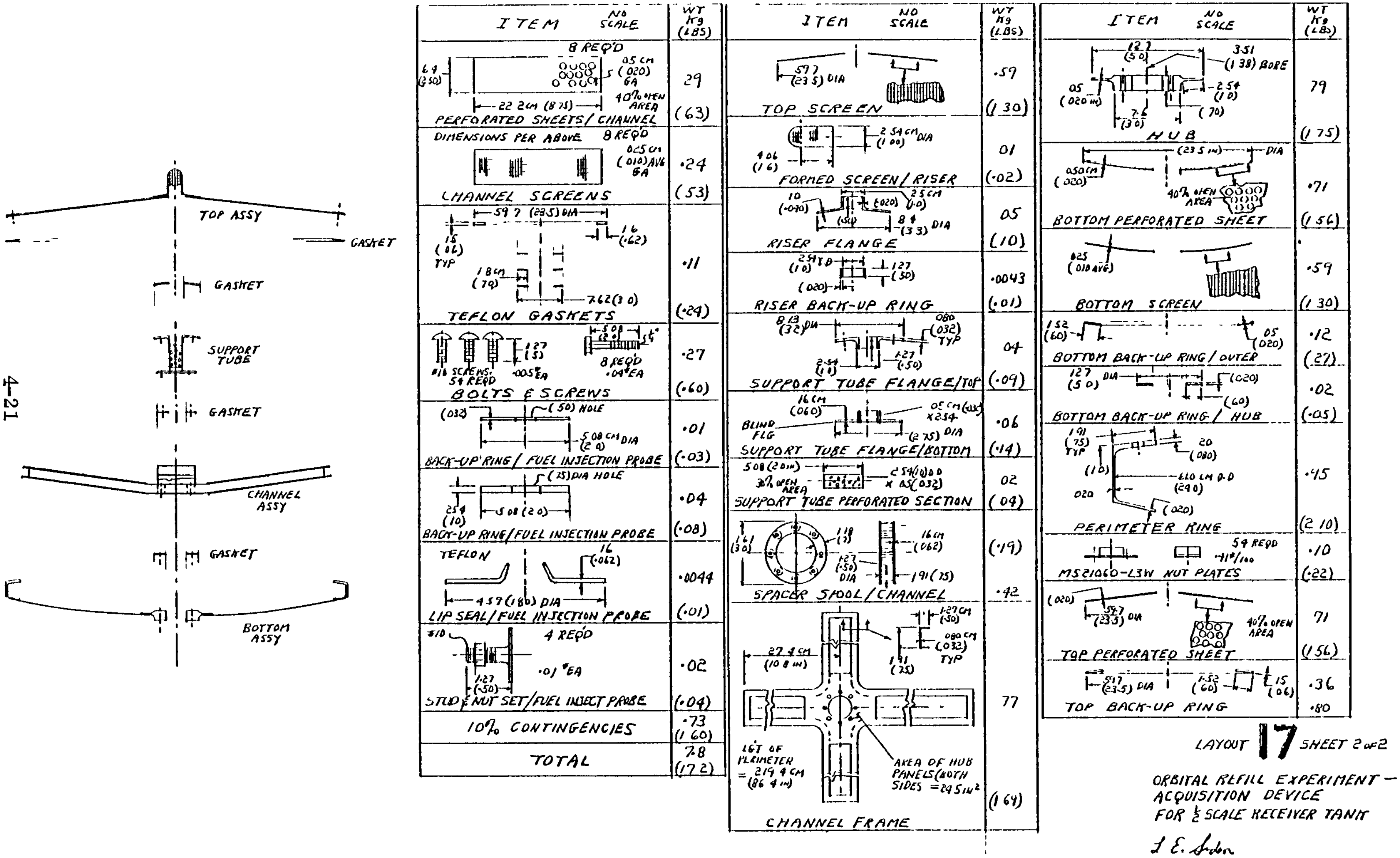


Figure 4-5. Half-Scale Receiver Tank Acquisition Device (Continued)

4.1.5.2 Channel Assembly. The internal channel is a hub with four spokes sloping toward the lid. Each spoke has a rectangular cross section (3.81 cm x 1.91 cm). The two long sides (3.81 cm) consists of screens attached to perforated sheets, similar to that for the bottom assembly except the screens are located inside the perforated sheets. The screens and perforated sheets are continuously welded to a frame assembly as shown in Detail E. The walls in the hub area are solid sheet metal (no perforations or screens).

The cross section of a typical frame member is two angles butt-welded together to form a "C" section. The purpose for these two separate angle pieces is to permit continuous seam welding in the area near the hub where the screen ends. The total channel therefore consists initially of two angle frames equipped with perforated sheets and screens. The last assembly operation consists of bringing the two angle frames together and welding (Detail "E") to form the rectangular flow path. This technique also permits the installation of the spacer spool which is located between the two walls at the hub area.

4.1.5.3 Support Tube. The support tube is a perforated section equipped with an open flange at one end facing the lid assembly and a blind flange at the opposite end. The tube serves as a center support for the lid and provides a closure for the channel hub. Before assembly, the inside wall of the channel hub is open for inspection and cleaning. The flange facing the lid is equipped with nut plates on the inside face for attaching to the lid.

4.1.5.4 Lid Assembly. The lid assembly is one conical screen and one conical perforated sheet continuously seam welded together at the perimeter using a backup ring. The arrangement is shown in Detail "B". The center of the lid is equipped with a riser which is a preformed cylindrical screen with a spherical end. The open end of this riser has a flange which is seam welded to the lid (see Detail "D").

4.1.5.5 Assembly. Prior to final assembly, the bottom section, lid, and channel are cleaned, inspected and tested. The bottom section and a Teflon gasket are positioned onto the tank access door boss with the LH_2 injection tube engaged with the hole in the bottom wall. A Teflon gasket is next placed over the center hub and the channel assembly positioned over this gasket. A third gasket is then placed over the channel hub and the support tube placed over this gasket. The three subassemblies (bottom, channel and support tube) are attached to the access door using eight bolts which pass through these three assemblies and engage with threaded inserts in the access door boss. The LH_2 injection tube is next sealed to the bottom wall using the "KEL-F" lip seal, a backup ring and 4 nuts which engage with flanged studs. The first part of the assembly is now completed, and the joints at the gaskets are leak-checked before proceeding with the final part of the assembly.

A Teflon ring gasket is positioned on the bottom section flange and a second gasket placed over the support tube flange. The lid assembly is placed over these gaskets and attached with 54 CRES screws. The assembly is now completed. Prior to installing into the tank, the two joints for attaching the lid are leak-checked.

The assembly procedures described above do not include any instrumentation that may be required. Instrumentation inside the device would be wired and the penetration points checked for leaks prior to installing the lid. Penetration fittings for the wires will probably be located through the web section of the perimeter ring. All wires would be bundled into a single cable equipped with an end fitting for attaching to the tank wall penetration fitting. Excess length in the cable would permit the final connection before the access door is positioned and sealed.

4.1.6 QUARTER-SCALE RECEIVER TANK. The design of the quarter scale receiver tank is identical to the half scale tank (see Figure 4-3 and 4-4) except for its size and the absence of a propellant acquisition device. The basic tank is 105.4 cm (41.5 in) in diameter x 231.9 cm (91.3 in) in length including the two ellipsoidal bulkheads. The total volume is 1.81 m^3 (64 ft^3) and the weight is 49.4 Kg (108.6 lbs). The preliminary design for this tank is shown in Section 3.3 as Layout #12 (Figure 3-35).

4.1.7 SUPPLY AND RECEIVER TANK SUPPORT STRUCTURE. The two receiver tanks, the supply tank, interconnecting plumbing, and electrical systems are assembled into one module and checked out. The module is then installed in the Shuttle and the system interfaces connected to the payload service panels. To accomplish this, the structure shown in Figure 4-6 (Layout #21) is required. The design consists of a cylindrical body section, two purge enclosure bulkheads, receiver tank support beams, and supply tank support struts. A detail parts list with weights is also included on Sheet 2 of the Layout.

4.1.7.1 Cylindrical Body Section. The cylindrical body section is an aluminum alloy skin stringer frame structure. The primary members are two box rings (one aft and one forward) incorporating supply tank support fittings, four trunnion fittings and two keep fittings. Detail "C" in the Layout shows a typical trunnion fitting arrangement. The two box rings are interconnected with a cylindrical skin, 48 stringers and 10 stabilizing frames. The stringers are "I" shaped members spaced at 0.13 radians (7-1/2°) and running continuously between the two box rings. The stabilizing rings are located inboard and are spaced along the length of the cylinder. Two of these stabilizing frames are positioned back to back near the mid-point of the cylinder to form the drag frame arrangement shown in view "A-A". A third frame (having a deeper section) is located near the forward end and serves as an interface for the purge enclosure bulkhead.

4.1.7.2 Purge Enclosure Bulkheads. The cylinderical section with two bulkheads attached forms an enclosed volume for conditioning the supply tank insulation system. Both bulkheads are fiberglass and the inside surfaces are covered with a teflon film. "Z" shaped fiberglass stabilizing rings are bonded to the outside surfaces. The aft bulkhead is ellipsoidal and the forward bulkhead is a spherical segment. Each bulkhead has an integral ring at the base attaching to the structure.

The supply tank has outlets for fill, drain, vent, transfer and electrical. These outlets penetrate the bulkheads as shown in Detail "E" on the Layout. The penetration consists of a split fiberglass collar, two aluminum alloy backup rings, a CRES band clamp,

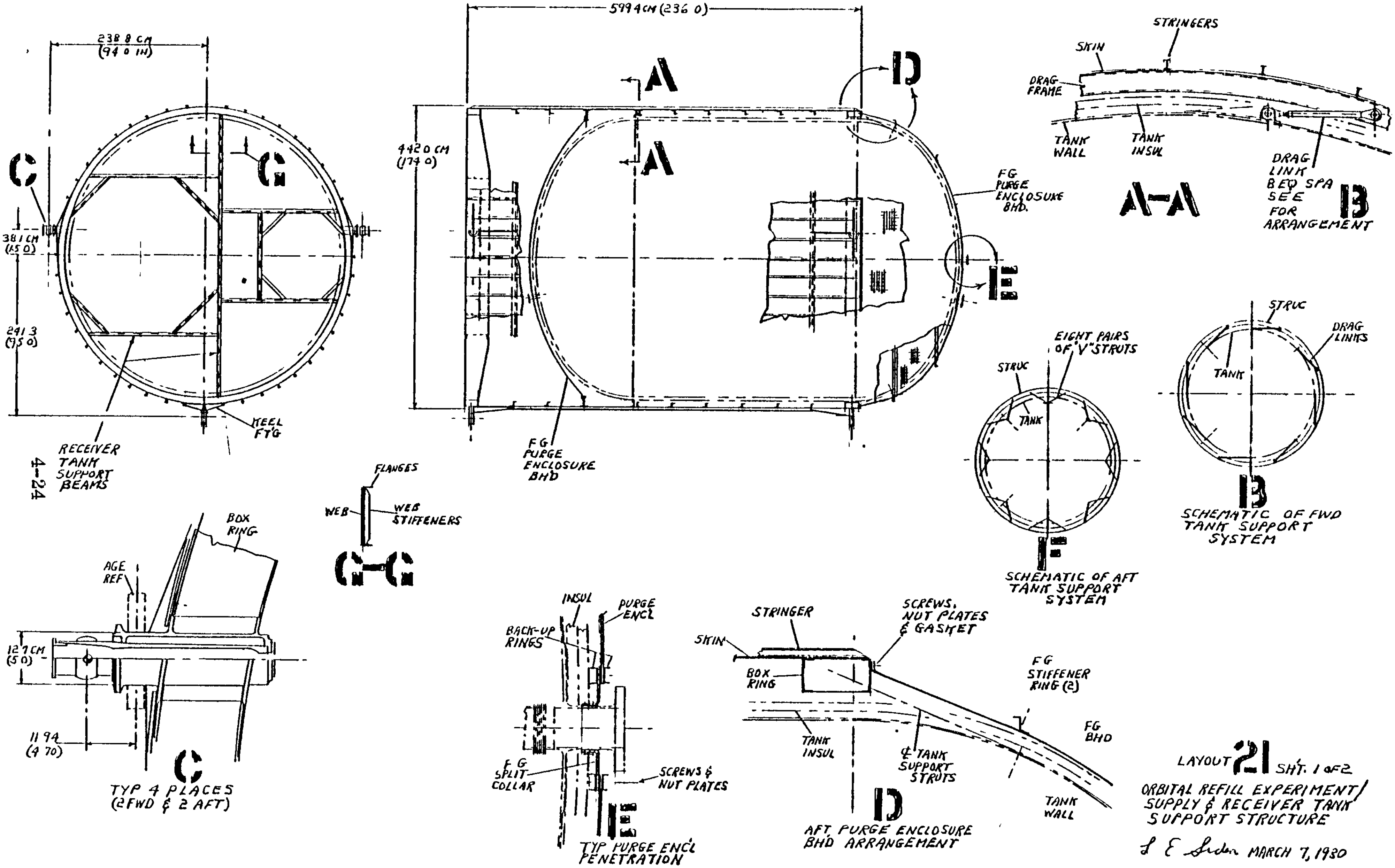


Figure 4-6. Tank Support Structure

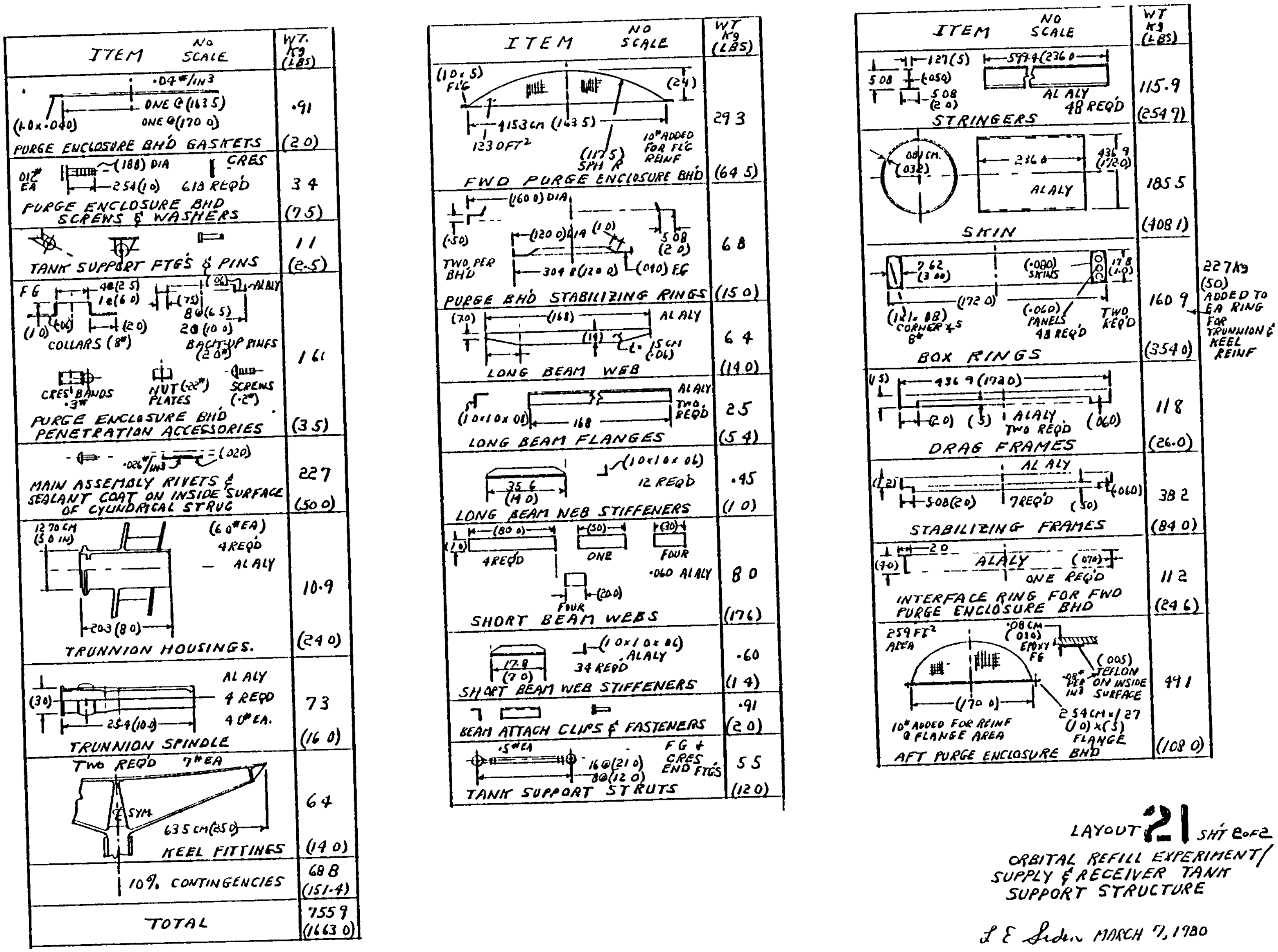


Figure 4-6. Tank Support Structure (Continued)

and a set of nut plates and screws. The split fiberglass collar is clamped to the neck of the outlet with a CRES band and the split line sealed. One back-up ring equipped with nut plates is located at the inboard side of the collar and the second ring is located on the outside surface of the bulkhead. A gasket or an adhesive coating is used between the collar and the bulkhead. The purpose for the back rings is to distribute the clamping load between the screws.

4.1.7.3 Receiver Tank Support Beams. The half-scale and quarter-scale receiver tanks are positioned in parallel and supported from the forward end of the structure with a network of beams. The beams are attached to the box ring at ten points and are arranged to interface with each receiver tank at eight points. A typical beam cross section is shown in view "G-G" on the Layout.

4.1.7.4 Supply Tank Support System. The aft supports for the supply tank are eight pairs of low conductive struts arranged in a "V" pattern. A schematic is shown in Detail "F". The struts are oriented so that the loads are directed tangentially into the bulkhead. This system provides restraint in all directions while allowing tank dimensional changes.

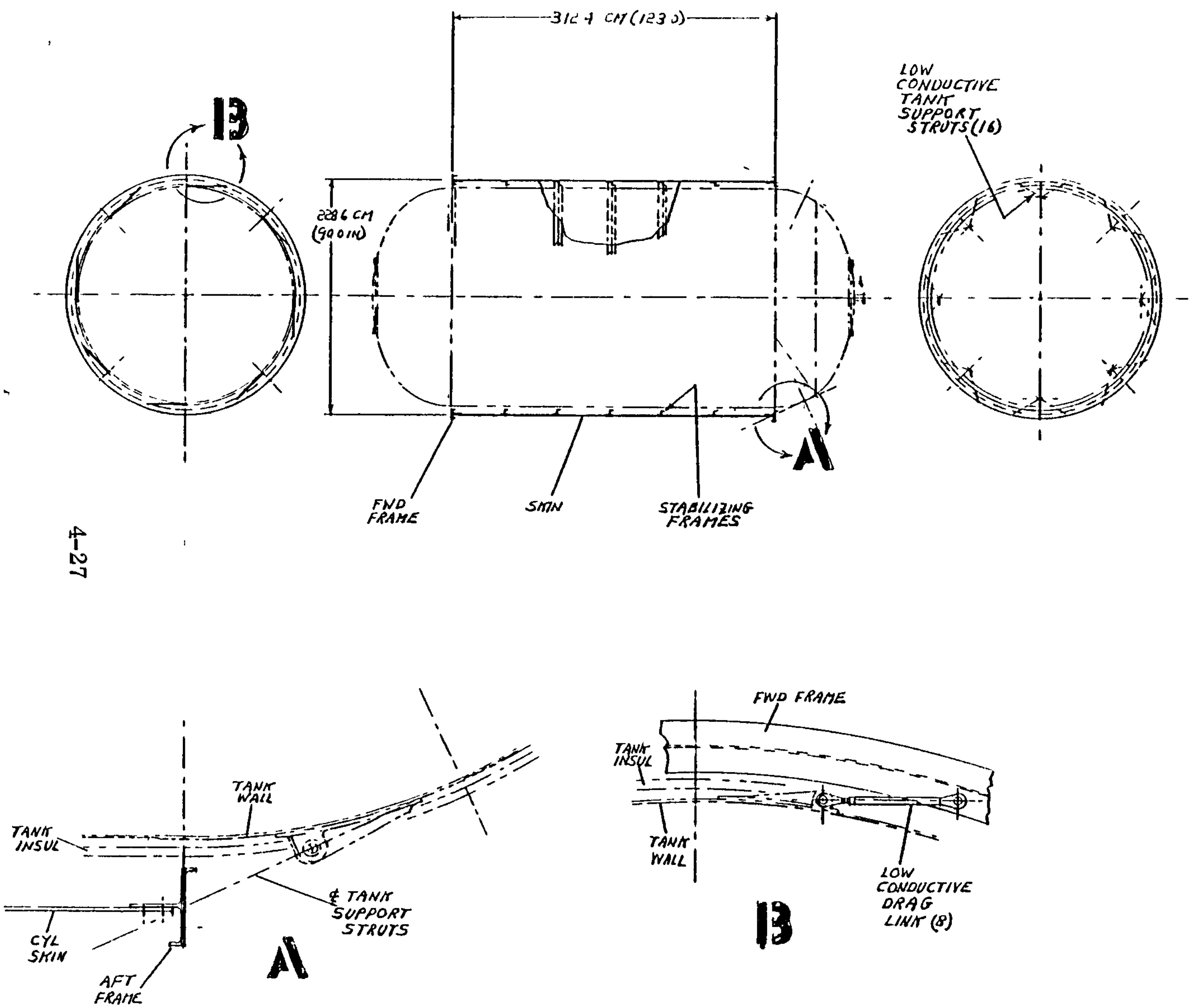
The forward end of the tank is supported with eight drag struts as shown in View "A-A" and the schematic in Detail "B". This arrangement provides radial restraint only while compensating for tank dimensional changes.

4.1.7.5 Half-Scale Receiver Tank Support Structure. The half scale receiver tank must be supported at each end from a cylindrical structure which in turn interfaces with the beams on the supply tank support structure. Several types can be used such as an open truss, open isogrid, honeycomb, skin stringer frame, and semi-monocoque. In the interest of low cost, the semi-monocoque shown in Figure 4-7 (Layout #22) was selected. Since the experiment is Shuttle dedicated, weight in this case is not regarded as a disadvantage.

The design is a simple 228.6 cm (90 in) diameter x 312.4 cm (123.0 in) length cylinder equipped with two end rings and five intermediate stabilizing rings. The aft ring has a tee-shaped cross section and is equipped with clevis type fittings for attaching the tank support struts (detail A). The aft ring also has holes in the outboard flange for attaching to the supply tank support structure beams. The forward ring also has a tee-shaped cross section and is equipped with fittings for attaching the tank support drag struts (Detail B). The intermediate stabilizing rings have "Z" shaped cross sections and are equally spaced along the length of the cylinder. End bulkhead closures are not required since the tank insulation does not require a purge system.

The tank supports are the same as that described for the supply tank which uses a system of low conductive struts at the forward and aft ends. Loads through these struts are directed tangentially into the tank shell.

Included in Layout #22 is a parts list with weights. This list shows material gages and the basic geometry of each component.



ITEM (NO SCALE)	WT Kg (LBS)
AFT RING (AL ALY)	7.7 (17.0)
AFT RING (AL ALY)	7.7 (17.0)
SKIN (AL ALY)	158.1 (347.8)
STABILIZING FRAMES (AL ALY), FIVE REQ'D.	28.9 (63.6)
SUPPORT STRUTS (FG & CRES END FTG'S)	3.4 (7.5)
FITTINGS, RIVETS, PINS, NUTS, BOLTS	2.3 (5.0)
10% CONTINGENCIES	20.8 (45.8)
TOTAL	229.0 (503.7)

LAYOUT 22
ORBITAL REFILL EXPERIMENT/
½ SCALE RECEIVER TANK
SUPPORT STRUCTURE
L.E. Siden MARCH 10, 1980

Figure 4-7. Half-Scale Tank Support Structure

4.1.8 EXPERIMENT MODULE ASSEMBLY. The complete experiment module assembly shown in Figure 4-8 (Layout #23) consists of a support structure, a supply tank, two receiver tanks, power supply unit, remote acquisition interface unit, pneumatic control unit, three helium storage bottles, interconnecting plumbing, an instrumentation system, and wiring. The experiment module assembly contains all systems and interfaces necessary to conduct, monitor and record data for propellant transfer. Also included are provisions for structural, fluid and electrical interfacing with the Shuttle as well as systems for status monitoring during ascent and descent. The equipment is arranged for easy accessibility during factory checkout and KSC ground operations when installed in the Shuttle.

4.1.8.1 Support Structure. The support structure consists of a large cylindrical shell for supporting the supply tank and two smaller cylindrical shells which in turn support the receiver tanks. The large shell has support trunnions and keel fittings for interfacing with the Shuttle. This large shell also contains support beams at the forward end for attaching the two smaller shells and two purge enclosure bulkheads which form a closed cavity for purging the supply tank insulation system. The smaller cylinders are cantilevered from the forward beams, therefore additional support struts and an interconnecting shear panel are employed. The support struts are attached to the main forward box ring on the large cylinder. The shear panel interconnects the two small cylinders and is also attached to the forward beams.

During assembly, both the receiver tanks and the supply tank are suspended inside the shells prior to final structural connections between the shells.

The aft support trunnions are positioned in the payload bay at X_o 1202.7 and the forward trunnions at X_o 974.6. The keel fitting locations are slightly offset from the trunnions due to available locations. Station X_o 1202.7 provides sufficient clearance between the aft end of the module and the X_o 1307 bulkhead for routing plumbing and accessibility for making connections. The overall length from X_o 1302.0 is 12.5 meters (41.0 ft).

The system connections and controls between the Shuttle and the experiment module assembly are abort dump, ground fill and drain, ground vent, helium fill, helium purge, flight vent, data management and electrical. The abort dump duct routes from the dump valve on the module to an overboard interface located at Z_o 331.2 and X_o 1295.0. The duct is an offset "S" shaped assembly incorporating three axially restrained flex joints for absorbing dimensional changes and tolerances. A flanged connection, incorporating dual seals with overboard vented cavity, is used to connect duct to valve. The duct is also equipped with insulation.

The fill and drain duct starts at a valve located adjacent to the abort dump valve and is routed to the Shuttle fuel umbilical panel. The location of this umbilical panel is shown in Figure 4-9 (Layout #24). The duct incorporates three axially restrained flex joints, a disconnect and a purged insulation system. Similar to the abort duct, a flanged connection with dual seals is used at the fill and drain valve.

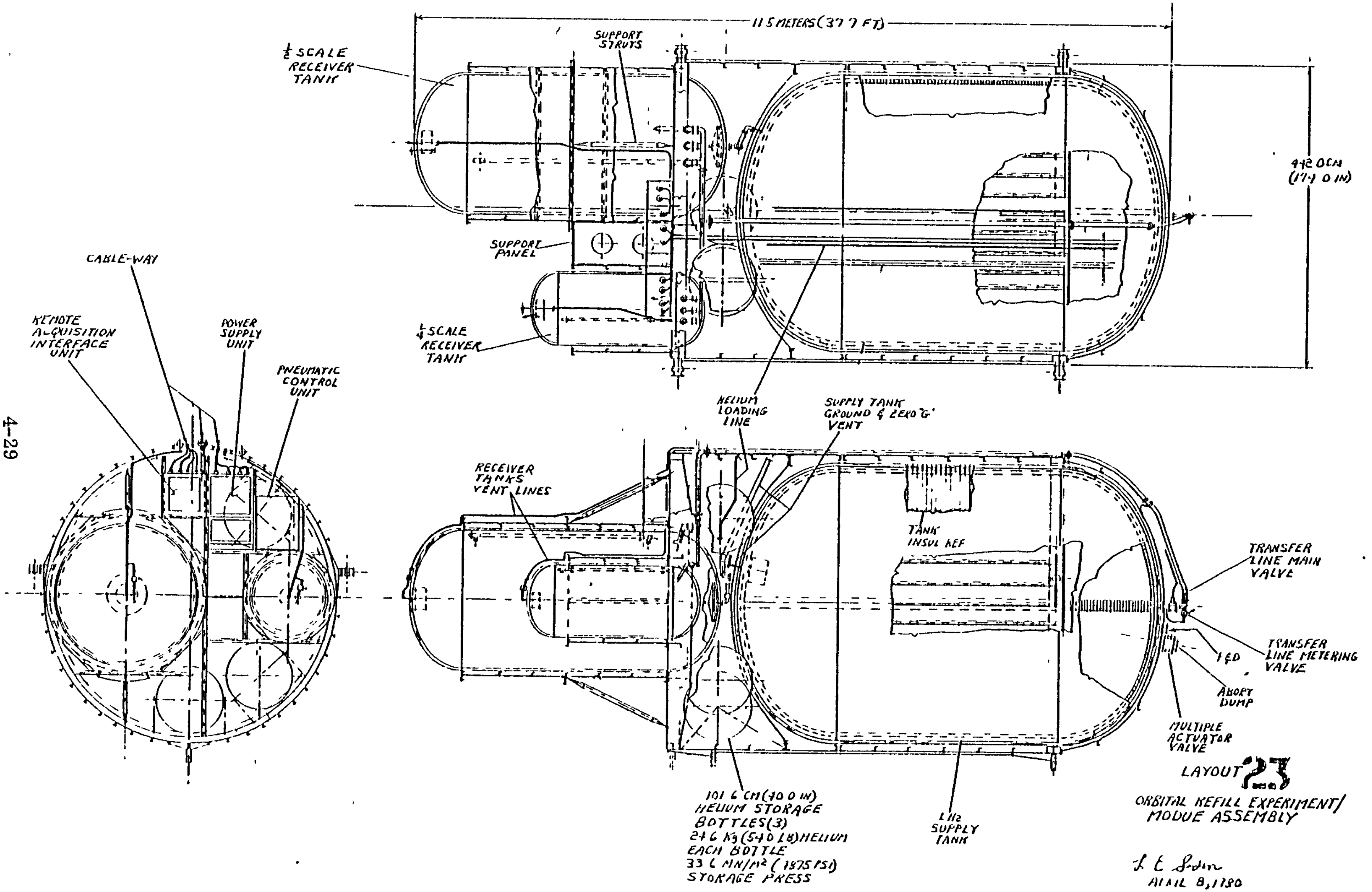


Figure 4-8. Experiment Module Assembly

4.1.8.2 Supply Tank. Details for the supply tank were shown previously in Figures 4-1 and 4-2. The tank contains an acquisition system, an insulation system, and provisions for fill, drain and vent. The tank is suspended inside the large cylindrical shell with a system of low conductive struts located at the aft and forward ends.

4.1.8.3 Plumbing. The supply tank is equipped with circuits for ground fill/drain, ground vent, flight vent abort dump, and experiment fluid transfer. The receiver tanks have circuits which permit filling in three different modes (manifold spray, single spray or direct injection) and also vent provisions.

The 1/2 scale receiver tank has an acquisition system which permits transfer back to the supply tank. Both can be emptied by boiling off thru an overboard vent circuit. The helium storage bottles are also interconnected to permit pressurization of the supply tank for transfer or abort and for actuation of control valves. The plumbing for these systems is basically 304L CRES tubing supported from the three structural cylinders which envelop the tanks. Both pneumatic and solenoid operated valves are used. For the abort dump, a multiple actuated harpoon valve is located at the tank outlet. Overboard plumbing for the abort dump and for other circuits are provided at installation level in the Shuttle.

As a safety measure all joints that are operationally amenable to welding are welded. When it is necessary to use a flanged connected dual seals are used with the cavity between the seals vented overboard. For small mechanical connections such as in the helium circuits, the AFRPL bobbin seal connectors or shrink couplings may be used.

All lines are routed over the top side of the supply tank support structure. The transfer line for example starts at the supply tank aft bulkhead and is routed forward over the purge enclosure bulkhead and the cylindrical support structure. At the forward end, the line branches out into two manifolds which attach to the receiver tanks. This transfer line incorporates axially restrained flex joints for absorbing dimensional changes and is enveloped with a multi-layer insulation (MLI) system. Those lines which must be routed overboard are terminated near the aft end of the purge enclosure bulkhead. At the Shuttle installation level, a plumbing kit is used to make the overboard connections. The purge enclosure bulkhead is equipped with stiffner rings which provide support for these lines.

4.1.8.4 Electrical Systems. Instrumentation, receiver tank wall heaters, valve actuation, monitoring, data collection, and interfacing with Shuttle systems are functions of the electrical system. Also included are provisions to satisfy the safety grounding and redundancy requirements for Shuttle payloads. The wiring harnesses for this system are located on the top side of the supply tank support structure adjacent to the fluid lines. Excess length is provided at the aft ends of these harnesses so that connections to the Shuttle payload service panel at station X_o 1307 can be made without additional splices.

4.1.8.5 Remote Acquisition Interface, Power Supply and Pneumatic Control Units. These units are located at the forward end of the supply tank support structure and are oriented for easy accessibility. Data management, electrical and tubing lines going to and from these interface units are routed along the cableway (see Figure 4-8).

4.1.9 INSTALLATION IN THE SHUTTLE. The main cylindrical structure which contains the supply tank has two aft trunnions, two forward trunnions and two keel fittings which interface with supports on the Shuttle. Each trunnion has an outboard fitting which engages with the Shuttle and an inboard flange which is designed to accept AGE equipment. A typical arrangement was shown previously in View C of Figure 4-6 (Layout #21). The complete module is picked up by these flanges, placed into the Shuttle payload bay and attached. Referring to Figure 4-9 (Layout #24), the centerline of the module is slightly below the payload bay centerline. The purpose for this offset is to provide added space on the top side between the payload bay envelope and the module plumbing. The module structure is 448.0 cm (174.0 in) diameter across the tops of the stringers. At the bottom side, this structure clears the payload bay envelope by 5.08 cm (2.00 in) and at the top by 15.24 cm (6.0 in). Assuming 2.54 cm (1.0 in) depth stringers and subtracting 5.08 cm (2.0 in) for envelope clearance, the net space available for plumbing is 7.62 cm (3.00 in). Both plumbing and wiring is located between the stringers and supported with fairleads attached to the tops of the stringers.

On the experiment module assembly, the ground vent duct starts at the top of the supply tank and terminates at the stub-up located near the end of the aft purge enclosure bulkhead. The stub-up is supported from the purge enclosure stiffener ring. The overboard duct section routes from this stub-up to the fuel umbilical panel. Similar to the fill and drain this vent duct incorporates flex joints, a disconnect and insulation.

The helium fill line is routed similar to that described for the vent. The helium fill is a high pressure tube having flex loops for absorbing deflections and tolerances. The tube terminates at the fuel disconnect panel through a disconnect.

The helium purge is a low pressure tube which starts at the aft purge enclosure bulkhead and terminates at the fuel disconnect panel thru a disconnect. This line supplies helium for conditioning the supply tank MLI prior to ascent.

The flight vent duct and the electrical harness interface with the Shuttle at two service panels located in the X_o 1307 bulkhead. Location of these panels is shown on Layout #24. The vent duct branches off the ground vent near the aft purge enclosure bulkhead and is equipped with a shut-off valve. In addition to venting the supply tank during ascent, this flight vent duct will also convey gases from the zero-g vents and boiloff from the receiver tanks.

4.1.10 CENTER OF GRAVITY AND WEIGHT SUMMARY. A weight summary for the complete module, the c.g. location, and the relation of the module c.g. to the Shuttle

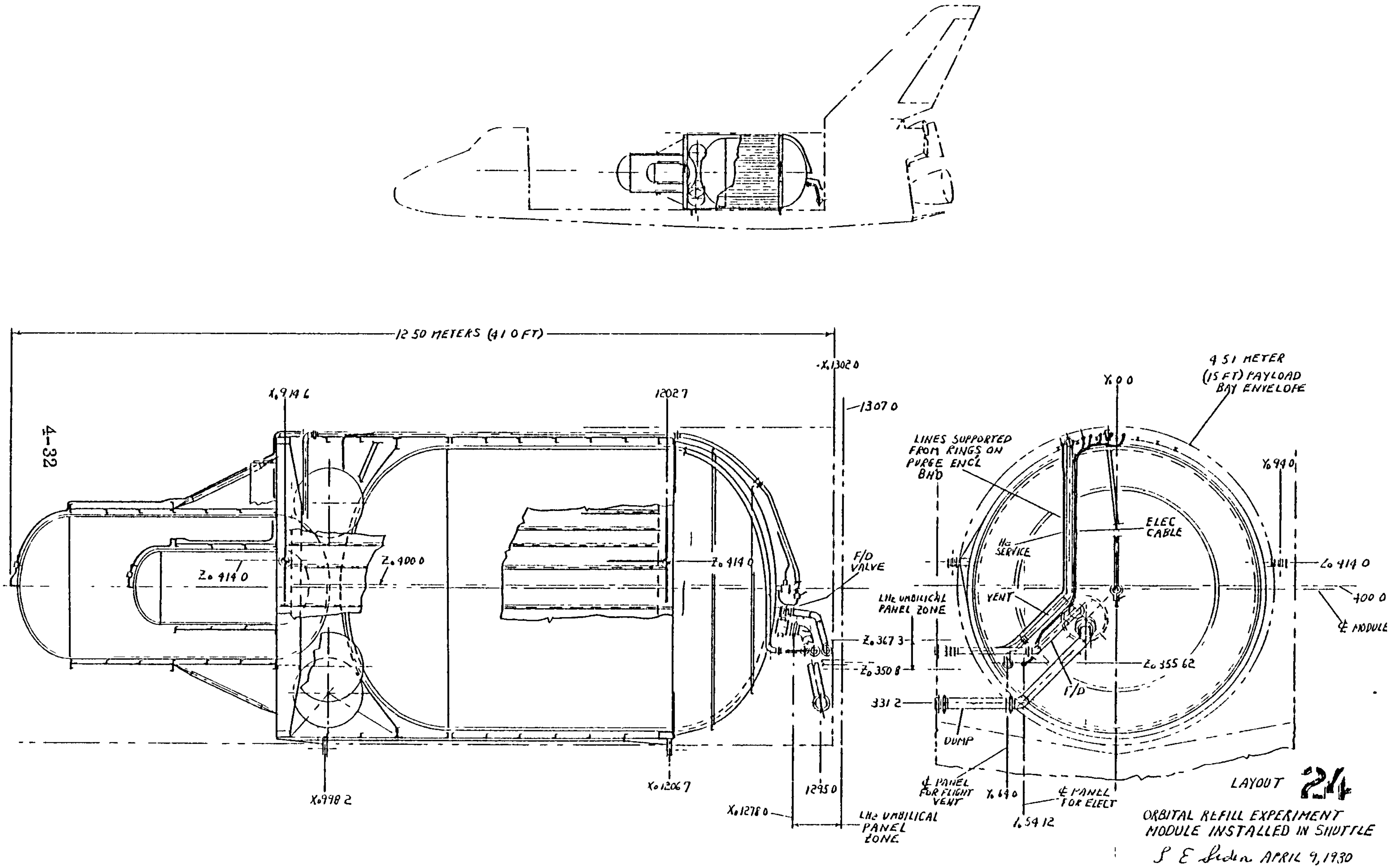


Figure 4-9. Shuttle Installation

allowables is shown in Figure 4-10 (Layout #25). The weight summary is broken down into major areas such as tanks (including insulation), support structure, plumbing, etc. Those items which have been previously designed with detailed weight analysis are noted on the parts list. Weights for the remaining items were extrapolated from similar systems which have been detailed.

4.2 PRE-FLIGHT PROCEDURES

The more significant pre-flight procedures for the propellant transfer experiment involve the ground operations and integration at Kennedy Space Center (KSC), and the experiment design and operational controls imposed by the required STS safety and hazard analysis criteria. Section 4.2.1 provides an overview of the ground operations at KSC. The preliminary safety and hazard analysis for this conceptual design phase of the experiment is presented in Section 4.2.2.

4.2.1 GROUND OPERATIONS. The Propellant Transfer Experiment (PTE) integration and ground operations will take place at the Kennedy Space Center (KSC). Figure 4-11 presents an overview of this planned ground operations scenario.

This section describes typical operations which must be performed at KSC to ready a PTE payload for launch on the Space Shuttle Vehicle (SSV). Payloads for each Shuttle are manifested by JSC into a complete Shuttle cargo. KSC then prepares an integrated ground operations flow for each Shuttle flight. A part of the integration analysis by KSC is to determine whether the payload will be installed in the Orbiter at the OPF or at the launch pad. Certain hazardous operations cannot be performed in the OPF; consequently, some payloads must be installed at the launch pad. The type of hazardous operations to be performed is the most important criterion in deciding whether a payload will be installed in the OPF or at the launch pad.

A preliminary analysis of PTE launch site requirements indicates the vertical processing mode of operations, e.g. launch pad payload installation appears to be compatible with PTE requirements.

Some of these requirements, the on-pad propellant loading in particular, were identified during the Centaur-in-Shuttle study and solutions were recommended. These solutions have been incorporated into the PTE scenario to the extent that they apply.

Several baseline data sources were used for this analysis. The most important were:

- K-STSM-14.1 Launch Site Accommodations Handbook for STS Payloads, Vol. VI
- K-STSM-09 Rev. 4 Operations and Maintenance Management Plan, Vol. 1
- Shuttle Turnaround Analysis Report (STAR) No. 17
- K-STSM-14.1.12 Vertical Processing Facility Handbook

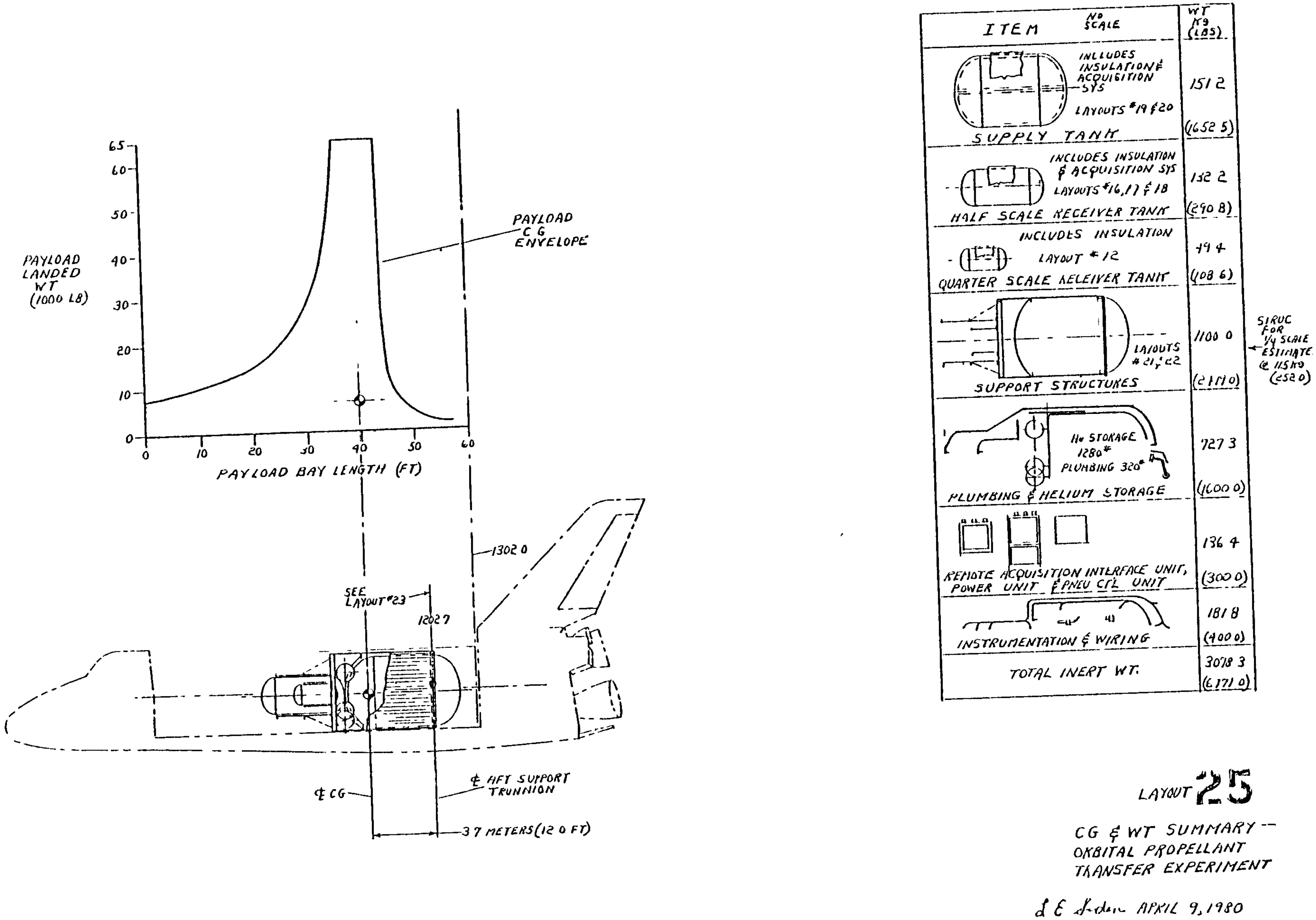


Figure 4-10. Center of Gravity & Weight Summary

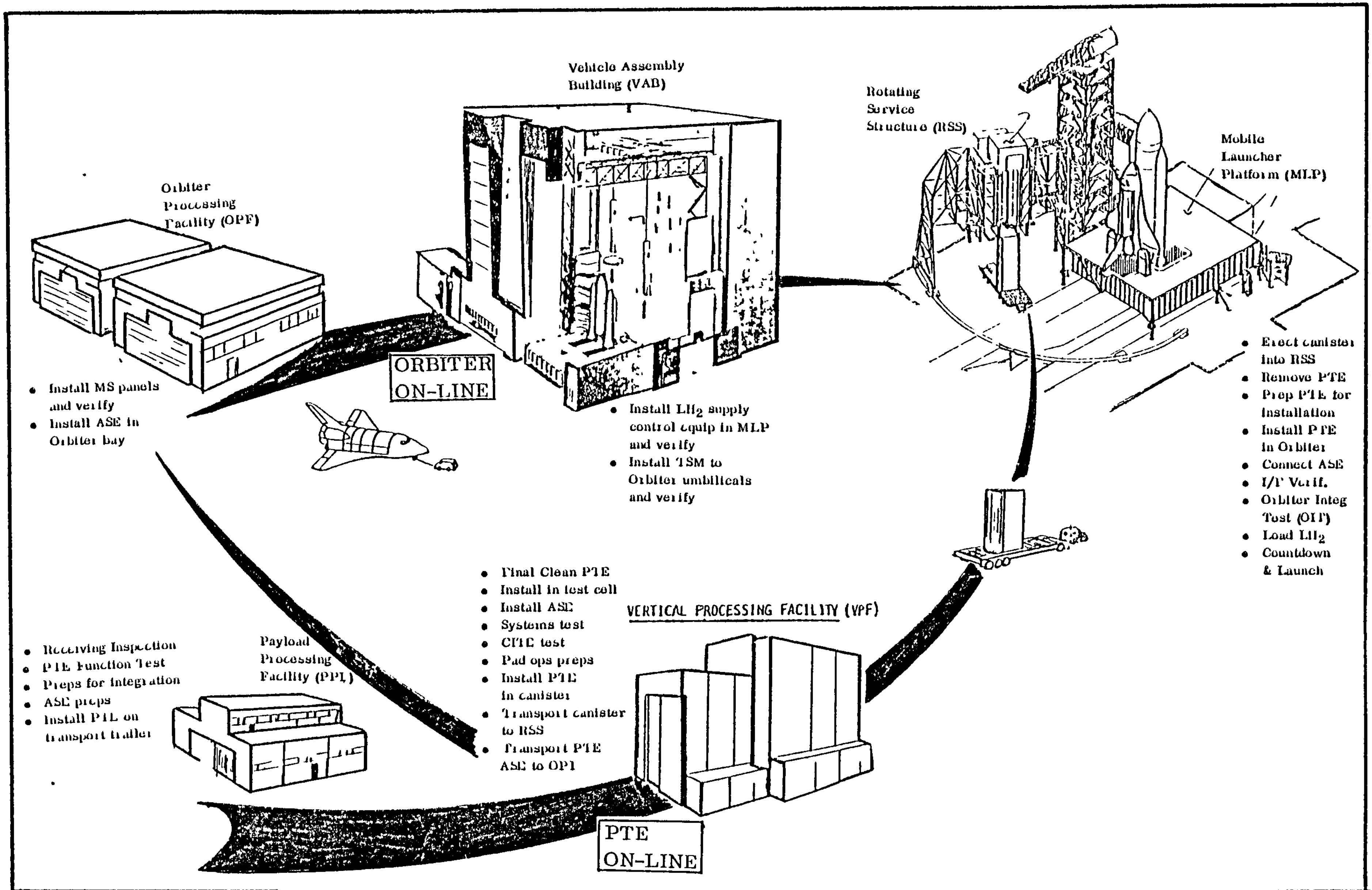


Figure 4-11. Propellant Transfer Experiment (PTE) Ground Operations (KSC Pre-Flight Integration Scenario)

- GDC 979-STS-79-1 STS/Centaur Integration Launch Operations Plan

The following ground rules and assumptions were used in the development of the integration and ground operations for the PTE configuration:

1. The PTE is installed with the Orbiter vertical at the launch pad.

2. The current 160-hour KSC Shuttle turnaround is used.

3. LH_2 loading will be remotely controlled from the STS launch control center (LCC).

4. Remote PTE payload fill and drain operations will be accomplished via the Orbiter T minus 0 umbilical system capability.

5. It is assumed that a Shuttle will be exclusively dedicated to support a Propellant Transfer Experiment mission. In this case, there is only one P/L in the cargo which is the PTE.

4.2.1.1 PTE Payload Processing Facility. Payload Processing Facility (PPF) will be required for the receiving inspection, assembly, test and checkout operations. An electrical ground support equipment (EGSE) station to monitor and conduct checkout will be established. Mechanical, electrical and functional tests will be performed to meet the interface requirements of the STS EGSE and mechanical ground support equipment (MGSE) at the pad, mobile launcher platform (MLP) and the LCC. The test will include a cryogenic tanking simulating as close as possible to the Shuttle conditions and interfaces.

The following is a checklist of PTE operations which may be performed in the PPF:

a) Receiving/inspection

b) Removal/installation of transport covers

c) Initial pressure system test

d) LH_2 loading system, pressurized and leak-tested

e) Functional/performance verification test

f) Weight and center-of-gravity determination

Upon completion of PPF operations, the PTE will be transported to the Vertical Processing Facility for Orbiter to PTE interface verification.

4.2.1.2 Vertical Processing Facility (VPF). The PTE will be transported to the airlock in the VPF where the PTE will undergo an exterior cleaning operation prior to entering the Class 100,000 high bay. The PTE, after an initial interface check, will be installed in the Vertical Payload Handling Device (VPHD) and installed into one of the test cells. After a series of mechanical and electrical interface validation and compatibility tests, including end-to-end, the Cargo Integration Test Equipment (CITE) test operation will be run with the entire flight manifest. Trunnion and keel fittings will be verified and an electrical compatibility test with the Orbiter interface will be performed. Upon completion of the CITE test, the payload canister is moved vertically up to the workstand and positioned such that the vertical payload handling device on the workstand can transfer the entire PTE into the canister for movement to the rotating service structure (RSS) at the launch pad.

a) Operations in the VPF are conducted under environmentally controlled conditions. The entire VPF is a class 100,000 clean room with temperature at 297.2 $\pm$ 2 K (75 $\pm$ 3 F), and relative humidity controlled at 45 $\pm$ 5 percent.

b) VPF operations include:

1. Removal of PTE from the transportation canister.

2. Electrical systems test.

3. Mechanical systems test.

4. CITE testing.

5. Removal of MSS control panels from PTE-peculiar GSE for movement to OPF for installation into the Orbiter.

6. Installation of complete PTE cargo assembly into canister.

4.2.1.3 Pad Operations. Installation of the PTE into the RSS will occur prior to the Space Shuttle Vehicle (SSV) transfer to launch pad, and begins with the positioning of the canister below the retracted rotating service structure. Once at the pad, the payload canister will be hoisted into position, the entire PTE extracted from the canister by the Payload Ground Handling Mechanism (PGHM) and retracted into the RSS. Some RSS time may be available in the rollback position for systems test prior to or during Orbiter-to-Pad transfer operations.

After the Mobile Launch Platform (MLP) is hard down on the pad, the RSS will rotate into position for PTE payload insertion into the Orbiter bay. Following RSS and Orbiter cargo bay door opening operation, the PTE will be inserted into the Orbiter bay by the PGHM and secured. Prior to the cargo bay doors closing, the total cargo-to-Orbiter interface verification tests, closeout procedures, and payload-unique tests (end-to-end test) will be accomplished. Orbiter cargo bay door closing will be the last time that the PTE may be accessed prior to liftoff.

RSS and launch pad operations include:

- Installation of PTE-peculiar GSE into RSS.
- Hoisting canister into RSS.
- Removal of PTE from canister.
- Removal of canister from RSS.
- Inspection, test and servicing of PTE payload prior to arrival of Orbiter at launch pad.
- Insertion of PTE into Orbiter.
- Connection of PTE to Orbiter interfaces.
- Interface verification test.
- Final PTE payload servicing.
- Payload bay closeout.
- LH_2/GHe loading (see Tanking Operations).
- Retraction of PCR.
- Launch countdown.

4.2.1.4 Tanking Operations. To support the PTE tanking operations, LH_2 supply control skids will be installed on the Mobile Launcher Platform (MLP). The skids will interface between the propellant supply stub-ups and the Orbiter T-0 umbilicals. A TBD-supplied GHe control panel installed in the MLP will control GHe flow from the MLP supply interface to the T-0 panel.

PTE remote monitoring, tanking, and control functions will be processed thru hardwires via the Orbiter T-0 umbilicals from the LH_2/GHe control skids to the launch control center at the VAB.

4.2.1.5 Post-flight Processing. After landing at the Orbiter Landing Facility (OLF), the Orbiter is towed to the Orbiter Processing Facility (OPF) for deservicing/safing operations. Once the deservicing/safing operations have been completed, the PTE payload (utilizing the OPF payload strongback) will be removed from the Orbiter cargo bay and placed in the PTE transporter and moved to TBD facility for post-mission processing.

4.2.1.6 Summary of Preliminary Launch Site Requirements

Payload Processing Facility (PPF):

- LH_2 tanking supply and control system
- PTE transporter
- Transport covers

- Handling GSE
- Electrical interface checkout equipment

Orbiter Processing Facility (OPF):

- Provisions for installing Orbiter cabin located PTE remote control panels
- Provision for installing fluid lines connecting PTE and Orbiter T-0 umbilicals

Vertical Assembly Building (VAB):

- Connecting cables between PTE and CITE launch control center
- Provisions for remote control of PTE LH_2 and He tanking and checkout

Rotating Service Structure (RSS):

- Electrical power for PTE-peculiar GSE
- GHe interface for purging operations

It is apparent that most of the major launch site facilities required for the PTE are presently available at KSC. There are no significant unique requirements. Other facility elements specifically required to support future OTV operations such as the LH_2 tanking and helium pressurization control skids would become available to support any needs of the PTE program.

4.2.2 PRELIMINARY SAFETY AND HAZARD DESIGN ANALYSIS. In order to insure the design of an operationally safe experiment, specific safety and hazard guidelines were used as an integral part of the design effort. The intent at this conceptual stage of the experiment design development was to highlight these safety and hazard guidelines which directly relate to major operational, or design decisions. These fundamental safety and hazard guidelines were selected from References 4-1 thru 4-5.

Table 4-2 lists the requirements and guidelines that were used during the conceptual design phase of the program. Examples of the design and/or operational compliance are summarized for each of the safety and hazard guidelines listed. In addition, safety oriented design practices were used in all the design concept considerations and would normally be expanded in subsequent program phases as the level of the design detail expands.

Table 4-2. Hazard and Safety Analysis of Propellant Transfer Experiment Conceptual Designs

Typical Requirements and Guidelines	Specific Experiment Designs/Operations Interfaces/References
1. Experiment LH_2 tank and pressure vessel design factors of safety shall be at least as conservative as the Orbiter design factors of safety taking into consideration their operational status during flight.	1. The LH_2 tanks (supply, 1/2 scale and 1/4 scale) safety factor is 1.4 or greater. Helium pressure vessel safety factor is 2.0 or greater. Pressure not required for structural stabilization of LH_2 tanks. Example of tank layouts 10, 19 and 22. (See Sections 3.3 and 4.1).
2. A pressure-relief capability shall be provided for the experiment tanks which automatically limits the maximum pressure. Venting shall be overboard and shall be arranged so that reactive fluids cannot mix.	2. All tanks are designed with adequate pressure regulators and pressure relief systems. Overboard relief is of hydrogen gas only and will be arranged so as not to mix with any Shuttle reactive gases that may be released at the same time.
3. A capability shall be provided for the Shuttle crew to dump experiment fluids and vent payload pressurants overboard within the time constraints imposed by an abort situation. This capability shall be available with the payload-bay doors open or closed.	3. The Centaur RTLS abort criteria were used in the design of the LH_2 dump. Redundancy and 300 second time requirements defined the size and configuration. See Layout 14, Section C-C for example. (See Section 4.1).
4. Experiment tanks and their support equipment shall be designed and qualified at serviced conditions to withstand the Orbiter payload-bay environment, including that encountered during emergency maneuvers and the post -landing heat soak.	4. Support structure for the supply tank and two scale receiver tanks have been designed for Shuttle environment and loads. Layout 21 provides a preliminary design of the tank support structure (see Section 4.1). Post-flight processing has been defined in Section 4.2.1.
5. The experiment payload propellant fill, drain, and vent interface with the Orbiter shall permit system propellant transfer, venting, and emergency de-tanking with the payload-bay doors closed and latched in a safe mode.	5. Section 4.2.1 defines the guidlines used for our planned ground operations. The tanking operations and the required equipment will be in the mobile launcher platform (MLP).

Table 4-2. Hazard and Safety Analysis of Propellant Transfer Experiment Conceptual Designs (Continued)

Typical Requirements and Guidelines	Specific Experiment Designs/Operations Interfaces/References
6. A capability for remotely controlled exhaustion of payload hydrogen residuals to space before retrieval operations.	6. The Orbiter crew station control panel will provide for final checkout of the automatic test sequence system. Override capability will be designed into the control station to permit hydrogen dump before return to the landing site.
7. The LH_2 tank thermal protection system and the tank overpressure vent capability shall be designed to maximum heat rates during ground tanked, inflight operational and abort modes including the post landing heat soak. Overpressure relief capacity shall be redundant to vent capacity.	7. The supply tank is designed with MLI and a He purge system for ground tanking. Ground vents and TVS are an integral part of the experiment design. An example of the thermal protection system is shown in Layout 18. (See Section 4.1).
8. LH_2 fill and drain umbilical disconnects shall have positive sealing at disconnect. A redundant shutoff valve inboard of the payload disconnect shall be provided.	8. Section 4.2.1 defines the umbilical disconnects. This disconnect is interfaced with the T-0 control panel.
9. Cleanliness requirements and water restrictions for propellants and propellant systems shall be controlled and monitored. The level required shall be consistent with Shuttle systems cleanliness requirements.	9. The ground operations scenario includes the vertical processing facility (VPF) where the experiment will undergo external cleaning and then enter the class 100,000 high bay clean room. Reference Section 4.2.1 for details of ground operations.
10. Experiment payloads shall not have structures that depend on tank pressure for structural stabilization where Shuttle damage could result if the tank pressurization were lost.	10. LH_2 supply and receiver tanks as designed do not require internal pressure for support. See Layouts 16, 19, 22 for examples of tank designs. (See Section 4.1).
11. A structural interface shall be provided between the payload and the Shuttle payload-bay support points that transmits the payloads into the Shuttle structure with a 25% margin of safety under the most adverse Shuttle design loads.	11. The support structure for the experiment is designed to required Orbiter safety margins. An example of some of the structural aspects are shown in Layout 21; see View C for a trunion design concept. (See Section 4.1).

Table.4-2. Hazard and Safety Analysis of Propellant Transfer Experiment Conceptual Designs (Continued)

Typical Requirements and Guidelines	Specific Experiment Designs/Operations Interfaces/References
12. The payload-to-Shuttle interface structure shall position the payload center of gravity to assure controllable stable aerodynamics in all flight regimes.	12. Item 11 above includes the basic reference design. Layout 25 gives a preliminary indication of CG locations during landing. (See Section 4.1).
13. The payload cryogen-tank thermal protection systems surfaces that are exposed to the payload-bay environment shall be at temperatures in excess of nitrogen liquification temperatures.	13. During tanking and prior to lift-off the MLI covered supply tank containing the LH_2 is purged with He to prevent condensation of nitrogen. See Layout 18 for design concept example. (See Section 4.1).
14. All vents of the payload shall be non-propulsive.	14. All vents have balanced force "steer horn" outlet designs.
15. Payloads shall have operation procedures established for each redline limit that include those circumstances that require payload jettison, propellant and pressurant dump, and hazardous system safing for mission abort.	15. Experiment control operations will provide the procedures to be used in an automatic mode various interlocks and checks will be considered for safe operation. As a back-up, the crew can override the system to accomplish the desired safe operating mode.
16. Integrated checkout and testing of safety critical payload support systems shall be conducted to the extent possible on the ground before installation into the orbiter.	16. Section 4.2.1 describes hazardous operations and checkout procedures. Safety mechanisms will be ground checked prior to shipment of experiment payload from the manufacturer's facility.
17. Contingency equipment and procedures shall be available for extravehicular inspection and securing or emergency operation of a system that jeopardizes safe Shuttle earth return.	17. No special equipment is anticipated for the experiment. EVA capability and standard tools are presently considered adequate as contingency support.
18. Experiment payload and payload support equipment leakage sources shall be minimized by use of all welded construction where practical.	18. All pressure lines, seals and flanges, where possible, are of welded construction. See Layout 19 for example. (See Section 4.1).

Table 4-2. Hazard and Safety Analysis of Propellant Transfer Experiment Conceptual Designs (Continued)

Typical Requirements and Guidelines	Specific Experiment Designs/Operations Interfaces/References
19. Message signals from the experiment payload systems shall be provided at the Shuttle data management system interface. Measurements shall include sequence logic status, valve positions, temperature and pressure measurements, and failure indications.	19. RAU will be used to gather experiment data for transmittal to the Orbiter data management system. Additionally, at the crew station monitor, data will be available to oversee and when required override automatic functions.
20. All experiment module cases shall be electrically bonded to the Shuttle structure to prevent electrostatic charge buildup and electrical shock hazard.	20. Basic electrical overloading and grounding approach will be developed during detail electrical system design. Interface modules and panels shown in Layout 23 would be the focal point of these safety design considerations. (See Section 4.1).
21. Experiment modules utilizing the Shuttle electrical grounding system shall comply with the grounding requirements for the Shuttle.	21. Same as Item 20.
22. Experiment modules utilizing Shuttle electrical power shall comply with overload protection and wiring requirements of the Shuttle.	22. Same as Item 20.
23. Electrical umbilical disconnects between the Orbiter and the experiment shall be separated from hazardous-fluid disconnects, shall be qualified as explosion proof, and shall not have power applied during disconnect.	23. Section 4.2.1 describes umbilical disconnect for ground operations and servicing. All Orbiter to experiment electrical panels will consider these guidelines. Layout 23 provides a preliminary interface design. Preliminary electrical penetration concept is shown in Layout 16, View F-F. (See Section 4.1).
24. Electrical connectors, wiring functions, and all electrical and electronic devices used in the payload and its flight support equipment shall be hermetically sealed or otherwise positively protected against moisture.	24. Basic design of electrical systems will follow guidlines. Ground functional and environmental tests, along with the launch site electrical system tests in the VPF will establish flight readiness. Example of an electrical connector design is shown in View F-F of Layout

Table 4-2. Hazard and Safety Analysis of Propellant Transfer Experiment Conceptual Designs (Continued)

Typical Requirements and Guidelines	Specific Experiment Designs/Operations Interfaces/References
	24. Continued 16. Other typical electrical interfaces are indicated in Layout 23 for the RAU, power and pneumatic modules. (See Section 4.1).
25. Redundant electrical circuits in experiment elements shall not be routed through the same connector.	25. Typical wiring circuit for both the control and instrumentation will prevent total loss of control or data by using redundant connectors as well as redundant circuits. Layout 23 provides a preliminary design of circuit interface modules that will include proper redundancy provisions. (See Section 4.1).

4.3 TYPICAL EXPERIMENT CONCEPTS

The preliminary experiment analyses and definitions as outlined in Section 3.2 were channeled during this task to emphasize typical instrumentation and control procedures. Figure 4-12 is a total system schematic showing the location and identification of all sensors, valving, plumbing and propellant tanks. A listing of the various system control valves, their size and type of operation is presented in Table 4-3.

The individual test procedures and instrumentation needs that have been defined are summarized in Table 4-4. These tests are typical of the family of tests that the experiment hardware can accommodate and are not meant to be a final selection. The three primary experiment areas of: transfer line chilldown; receiver tank pre-chill; and receiver tank fill also provide opportunities to simultaneously investigate many of the secondary experiment goals. In addition specific ancillary experiments as well as the sensor requirements are defined.

4.3.1 TRANSFER LINE CHILLDOWN. The transfer line from the supply tank to the half-scale receiver has been sized to 3.81 cm (1-1/2 inch) diameter. The branch to the quarter-scale receiver has been scaled to a 1.91 cm (3/4 inch) diameter. For a previous preliminary analysis of 7.62 cm (3-inch) line 6 m (20 foot) length required a chilldown time of 15 minutes using vapor at 0.45 Kg/min (1 lb/min). The time will vary directly with the line size (for equal line lengths) and inversely with the flow-

Symbol	Measurement
F	Flow Rate
T	Temperature
P	Pressure
M	Mass
Q	Quality

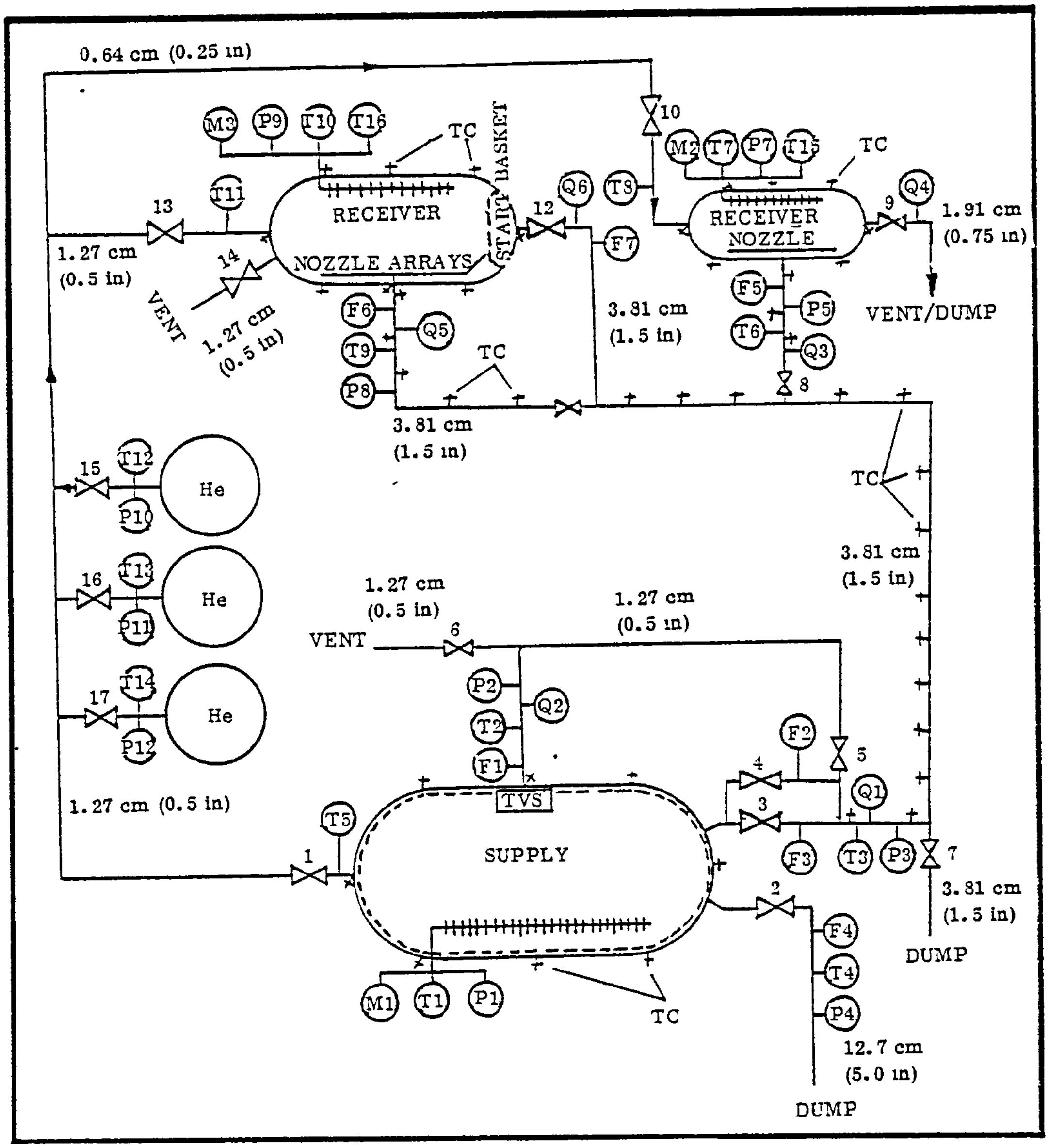


Figure 4-12. Experiment Flow Schematic and Instrumentation Location

Table 4-3. Valves Required for Experiments

Valve	Nominal Size cm	(In.)	Type Action
1	1.27	(1/2)	Open-Close
2	12.7	(5)	Open-Close
3	3.81	(1-1/2)	Open-Close
4	1.27	(1/2)	*Open-Close
5	1.27	(1/2)	*Open-Close
6	1.27	(1/2)	Open-Close
7	3.81	(1-1/2)	Open-Close
8	1.91	(3/4)	**Throttling
9	1.91	(3/4)	Open-Close
10	.64	(1/4)	Open-Close
11	3.81	(1-1/2)	**Throttling
12	3.81	(1-1/2)	Open-Close
13	1.27	(1/2)	Open-Close
14	3.81	(1-1/2)	Open-Close
15	1.27	(1/2)	Open-Close
16	1.27	(1/2)	Open-Close
17	1.27	(1/2)	Open-Close

* Assume control valve on thermodynamic vent system.
** Valve required for each nozzle array (4 per tank). Valves to be open-close action.

Table 4-4. Typical Experiment Concepts

Test Procedures	Section
Transfer Line Chilldown	4.3.1
Receiver Tank Pre-Chill	4.3.2
Receiver Tank Fill	4.3.3
Secondary Experiments	4.3.4
- Start Basket	
- Helium Pressurization	
- Emergency Dump	
- MLI & TVS	
Sensor Identification	4.3.5

rate. Four runs each with vapor and liquid have been planned; however, for the smaller line diameter chosen (3.81 cm and 1.91 cm) more runs are feasible. Reheat power for each run will vary directly with line diameter.

The nozzle used to inject the coolant into the transfer line at the upstream end is sized to deliver 0.45 Kg/min(1 lb/min) of LH_2 at 117 Kn/m^2 (17 psid). Vapor flow rate will be controlled using a valve integral to the TVS. Refer to Figure 4-12 for the flow path during a typical chilldown run through the transfer line to the half-scale receiver using GH_2 from the TVS. All of the chilldown runs will be made through the larger receiver tank line, with the exception of a single run prior to conducting a prechill of the quarter-scale tank. Thus, only this portion of the transfer line which goes to the larger receiver tank need be configured with heaters.

During a vapor run, the flowmeter (F1), bulk flow temperature sensor (T2), pressure transducer (P2), and quality sensor (Q2) will provide data on the state and mass flow rate of the vapor leaving the TVS. Just downstream of valve 5, the vapor will be injected into the transfer line through the nozzle. At that time another quality (Q1), bulk flow temperature (T3), and pressure (P3) check will be made. Thermocouple pairs, 180° apart will be located along the transfer line outer wall to record the wall temperature. They will be equally spaced at 20 locations along the line. At the receiver end of the line, quality (Q5), bulk temperature (T9), and pressure (P8) will again be recorded. The flow will continue into the receiver and out through vent valve 14.

A typical liquid injection run will be made by routing the source LH_2 from the tank, where its initial pressure (P1) and temperature (T1) are known, through a 1.27 cm (1/2 inch) bypass to the injector nozzle. From that point, flow path and instrumentation is the same as for the vapor injection run described above.

Figure 4-13 shows a schematic of the line heater circuit and the required controls and instrumentation. The controller should provide circuit breaker protection overriding the constant voltage demand. Since heater resistance will be fixed by design, wall temperature feedback to the controller should be employed to protect against inadvertent overheating of the system. All sensor requirements for this experiment are summarized in Section 4.3.5.

4.3.2 RECEIVER TANK PRE-CHILL. Each pre-chill run will consist of a series of cycles, each including an injection, a soak, and a vent period. Refer to Figure 4-12 for the typical flow path for an injection into the large receiver tank. Following a suitable soak period the tank contents will be vented by opening valve 14. During the injection function, liquid will leave the supply tank through the main transfer line and will be immediately monitored to determine flow rate (F3), bulk temperature (T3), quality (Q1), and pressure (P8). Near each receiver inlet, flow rate (F5, F6), bulk temperature (T6, T9), quality (Q3, Q5), and pressure (P5, P8) can again be monitored if desired. (The redundancy here is available due to requirements for other experiments.) The liquid will be injected through the selected nozzle array (1 of 3 provided). A schematic showing the piping for the half-scale receiver nozzles is included in Figure 4-14.

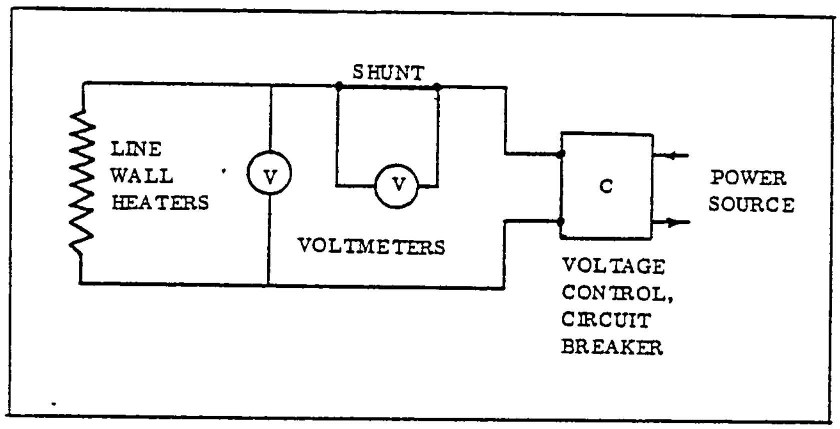


Figure 4-13. Suggested Circuit Schematic for Transfer Line Wall Heaters

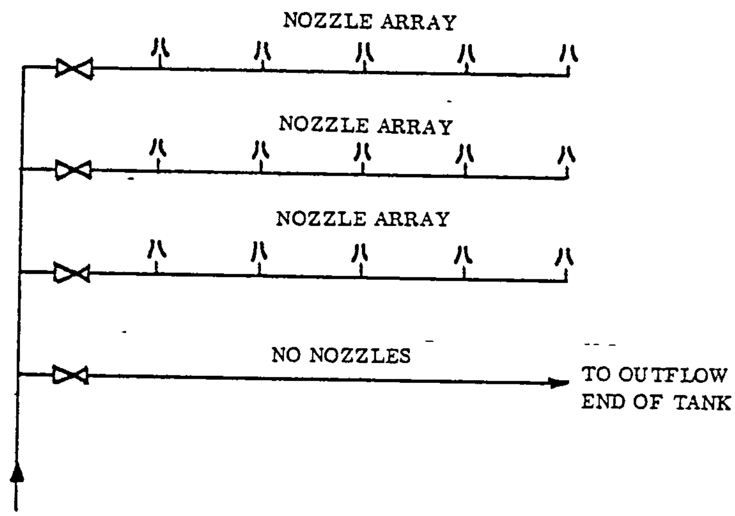


Figure 4-14. Typical Nozzle Schematic for Receiver Tank Pre-Chill and Fill Experiments

This is typical of both receiver tanks. During the entire pre-chill process, the receiver tank wall temperature will be monitored using wall-mounted thermocouples. Twelve thermocouples will be mounted on the cylindrical portion of each receiver tank in sets of four at the middle and each end. The thermocouple in the set will be spaced at 90° intervals. At the ends of each tank single thermocouples are located.

The fluid condition inside each receiver tank will be monitored using bulk temperature sensors (T7, T10) and pressure transducers (P7, P9). Each receiver tank will contain 12 temperature sensors for the range 28-290K (50-520R) and 12 sensors for the range 14-28K (25-50R), mounted on an instrument "tree." Each tree will also contain three pressure transducers. All sensor requirements are summarized in Section 4.3.5.

Following each pre-chill run, the chilled receiver tank will be reheated to the ambient condition, approximately 290K (520R). A schematic of the tank wall heater circuit is shown in Figure 4-15. The same controller and instrumentation which will be used for the transfer line heaters can be used for the receiver tank heaters.

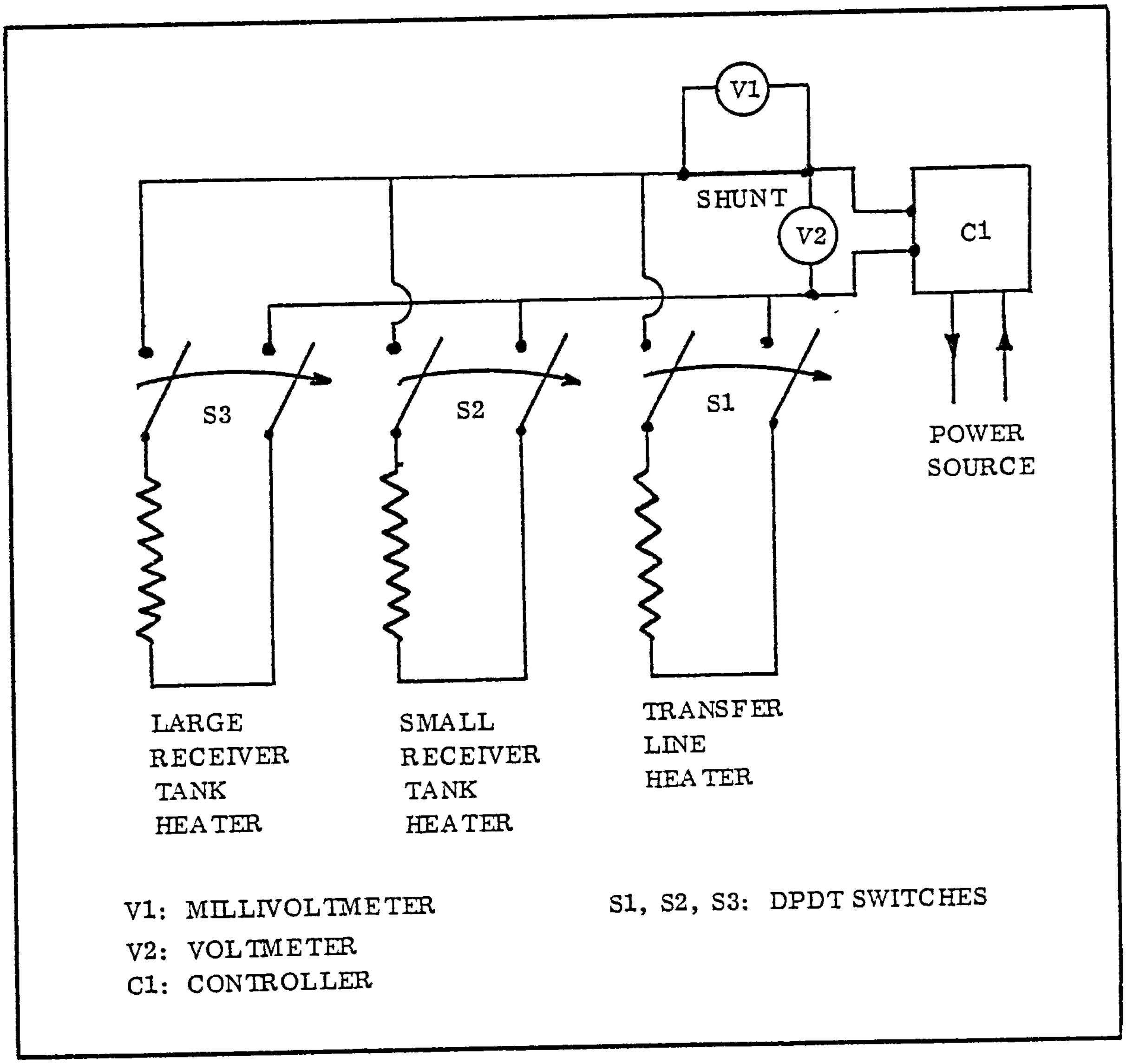


Figure 4-15. Suggested Circuit for Experiment Heaters

4.3.3 RECEIVER TANK FILL. This experiment will contain several flow scenarios: fill of large and small receivers, return of large receiver contents to supply on some of the runs, dump of large and small receiver contents following a fill. During a typical filling run on the small receiver, helium will be used as necessary to bring the supply tank to a proper tanking pressure. LH_2 outflow will then be initiated.

At the supply tank exit, the outflow rate (F3) will be measured and the state of the liquid recorded (Q1, T3, P3). At the receiver entrance, the state will again be determined (Q3, T6, P5) and the flow rate recorded with (F5). The flow will enter one of the selected nozzle arrays and then be injected along the tank wall. Mass content (M2), pressure (P7), and temperature (T7, T15) will be recorded at various positions on an instrument tree in the tank. Twelve temperature sensors (T7) will have an extended range and modest accuracy to determine the state of tank contents. Twelve more sensors (T15) will be employed to get better accuracy in the limited range of liquid temperatures. The wall-mounted thermocouples will provide data on the wall temperature drop from the pre-chill value during fill.

Following the fill run on the small receiver, the contents will be dumped by opening valve 9. The quality (Q4) will be monitored during this operation to determine when liquid flow stops. To facilitate dumping, some helium pressurant may be used. It will be necessary during dump operations to provide thrust for settling. This is to avoid formation of solid H_2 at 6.89 Kn/m^2 (1 psia). The RCS propellant requirement will be approximately 50 Kg to dump all the small receiver runs and all the large receiver runs that are not returned to the supply tank.

Fill of the large receiver is accomplished in a similar fashion. The instrumentation requirements are the same as for the fill of the small receiver. Throughout the fill experiment the contents of the supply tank will be monitored with a mass gauging device (M1), temperature sensors (T1), and pressure transducers (P1). Helium temperature will be taken at the supply inlet (T5).

During a transfer back to the supply tank following a fill run of the large recceiver, the receiver tank pressure is increased above supply tank pressure with helium. Pressurant temperature at the tank inlet will be recorded using sensor T11. At the outlet, the quality (Q6) and flow rate (F7) will be measured. At the supply tank inlet, the quality (Q1) and state (P3, T3) is checked. Within the supply tank, the instrumentation on the tree will provide information on the filling progress. When it is determined that liquid is no longer flowing (using Q6, M3, and M1), the valve 12 will be closed and the remaining contents vented through valve 14. Of course, throughout the transfer process settling thrust will be employed.

In those circumstances where a transfer back to the supply tank is not chosen, the large receiver contents must be dumped. Some of the transfer line will be used for this function. Outflow will be monitored at the receiver exit (Q6, F7). Procedures identical to the dump function for the small receiver will be employed, utilizing thrust settling and helium pressurant as needed.

Between fill runs, the receiver in use will be vented and heated to the pre-chill temperature.

4.3.4 SECONDARY EXPERIMENTS.

Start Basket

During a dump operation from the large receiver tank, a performance test of the receiver start basket can be made. The procedure outlined in Section 3.2 will be used. The instrumentation in the large receiver outflow line (Q6, F7) will be used to assess the nature of the outflow.

Helium Pressurization System

The condition of the helium pressurant will be monitored using the temperature (T12, T13, T14) and pressure (P10, P11, P12) sensors in the bottle outflow lines. No other special instrumentation is planned.

Emergency Dump Line

The rate at which supply tank contents can be dumped is potentially useful information. The LH_2 remaining in the supply tank following all other tests will be dumped out the 12.7-cm (5-inch) abort dump line while a flowmeter (F4), bulk temperature sensor (T4), and pressure transducer (P4) record the nature of the flow. During this test, settling thrust should be employed and pressure kept as high as possible with helium pressurant. Following the dump test, the supply tank should be purged with helium, while continuing to vent out the dump line.

Supply Tank Screen Acquisition Device

During the emergency dump test, the capability of the supply tank screen acquisition device will be assessed. Performance can be monitored during offloading of the last 5 percent of fuel using the mass gauge (M1).

MLI and TVS

Prior to the primary emphasis experiments discussed above, supply tank MLI and thermodynamic vent system (TVS) or zero-g vent system performance can be evaluated. MLI performance can be assessed from data taken using sensors P1, T1 and the thermocouples on the outer wall. Data on performance of the TVS can be obtained from basic instrumentation on the vent package and using sensors F1, T2, P2 and Q2. During periods of operation of the vent mixer only (no venting), mixer performance (ability to maintain equilibrium of tank contents) data can be gathered using vent package instruments and the supply tank sensors (P1 and T1).

Receiver tank pressures and temperatures (P7, P9, T10, T16, T7, T15) after each filling operation will be useful in evaluating the performance of the MLI on those tanks.

4.3.5 SENSOR IDENTIFICATION. The sensor indicators in Figure 4-12 have been defined with respect to requirements. Table 4-5 and Table 4-6 presents a summary of these requirements in English units and SI units, respectively.

Table 4-5. Summary of Sensor Requirements
(English Units)

Meter or Sensor	Type	Fluid Environment	Quantity	Location	Range	Accuracy
F1	Flowmeter	GH_2 @ 38 R	1	TVS outflow line	0-0.1 lb/sec	±0.0001 lb/sec
F2	Flowmeter	LH_2 @ 38 R	1	Supply outflow bypass line	0.03 lb/sec	±0.0001 lb/sec
F3	Flowmeter	LH_2 @ 38 R	1	Supply outflow line	0-15 lb/sec	±0.2 lb/sec
F4	Flowmeter	DELETED: NOT SHOWN				
F5	Flowmeter	LH_2 @ 38 R	1	Large receiver transfer line	0-15 lb/sec	±0.2 lb/sec
F6	Flowmeter	LH_2 @ 38 R	1	Small receier transfer line	0-5 lb/sec	±0.05 lb/sec
F7	Flowmeter	LH_2 @ 38 R	1	Large receiver outflow line	0-20 lb/sec	±0.5 lb/sec
M1	Mass gauge	LH_2, GH_2 @ 38 R	1	Within supply tank	0-11,500 lb	±115 lb
M2	Mass gauge	LH_2, GH_2 @ 38 R	1	Within small receiver	0-280 lb	±3 lb
M3	Mass gauge	LH_2, GH_2 @ 38 R	1	Within large receiver	0-2250 lb	±20 lb
P1	Pressure transducer	LH_2, GH_2 @ 38 R	2	Instr. tree, supply tank	0-30 psia	±0.001 psid
P2	Pressure transducer	GH_2 @ 38 R	1	TVS outflow line	0-20 psia	±0.1 psid

Meter or Sensor	Type	Fluid Environment	Quantity	Location	Range	Accuracy
P3	Pressure transducer	LH_2, GH_2 @ 38-520 R	1	Supply outflow line	0-100 psia	±0.1 psid
P4	Pressure transducer	LH_2 @ 38 R	1	Supply dump line	0-25 psia	±0.1 psid
P5	Pressure transducer	LH_2, GH_2 @38 R	1	Small receiver transfer line	0-100 psia	0.1 psid
P6	Pressure transducer	DELETED: NOT SHOWN				
P7	Pressure transducer	LH_2, GH_2 @ 38-520 R	3	Small receiver instr. tree	0-75 psia	±0.001 psid
P8	Pressure transducer	LH_2, GH_2 @ 38-520 R	1	Large receiver transfer line	0-100 psia	±0.1 psid
P9	Pressure transducer	LH_2, GH_2 @ 38-520 R	3	Large receiver instr. tree	0-30 psia	±0.001 psid
P10 P11 P12	Pressure transducer	GHe @ 520 R	3	Helium bottle outflow lines	200-4500 psia	±25 psid
	Pressure transducer	GHe @ 520 R	3	Inside Supply tank MLI	0-5 psia	±0.1 psia
	Pressure transducer	GHe @ 520 R	3	Inside Supply tank MLI	10^{-6}-10^{-3} torr	± 2×10^{-6} torr
Q1	Quality sensor	Saturated H_2	1	Supply outflow line	*	*
Q2	Quality sensor	Saturated H_2	1	TVS outflow line	*	*
Q3	Quality sensor	Saturated H_2	1	Small receiver transfer line	*	*
Q4	Quality sensor	Saturated H_2	1	Small receiver dump line	*	*

Meter or Sensor	Type	Fluid Environment	Quantity	Location	Range	Accuracy
Q5	Quality sensor	Saturated H_2	1	Large receiver transfer line	*	*
Q6	Quality sensor	Saturated H_2	1	Large receiver outflow line	*	*
T1	Bulk temp sensor	LH_2, GH_2	12	Supply tank instr. tree	25-45 R	±0.02 R
T2	Bulk flow temp. sensor	GH_2	1	TVS outflow line	25-60 R	±0.1 R
T3	Bulk flow temp. sensor	LH_2 or GH_2	1	Supply outflow line	25- 520 R	±0.5 R
T4	Bulk flow temp. sensor	LH_2	1	Emergency dump line	25-60 R	±0.1 R
T5	DELETED: NOT SHOWN					
T6	Bulk flow temp. sensor	GH_2 or LH_2	1	Small receiver transfer line	25-520 R	±0.5 R
T7	Bulk temp. sensor	GH_2 or LH_2	12	Small receiver instr. tree	25-520 R	±0.5 R
T8	Bulk flow temp. sensor	GHe	1	Small receiver pressurant line	300-520 R	±0.5 R
T9	Bulk flow temp. sensor	GH_2 or LH_2	1	Large receiver transfer line	25-520 R	×0.5 R
T10	Bulk temp. sensor	GH_2 or LH_2	12	Large receiver instr. tree	25-520 R	±0.5 R
T11	Bulk flow temp. sensor	GHe	1	Large receiver pressurant line	300-520°R	±0.5 R

Meter or Sensor	Type	Fluid Environment	Quantity	Location	Range	Accuracy
T12 T13 T14	Bulk flow temp. sensor	GHe	3	Helium bottle outflow lines	300-520 R	±0.5 R
T15	Bulk temp. sensor	GH_2, LH_2	12	Small receiver instr. tree	25-60 R	±0.02 R
T16	Bulk temp. sensor	GH_2, LH_2	12	Large receiver instr. tree	25-60°R	±0.02 R
	Temp. sensor Thermocouple	Vacuum,GHe	14	Supply tank outer wall	25-60 R	±0.1 R
	"	Vacuum, GHe	14	Inside outer radiation shield, supply tank	400-600 R	±0.2 R
	"	Vacuum, GHe	4 ea penetration	Outer wall of penetration	36-520 R	±0.5 R
	"	Vacuum	40-60	Outer wall of transfer line	25-520 R	±0.5 R
	"	Vacuum	14	Outer wall of small receiver	25-520 R	±0.5 R
	"	Vacuum	14	Outer wall of large receiver	25-520 R	±0.5 R

*Sensor must detect liquid in gas flow, or gas in liquid flow. Gas flow rates as high as 0.03 lb/sec. Liquid flow rates as high as 20 lb/sec. On volume basis, range 0-100% gas ±2% accuracy.

Table 4-6. Summary of Sensor Requirements
(SI Units)

Meter or Sensor	Type	Environment	Quantity	Location	Range	Accuracy
F1	Flowmeter	GH_2 @ 21 K	1	TVS outflow line	0-0.05 Kg/sec	± 0.00006 Kg/sec
F2	Flowmeter	LH_2 @ 21 K	1	Supply outflow bypass	0-0.01 Kg/sec	± 0.00005 Kg/sec
F3	Flowmeter	LH_2 @ 21 K	1	Supply outflow line	0 - 7 Kg/sec	± 0.1 Kg/sec
F4	Flowmeter	DELETED: NOT SHOWN				
F5	Flowmeter	LH_2 @ 21 K	1	Large receiver transfer line	0 - 7 Kg/sec	± 0.1 Kg/sec
F6	Flowmeter	LH_2 @ 21 K	1	Small receiver transfer line	0 - 2 Kg/sec	± 0.02 Kg/sec
F7	Flowmeter	LH_2 @ 21 K	1	Large receiver outflow line	0 - 10 Kg/sec	± 0
M1	Mass gauge	LH_2, GH_2 @ 21 K	1	Within supply tank	0-5500 Kg	± 55 Kg
M2	Mass gauge	LH_2, GH_2 @ 21 K	1	Within small receiver	0-125 Kg	± 1.5 Kg
M3	Mass gauge	LH_2, GH_2 @ 21 K	1	Within large receiver	0-1000 Kg	± 10 Kg
P1	Pressure Transducer	LH_2, GH_2 @ 21 K	2	Instr. tree, supply tank	0- 207 Kn/m^2	± 0.007 Kn/m^2
P2	Pressure transducer	GH_2 @ 21 K	1	TVS outflow line	0 - 138 Kn/m^2	± 0.7 Kn/m^2
P3	Pressure transducer	LH_2, GH_2 @ 20 - 290 K	1	Supply outflow line	0 - 690 Kn/m^2	± 0.7 Kn/m^2
P4	Pressure transducer	LH_2 @ 20 K	1	Supply dump line	0 -172 Kn/m^2	± 0.7 Kn/m^2

Meter or Sensor	Type	Environment	Quantity	Location	Range	Accuracy
P5	Pressure transducer	LH_2, GH_2 @ 20 K	1	Small receiver transfer line	0 - 690 Kn/m^2	± 0.7 Kn/m^2
P6	Pressure transducer	DELETED: NOT SHOWN				
P7	Pressure transducer	LH_2, GH_2 @ 20 - 290 K	3	Small receiver instr. tree	0 - 517 Kn/m^2	± 0.007 Kn/m^2
P8	Pressure transducer	LH_2, GH_2 @ 20 - 290 K	1	Large receiver transfer line	0 - 690 Kn/m^2	± 0.7 Kn/m^2
P9	Pressure transducer	LH_2, GH_2 @ 20 - 290 K	3	Large receiver instr. tree	0 - 207 Kn/m^2	± 0.007 Kn/m^2
P10 P11 P12	Pressure transducer	GHe @ 290 K	3	Helium bottle outflow lines	1397-31433 Kn/m^2	± 175 Kn/m^2
	Pressure transducer	GHe @ 290 K	3	Inside Supply Tank MLI	0 - 35 Kn/m^2	± 0.7 Kn/m^2
	Pressure transducer	GHe @ 290 K	3	Inside Supply Tank MLI	10^{-7} 10^{-4} KN/m^2	± 2 x 10^{-7} KN/m^2
Q1	Quality sensor	Saturated H_2	1	Supply outflow line	*	*
Q2	Quality sensor	Saturated H_2	1	TVS outflow line	*	*
Q3	Quality sensor	Saturated H_2	1	Small receiver transfer line	*	*
Q4	Quality sensor	Saturated H_2	1	Small receiver dump line	*	*

Meter or Sensor	Type	Environment	Quantity	Location	Range	Accuracy
Q5	Quality sensor	Saturated H_2	1	Large receiver transfer line	*	*
Q6	Quality sensor	Saturated H_2	1	Large receiver outflow line	*	*
T1	Bulk temp sensor	LH_2, GH_2	12	Supply tank instr. tree	14 - 25 K	$\pm$.01 K
T2	Bulk flow temp. sensor	GH_2	1	TVS outflow line	14 - 35 K	$\pm$.05 K
T3	Bulk flow temp. sensor	LH_2 or GH_2	1	Supply outflow line	14 - 290 K	$\pm$.25 K
T4	Bulk flow temp. sensor	LH_2	1	Emergency dump line	14 - 35 K	$\pm$.05 K
T5	DELETED: NOT SHOWN					
T6	Bulk flow temp. sensor	GH_2 or LH_2	1	Small receiver transfer line	14 - 290 K	$\pm$.25 K
T7	Bulk temp. sensor	GH_2 or LH_2	12	Small receiver instr. tree	14 - 290 K	$\pm$.25 K
T8	Bulk flow temp. sensor	GHe	1	Small receiver pressurant line	150-290 K	$\pm$.25 K
T9	Bulk flow temp. sensor	GH_2 or LH_2	1	Large Receiver transfer line	14-290 K	$\pm$.25 K
T10	Bulk temp. sensor	GH_2 or LH_2	12	Large receiver instr. tree	14-290 K	$\pm$.25 K
T11	Bulk flow temp. sensor	GHe	1	Large receiver pressurant line	150-290 K	$\pm$.25 K

Meter or Sensor	Type	Environment	Quantity	Location	Range	Accuracy
T12 T13 T14	bulk flow temp. sensor	GHe	3	Helium bottle outflow lines	150-290 K	± .25 K
T15	Bulk temp. sensor	GH_2, LH_2	12	Small receiver instr. tree	14-35 K	± .01 K
T16	Bulk temp.	GH_2, LH_2	12	Large receiver instr. tree	14-35 K	± .01 K
	Temp. sensor Thermocouple	Vaccum, GHe	14	Supply tank outer wall	14-35 K	± .050 K
	"	Vacuum, GHe	14	Inside outer radiation shield, supply tank	200-350 K	± 0.1 K
	"	Vacuum, GHe	4 ea	Outer wall of penetration	20-290 K	± .25 K
	"	Vacuum	40-60	Outer wall of transfer line	14-290 K	± .25 K
	"	Vacuum	14	Outer wall of small receiver	14-290 K	± .25 K
	"	Vacuum	14	Outer wall of large receiver	14-290 K	± .25 K

* Sensor must detect liquid in gas flow, or gas in liquid flow. Gas flow rates as high as 0.015 Kg/sec. Liquid flow rates as high as 10 Kg/sec. On volume basis, range 0-100% gas ± 2% accuracy.

5

EXPERIMENT DEVELOPMENT PLAN (TASK IV)

This section summarizes the study effort directed toward the two principal subtasks of Task IV, 1) the preliminary definition of program development plans and schedules, and 2) a preliminary cost estimate of the flight experiment. The objective of the first subtask is to outline program planning requirements and to produce a program master schedule suitable for advanced planning applications. The objectives of the second subtask are to conduct a cost assessment of the selected final experiment configuration and provide a cost estimate, again usable for planning purposes. The results of these two efforts are discussed below.

5.1 PROGRAM PLANS AND SCHEDULES

A preliminary program development master schedule has been prepared based on the flight experiment definition from Task III and the programmatic groundrules and assumptions discussed below. The project schedule is summarized in Figure 5-1 and the detailed master schedule is shown in Figure 5-2.

5.1.1 APPROACH. The approach used to develop this schedule is first to establish the overall program milestones. All major functional task areas were then identified together with the necessary sequence of major activities and events. These were to include the complete sequence of functions and tasks required for each of the principal phases: experiment development and test, flight article fabrication, and operational flight. Once these major milestones and tasks were identified, detailed program milestones, task durations and other pertinent data were laid out in the master program schedule. The key activities of each functional task area discipline identified show time phased relationship to each other and to the external program milestones such as Shuttle activities. Thus, the interfaces and relationships between these activities and the program milestones were identified. This program master schedule therefore serves as a focal point for displaying and evaluating of interface constraints and time critical elements.

5.1.2 GROUNDRULES AND ASSUMPTIONS. The following groundrules and assumptions were used during the development of the program master schedule:

1) The initial experiment flight would occur in mid-CY 1985.

2) A Phase B Definition Study would precede the Phase C/D.

3) All system level development and qualification testing is conducted using the flight article which is refurbished prior to the flight (no complete system level prototype, engineering test model, qualification article or backup flight article is procured).

4) One dedicated set of tanks is required for ground testing during the tank development phase.

5) All purchased components are assumed close to or aerospace flight qualified and only minor modification and/or testing is required. New fabricated or procured components require normal design, analysis, and qualifications to meet the STS payload requirements.

5.1.3 PROGRAM MILESTONES. The summary Propellant Management Technology (PMT) Experiment Schedule for development, manufacturing, and ground and flight test is shown in Figure 5-1. The overall Phase C/D Design and Development schedule provides for a 36-month development program from Authority to Proceed (ATP) in mid-CY 1982, to the initial flight of the experiment (mid-CY 1985). A three-year period was selected as reasonably representative for an experiment such as this. A Phase C/D for a complex vehicle such as an upper stage typically extends for about four years. This experiment might be comparable to a single subsystem of an OTV and therefore the necessary sequential integration and testing would not be nearly as demanding timewise as a full vehicle program.

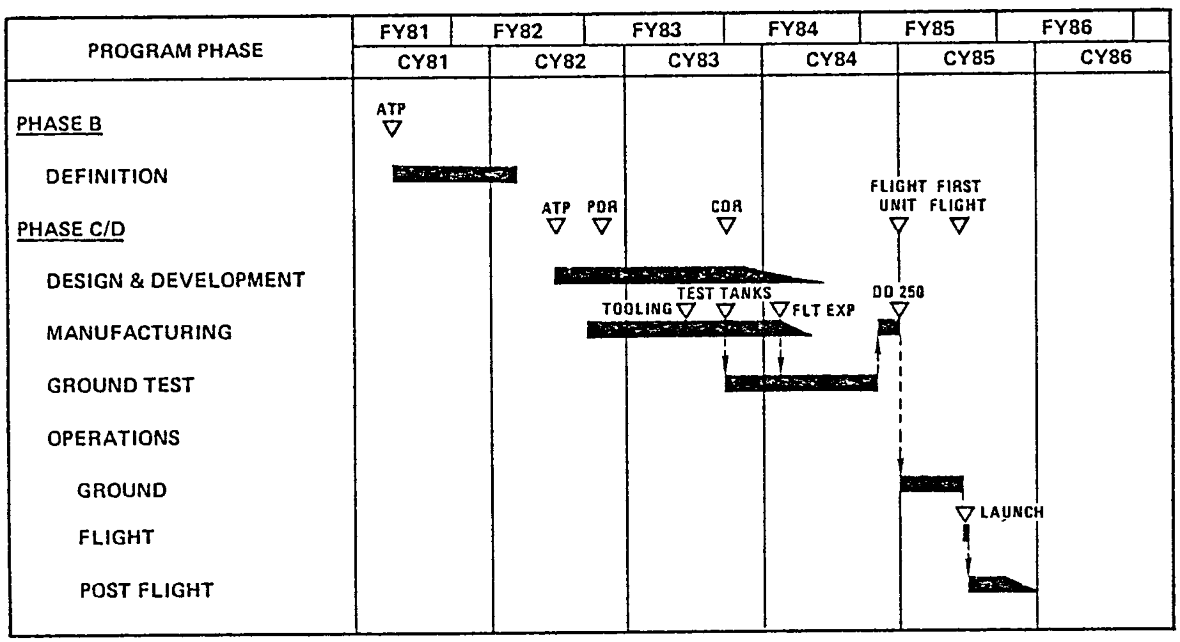


Figure 5-1. PMT Schedule Summary

This Phase C/D program is preceded by a Phase B Definition Study starting in the first quarter of CY 81 (mid-FY 81). This Phase B study will provide refinement of selected concept and tradeoffs and evaluation of any alternatives, system design data including preliminary systems specifications, a complete set of implementation plans including manufacturing, procurement, test, reliability and safety, quality assurance, configuration management, contract, data, operations, etc. Also produced will be detailed schedule and resource estimates (funds, manpower, facilities). The principal output from these activities are validated requirements, a design solution and supporting analyses, and a preliminary estimate of resource requirements. The Phase B effort thereby provides a firm foundation for efficiently proceeding with the subsequent C/D phase of activities.

Phase C/D is initiated (ATP) in mid-CY 1982 with the preliminary design review (PDR) in 3 months, and the Critical Design Review (CDR) following 9 months later. The tank test articles are available for testing by the 4th quarter CY 83 and the flight experiment is ready for testing early in CY 84. The ground testing phase is completed in late CY 84 and the experiment is then refurbished, checked out and available for shipment for the ground operating and integration phase by the start of CY 85. A six month flight preparation period is provided prior to the mid-CY 85 launch date. (Not all of this preparation period will necessarily be spent at KSC because of the desire to minimize STS payload on-site time spans.) A nominal post-flight period is allowed for experiment disposition or refurbishment and modification for potential reflights and for data retrieval and analysis.

This overall PMT experiment schedule was discussed and reviewed with team members of the ongoing Orbital Transfer Vehicle (OTV) Study (NAS8-33533) and it was determined to be compatible with the development program envisioned for the OTV evolutionary scenario.

5.1.4 PHASE C/D MASTER SCHEDULE. Figure 5-2 presents the PMT experiment baseline master schedule which identifies major functional Phase C/D tasks and activities, period of performance, and major milestones. The major activities at program initiation ATP are the requirements identification and definition (Systems Engineering and Integration), predesign activities (Design and Analysis) and finalizing of all Contractor End Item (CEI) specifications and program plans. The initial milestone in the review process is the Program Requirements Review (PRR) held two months after ATP. The predesign activities and specification finalization culminate in a Preliminary Design Review (PDR) 3 months after ATP. At the PDR the final requirements and the final hardware configuration are established.

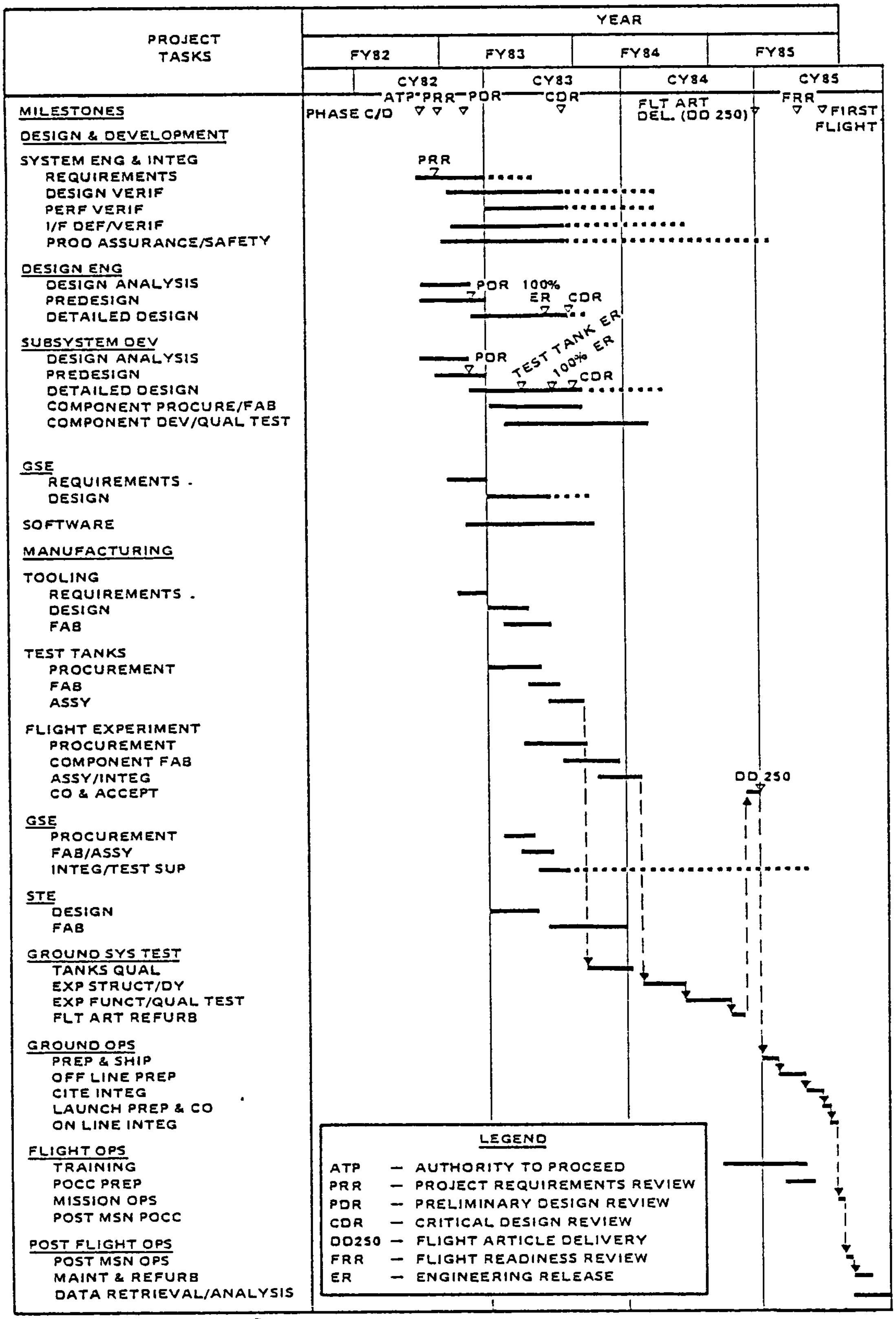


Figure 5-2. Propellant Management Technology Experiment - Master Schedule

Following the PDR the detailed design and drawing preparation process proceeds. Concurrent and coordinated with detailed design the design verification, performance verification and interface definition and verification activities and analyses are conducted. Similarly the plans for product assurance are implemented including safety, reliability and quality assurance, and parts materials and processes (PMP) analyses. During this detailed design period subsystem development activities (as well as GSE) proceed with the fabrication, or procurement of components hardware for development on qualification testing. It is during this period that tank tooling is designed and fabricated and the ground test tank articles are fabricated. These test articles are then used for the required structural and thermodynamic demonstration tests and qualification tests as necessary. Most of the required software tasks are also completed during this period.

These activities then culminate in a CDR wherein design adequacy is determined through formal comparison of the requirements to the experiment design and all analysis and supporting data is reviewed. Following the CDR, supporting system engineering and design and analysis are provided as required. The procurement and fabrication of components for the flight experiment itself are initiated following engineering release and the flight article experiment hardware is available for ground testing early in CY 84, 20 months after ATP. The required structural, dynamic, and experiment functional integration testing is then conducted using this flight article. System Test Equipment (STE) is provided to support these tests, which includes test facility setup, etc. Upon completion of this testing, the flight article is maintained and refurbished to flight configuration and undergoes final checkout and acceptance testing prior to sell-off (DD250) to NASA. This flight article is then available for flight preparation 30 months after ATP.

The ground operations and integration period activities include the preparation and shipment of the flight experiment to KSC, receiving and inspection, and off-line payload preparation. The experiment is then installed in the Cargo Integrating Test Equipment (CITE) which simulates the Shuttle Orbiter payload bay and all of its interfaces. Integration testing in this facility verifies and validates the payload as meeting all of the payload/orbiter interface requirements. The flight experiment may then proceed to the on-line integration where the payload is installed and checked out in the Orbiter's payload bay. Flight support functions such as training and Payload Operations Control Center (POCC) preparation, mission, and postmission activities are properly phased to support the nominal seven-day orbital operations.

Following landing post-mission operations,activities include payload removal from the Orbiter and payload disposition. In the case of potential reflights of this experiment, this period would be reserved for maintenance, refurbishment, modification and checkout. A nominal period is also allowed for data retrieval and analysis.

5.2 EXPERIMENT COST ESTIMATE

A cost analysis of the PMTE has been conducted and the results are presented herein. This section includes the WBS, the cost analysis methodology and ground rules, program definition and assumptions, and the program cost estimates themselves, including annual funding requirements.

These data represent preliminary top level estimates that can only reflect the program definition work performed to date and, therefore, cannot be considered complete or final. They do, however, represent a reasonable estimate based on information available at this time and are useful for planning purposes.

5.2.1 WORK BREAKDOWN STRUCTURE. The Work Breakdown Structure (WBS) is a comprehensive breakdown of all total program life cycle elements categorized or sorted into several levels of hardware and task or function-oriented end items. The resulting format is displayed for each major program phase, including project development, flight article production, and operational test flights. The WBS serves as the basic format for all cost reporting and programmatic data, and to organize, plan, and manage the subsequent program.

A preliminary WBS for the PMTE project is presented in Figure 5-3. This WBS is based on the final selected experiment concept hardware (Section 4.1) and the program schedule and groundrules defined in Section 5.1 of this report.

The WBS serves to identify all of the cost elements to be included in the cost analysis task. This WBS contains all of the hardware and tasks associated with program Phase C/D development and test, the test hardware refurbishment and modification, and fabrication of the flight hardware, and the operations activities incurred during the first flight. It is assumed that the Shuttle user charge includes all Shuttle-related activities such as on-line payload installation mission operations center activities, flight crew costs, and other common ground operations/mission operations and activities. Other Shuttle-related services such as energy kits and other optional services are added to the Shuttle user charge for the basic transportation. Potential user charges for tracking and data acquisition (TDRSS, etc.) are carried as separate program level items.

The nonrecurring development portion of the C/D phase includes the one-time tasks and hardware to design and test the PMTE payload. It includes the required design and analysis for all ground and flight hardware, including structural analysis, stress, dynamics, thermal, mass properties, etc. This phase also includes all software development. This nonrecurring category includes component development and test through

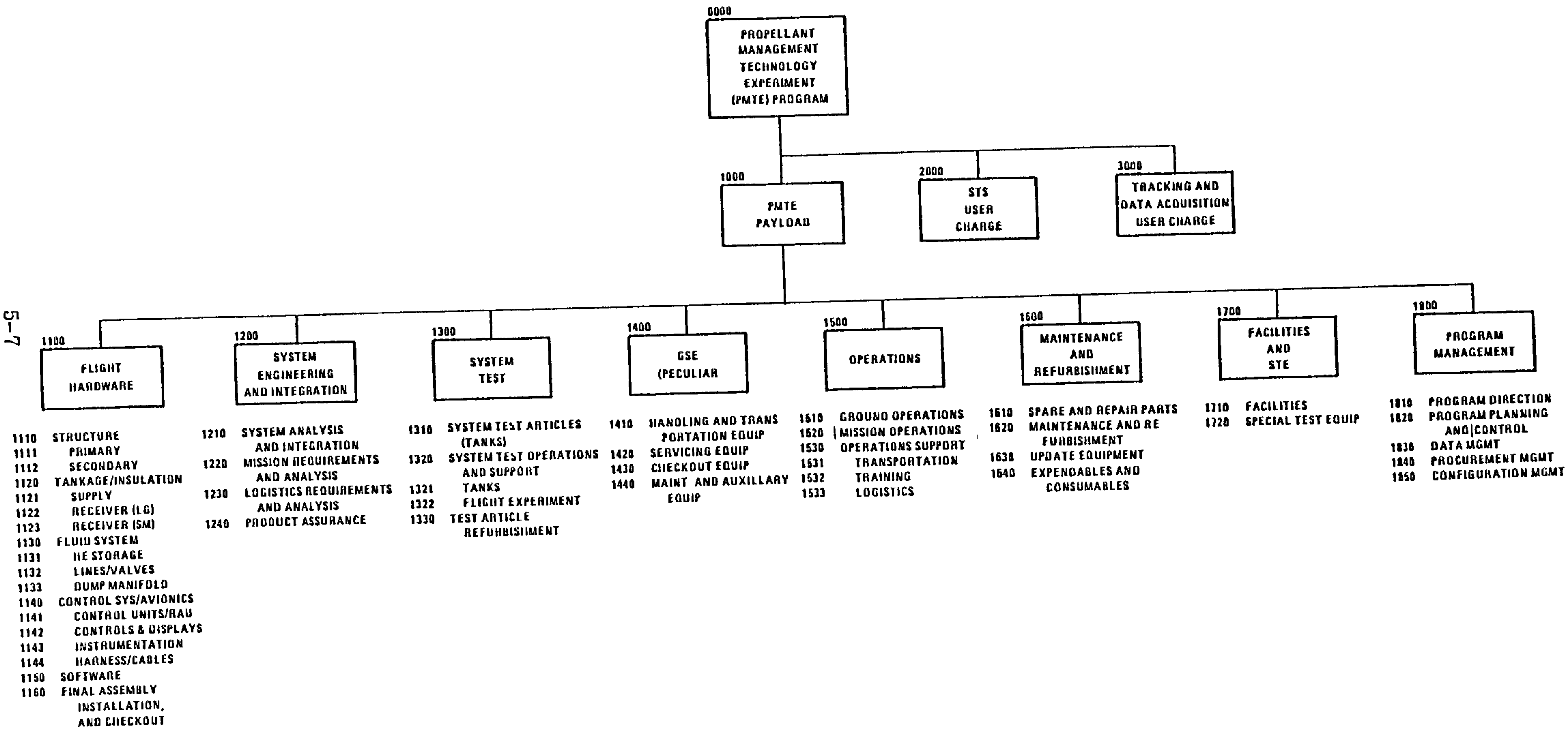


Figure 5-3. PMTE Work Breakdown Structure

component qualification, as well as all component development test hardware. In addition, this phase includes: system engineering and integration; system level test hardware and system test; GSE design, development test, and manufacture; facilities; and lastly, overall program management and administration.

The production portion of the C/D phase (unit cost estimate) includes all tasks and hardware necessary to provide one complete set of flight hardware equipment. It includes all material and component procurement, parts fabrication and hardware refurbishment, subassembly, and final assembly. In addition, this category includes the required quality control/inspection task, an acceptance test procedure for sell-off to the customer, and program management and administration activities accomplished during the manufacturing phase.

The operations phase includes all preparation, launch, and on-orbit operations associated with the PMTE payload. It includes all ground operations, Shuttle system integration (including postmission activities), and the mission operations (ground) activities themselves, including mission control, data handling, support, etc., together with program management and administration during the operations period.

A discussion and definition of the individual cost elements is included as the WBS dictionary in Appendix A.

5.2.2 COST METHODOLOGY. A cost work breakdown structure was developed (Section 5.2.1) that includes all elements, chargeable to the Propellant Management Technology Experiment Project for each of the program phases, i.e., development, production, and operations. This cost WBS sets the format for the estimating model, the individual cost estimating relationships (CERs), cost factors or specific point estimate requirements, and, finally, the cost estimate output itself. Cost estimates are made for each element, either at the WBS breakdown level shown or one level below in certain cases. These estimates are accumulated according to the WBS to provide the required development, flight article production, and first flight operations costs.

The estimating methodology varies with the cost element and with the availability of historical data or vendor quotes. For new non-off-the-shelf hardware, parametric CERs are used. These CERs were developed during past cost analysis activities performed by Convair on space experiment systems and during the Space Transportation Systems Payloads and Data Analysis (SPDA) study (Contract NAS8-29462). These CERs have been derived for various categories of hardware and many subcategories representing differing levels of complexity or technology families. These CERs are derived from available historical cost data or detailed estimating information and relate cost to a specific driving parameter such as weight, area, power output, etc. For example, the various facility structural mechanical items, mechanisms, control systems, etc., were estimated using such CERs. The tankage for this experiment represents a special problem since little or no historical cost experience is available for this type of flight experiment, i.e., a set of equipment that will not be operational in the sense of a launch vehicle stage yet still needs to meet the requirements and criteria necessary to fly in the Shuttle. Figure 5-4 shows a plot of cryogenic tankage cost vs. volume for three levels of technological complexity. These technology families are 1) uninsulated tanks, 2) insulated tanks, and 3) vacuum insulated devices. It should be noted that all data points shown represent operational programs, not an experiment as considered in this study. It may be expected the cost impact of being "an experiment" will be substantial in the development phase cost but not necessarily too significant in the unit cost.

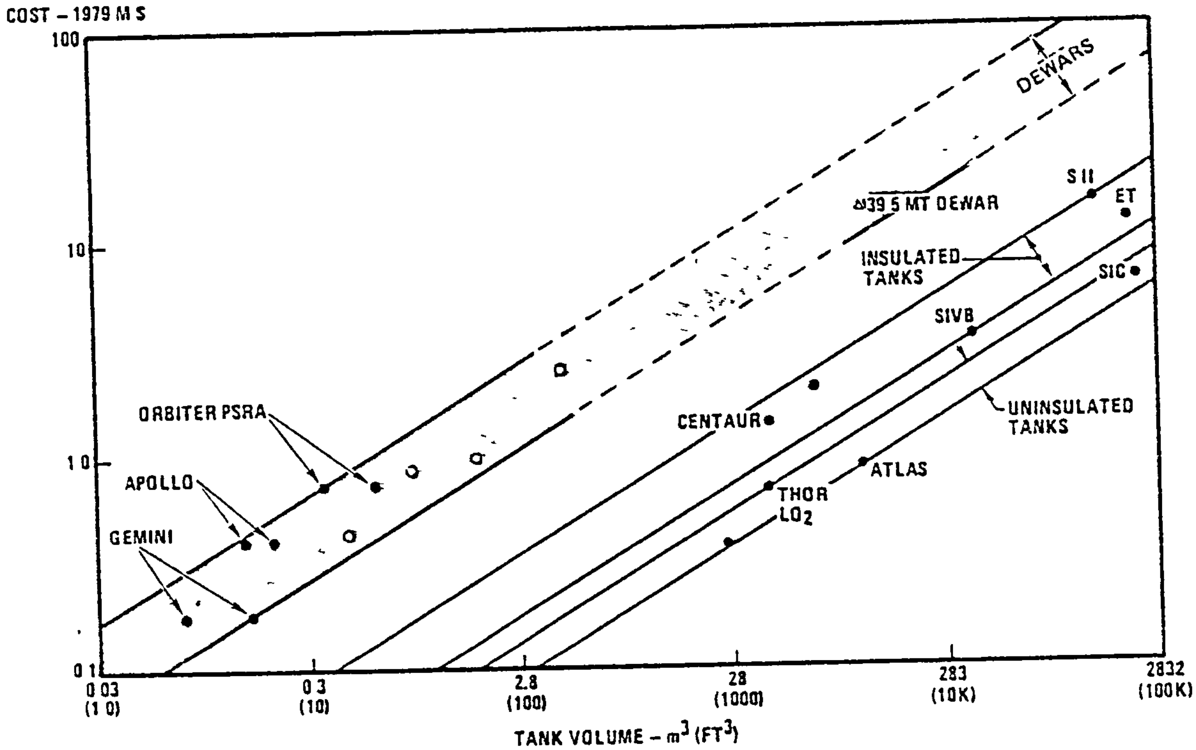


Figure 5-4. Cryogenic Tankage First Unit Cost Relationship

Hardware actual costs are shown with solid dots and estimates with open dots. They include the dewar family, a group of insulated tanks (mostly foam insulation) and a family of uninsulated tanks. Regressions for these three families produced nearly identical slopes. Uncertainty bands at a fixed average slope were then used to bound each family. As may be seen insulated tanks represent a factor of about 2.2 of the cost of uninsulated versions. A deficiency in this data is that the dewar does not overlap that of the other tank and therefore cannot provide a positive confirmation of the average slope used.

Non-recurring or development cost data are shown in Figure 5-5. Less data were readily available than for unit costs and also more difficult to interpret because of the widely varying design requirements and development environments and philosophies. With respect to these development costs historical data suggests that development and qualification costs may run as high as 25 times the Theoretical First Unit (TFU) production cost for users having stringent design requirements, and ranging down to 5 times the TFU for relaxed requirements in the area of weight, reusability, safety factor, etc. In fact, in cases with no weight limitations and very high safety factors, development may be equal to or even less than the unit fabrication costs. This would represent a high degree of qualification by analysis and similarity, and minimum testing. The multiplication 5 x and 25 x development cost lines have been included in the figure for reference.

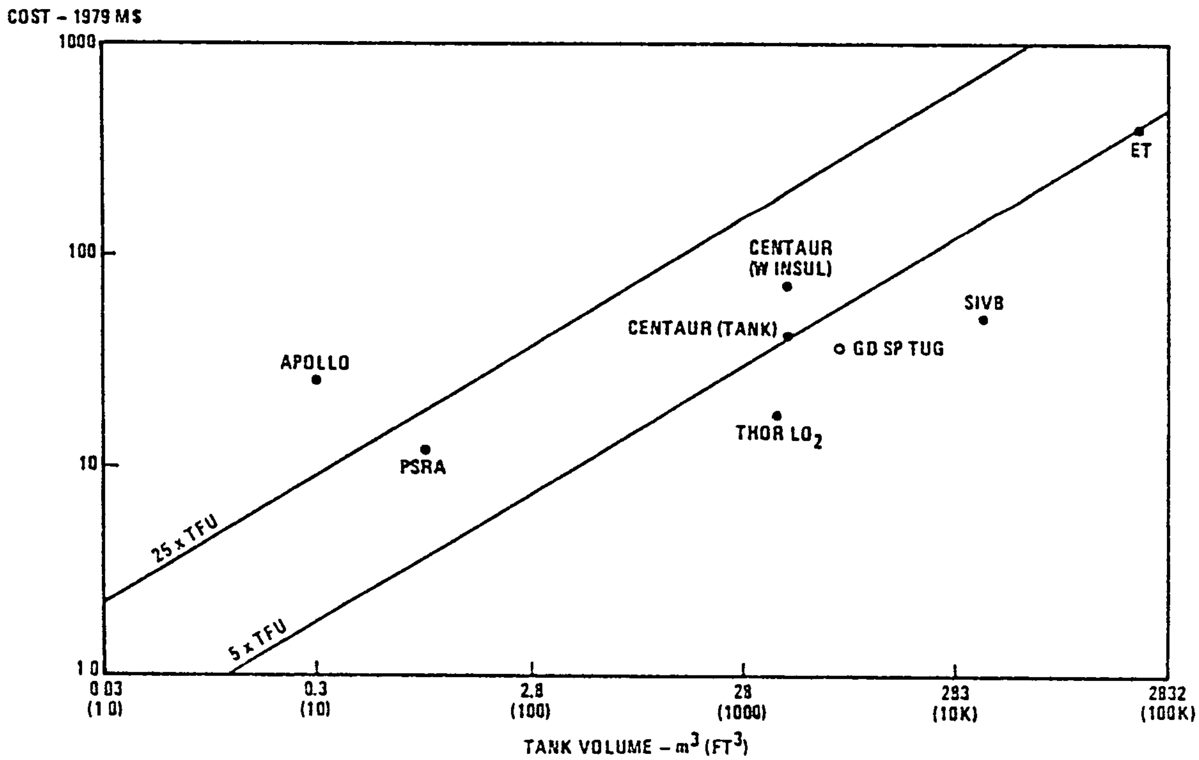


Figure 5-5. Cryogenic Tankage Development Cost Relationship

The conclusion from these data is that both development and unit production costs of these cryogenic tankages will be strongly dependent upon the design requirements imposed. As a result, specific assumptions need be made concerning each individual concept applications. Information obtained since the initial analysis indicates that dewar cost may indeed be less than indicated if design requirements are relaxed from the applications shown. The judgement made at this time is that the tank unit fabrication cost will not vary significantly from that shown for insulated tanks above. Development costs are assumed to be 2.5 times the unit cost for the supply tank and 5 times the unit cost for the receiver tanks. In the case of the receiver tanks the requirements and hence the design are quite close to flight weight tankage so as to obtain proper scaling of the resulting experiment data.

Point estimates were also used for specific pieces of equipment where the definition data was sufficiently detailed or the hardware item was existing equipment and cost data was available. In another example of point estimates, several task areas in ground and mission operations consist of all labor and, therefore, manloading estimates were made and converted to cost.

The remaining "floating item" cost elements such as system engineering and integration, program management, etc., are estimated using simple cost factors consisting of appropriate percentages of the applicable related program effort.

Ground Rules and Assumptions

The following general ground rules and assumptions were used in estimating the costs presented herein.

a. Costs are estimated in current/constant FY 1980 dollars.

b. No prime contractor fee is included in these estimates.

c. Costs are estimated for nonrecurring, recurring production, and recurring operation phases. The costs include all facility payload-related costs incurred from the start of Phase C/D (development phase) through a single (first) launch of the experiment including orbital monitoring and data acquisition.

d. All system level development and qualification testing is conducted using the flight article which is refurbished prior to flight.

e. One dedicated set of test tankage is required for ground test during tank development tests.

f. Most purchased components are assumed off-the-shelf and close to or aerospace flight qualified with only minor modifications or testing required. New components require normal design, analysis testing and qualification.

g. No new facilities will be required chargeable to PMTE payload.

h. NASA IMS and Program Office costs are excluded.

i. This cost data is for planning purposes only.

5.2.3 PMTE PAYLOAD TECHNICAL DESCRIPTION. The PMTE payload assembly installed in the Shuttle payload bay is shown in Figure 5-6 and the assembly itself in Figure 5-7. The experiment system schematic is shown in Figure 5-8. A brief summary technical description of the payload hardware assemblies and components is included below as used as a basis for the subsequent program cost estimate. The physical characteristics of these hardware items are summarized in Table 5-1. This hardware definition is based on the detailed system description included in Section 4.1 of this report.

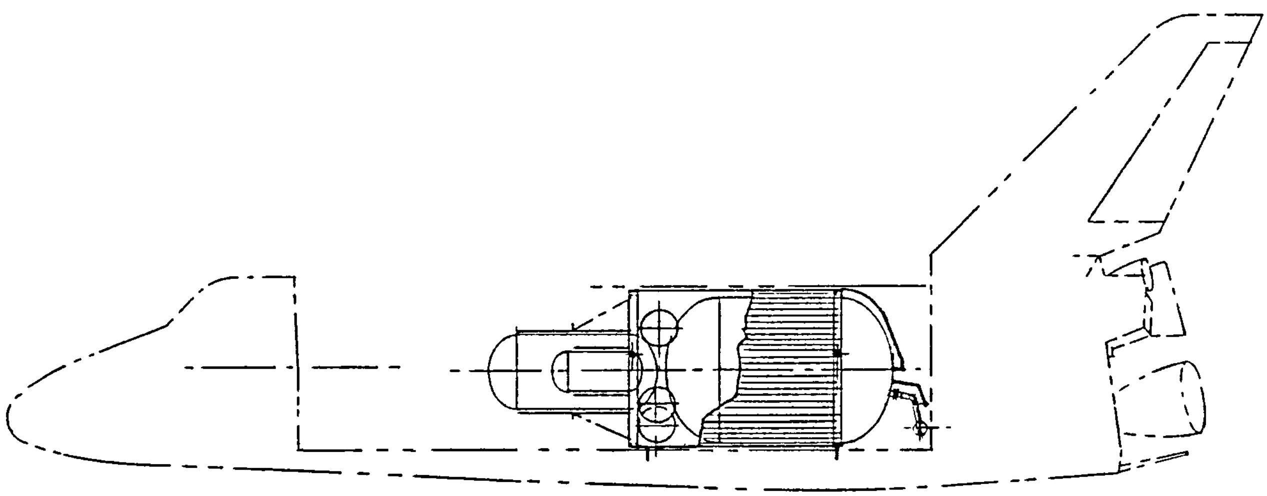


Figure 5-6. Shuttle Installation of PMTE Payload

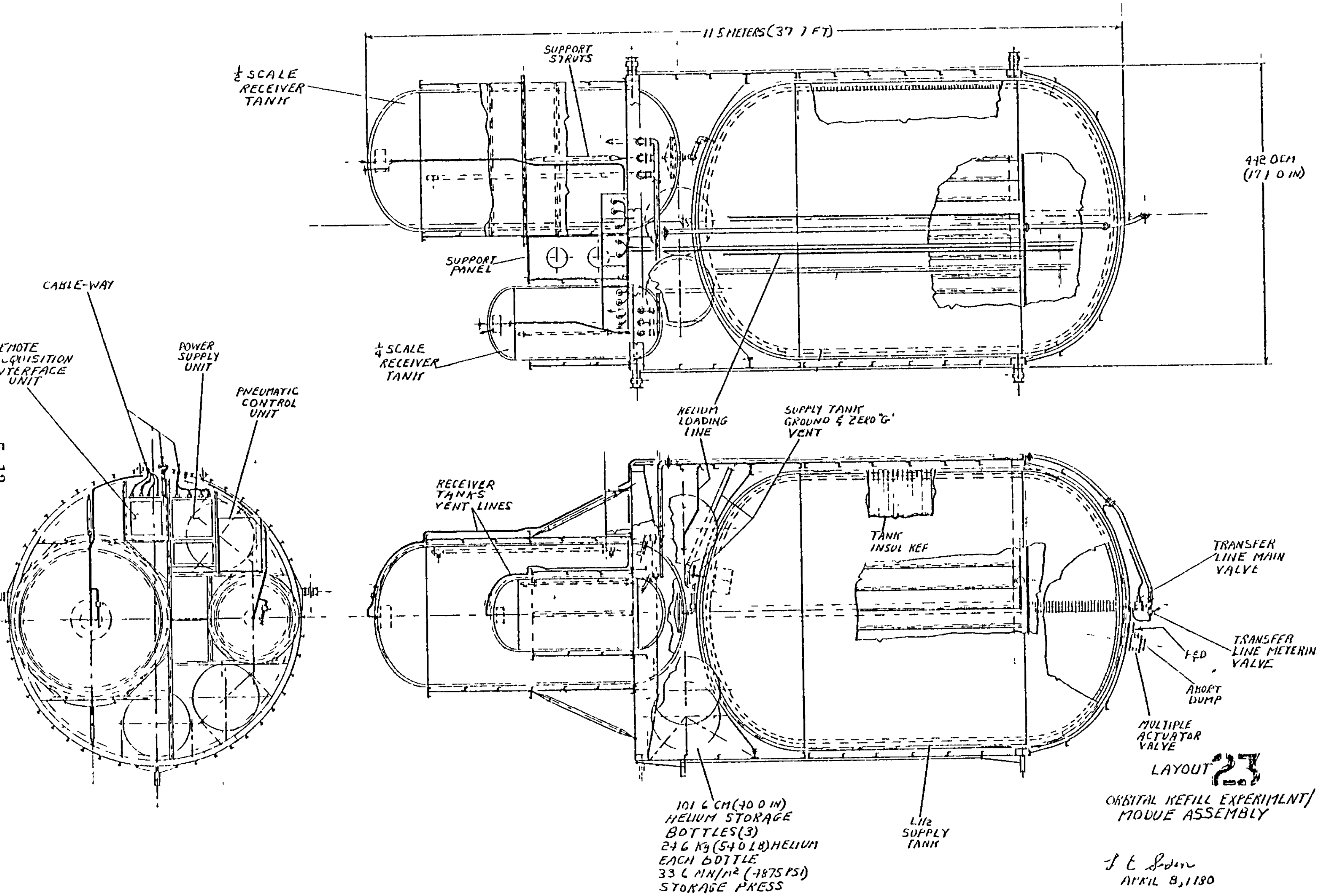


Figure 5-7. PMTE Payload Assembly

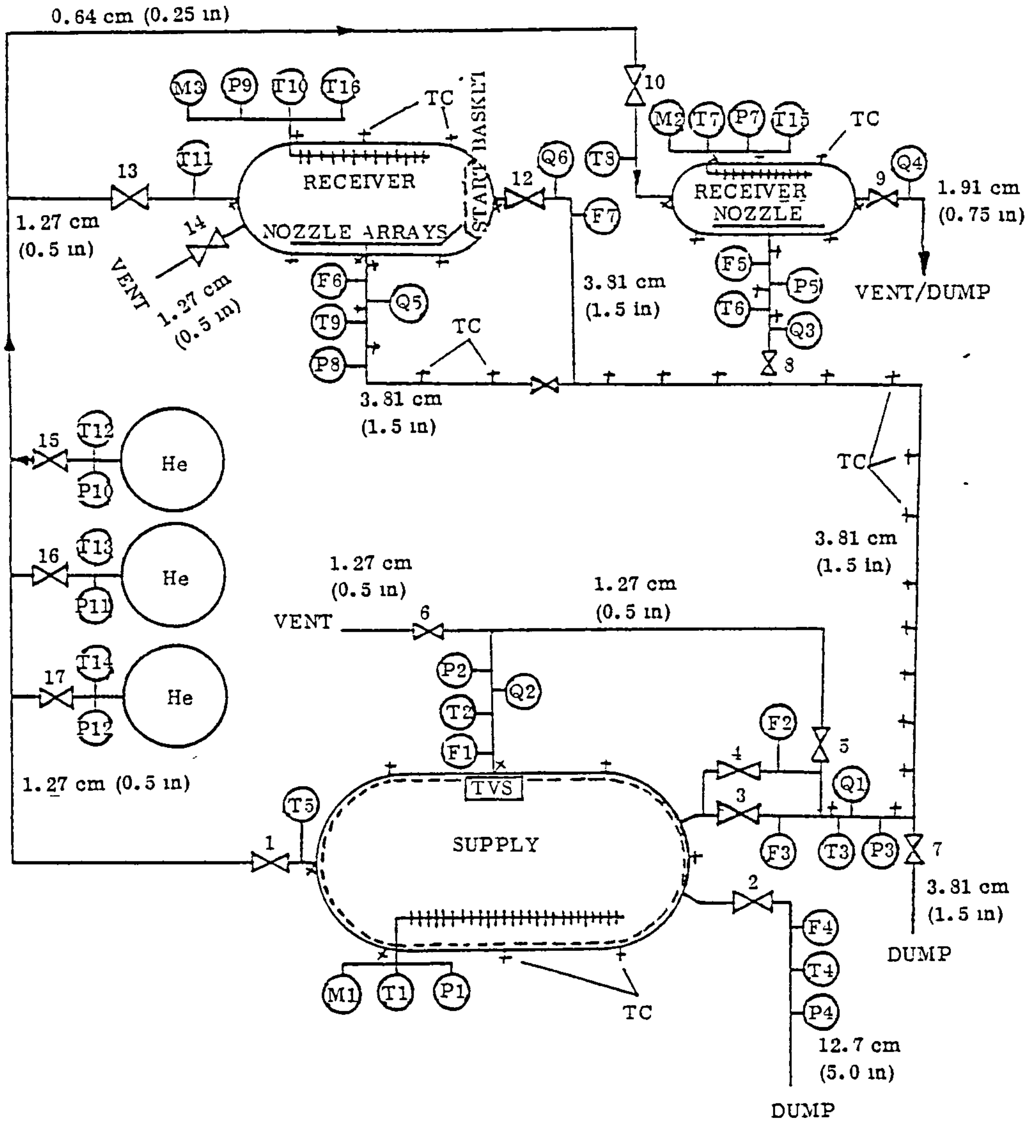


Figure 5-8. PMTE System Schematic

Structure - The primary structure consists of a large cylindrical shell of aluminum skin stringer frame construction supporting the supply tank and two small cylinders of semi-monocoque construction supporting the receiver tanks. The large shell has support trunnions and keel fittings for interfacing within the Orbiter payload bay. The large support cylinder also includes fiberglass purge enclosure bulkheads for conditioning the supply tank insulation system. The receiver tanks are cantilevered from forward beams on the supply tank support structure. The tanks are supported from these cylindrical shells by means of low conductive struts arranged in a V pattern.

Table 5-1. PMTE Physical Characteristics

			Kg (lbs) Weight		Volume m^3 (cu ft)	
Structure			1097	(2419.0)		
Primary	1041.3	(2296.0)				
Secondary	55.7	(123.0)				
Tankage						
Supply Tank			749.4	(1652.5)	73.62	(2600)
Receiver (1/2 Scale)			131.9	(290.8)	14.46	(511)
Receiver (1/4 Scale)			49.3	(108.6)	1.81	(64)
Fluid System			725.6	(1600.0)		
Helium Storage	580.5	(1280.0)				
Lines/Valves	77.1	(170.0)				
Dump Manifold	68	(150.0)				
Control System/Avionics			326.5	(720)		
RAU/Control Units	136	(300)				
Controls and Displays	9.1	(20)				
Instrumentation	22.7	(50)				
Harness and Cables	158.7	(350)				
	Dry Weight		3079.8	(6790.9)		
Liquid Hydrogen			4928.8	(10868.0)		
Helium			244.9	(540.0)		
	Expendables		5173.7	(11408.0)		
	Wet Weight		8253.5	(18198.9)		

The secondary structure consists of mounting bracketing attachment fittings, etc.

Tankage/Insulation - The 73.62 m^3 (2600 ft^3) supply tank is fabricated from aluminum with spin-formed and chem-milled bulkheads welded to the center cylindrical section. The tank includes a CRES capillary acquisition system and a bubbler manifold. The acquisition system is in the form of two rectangular tubes spaced to form 90° quadrants and following the contour of the tank bulkhead. Perforations in the tubes are covered with capillary screens. These tubes then lead to the tank outlet. The bubbler manifold is a circular aluminum alloy tube providing for injection of helium gas through a series of holes in the tube and provide the necessary cooling of the pressurizing gas. The tank insulation is a multilayer radiation shell (MLI) applied over the entire surface of the tank. Thirteen layers of aluminized mylar are used with each layer separated by flocking providing for purge and vent paths between each layer. A purge system guides gaseous helium between each layer. Appropriate fluid, gaseous, and electrical penetrations are provided in the tank/insulation combination. The insulated tank is then suspended in the support structure cylindrical shell with a system of low conductive struts located at the aft and forward ends.

The large half scale receiver tank 14.46 m^2 (511 ft^3) is constructed of aluminum in a similar manner to the supply tank and is equipped with accessories for on-orbit filling and venting, fill, drain, and vent for ground testing and an acquisition system. The latter permits transfer of propellant back to the supply tank. Three alternate methods of LH_2 injection are provided for, including a spray manifold, a single spray nozzle and a straight port with no spray nozzle. A CRES capillary acquisition system is also provided on the aft access door and a zero-g vent system is positioned on the forward bulkhead. The insulation for this tank consists of 16 layers of MLI of similar design to the supply tank. The small quarter-scale receiver tank 1.81 m^3 (64 ft^3) is similar to the half-scale tank, except no acquisition system is included.

Fluid System - The fluid system plumbing provides for circuits for ground fill and drain, ground vent, flight vent abort dump and experiment fluid transfer.

A helium storage system including three 33,600 kN/m^2 (4875 psi), 101.6 cm (40 in) pressure vessels provide for pressurizing the supply tank for transfer or abort and actuation of control valves. The plumbing for these systems is CRES tubing, welded where possible, and both pneumatically and solenoid operated valves together with other controls regulated and fittings. Cryogenic lines are insulated with MLI.

The abort dump system includes a multiple actuated harpoon valve located at the tank outlet. Overboard plumbing for abort dump and for other circuits is provided at the installation level of the orbiter.

Control System/Avionics - A computerized automatic operational experiment sequencing system will utilize a microprocessor for experiment control and will have provisions for mission specialist intervention in case of unanticipated problems. This computer system will provide the control signals necessary for operation of the pneumatic control units and solenoid valves for proper sequencing of the various experimental runs. Remote acquisition units and power supplies are provided for data acquisition and for electrical power for the control system and instrumentation and receiver tank wall heaters, respectively.

A control and display panel will be provided on the orbiter aft flight deck for monitoring and override control of the experiment payload operations. Caution and warning (C&W) signals and data will be integrated into the standard orbiter C&W panel.

Extensive instrumentation will provide for data collection as well as proper experiment operational sequencing and control. A list of the instrumentation sensors is presented in Table 5-2 below.

Table 5-2. Instrumentation Sensors

Flow Meters	6
Mass Sensors	3
Pressure Sensors	22
Quality Meters	6
Temperature Sensors	170

A wiring harness/cabling assembly will provide the proper electrical connections for experiment control, data acquisition, and electrical power.

Software - Computer software will include programs for the control computer experiment operations sequencing and data acquisition signal processing and formatting both within the payload itself as well as for interfacing with the Orbiter data systems.

5.2.4 COST ESTIMATE. The resulting nominal cost estimates for the experiment are summarized in Table 5-3 and detailed in Table 5-4 for the experiment hardware complement and for the complete experiment program. The costs are constant FY 1980 thousands of dollars and exclude prime contract fee. The experiment hardware estimates identify costs for both component development (design, modification, test article procurement) and component test and qualification.

This total experiment program shown in Table 5-4 includes software, Ground Support Equipment (GSE), and initial spares. Other wrap-around costs include facility level design and analysis, system engineering and integration, facility level testing, and project management. The operations costs include support operations and logistics, ground operations off-line and on-line, and post-mission operations, and Mission Operations (mission control data handling/processing and mission support). Post-flight maintenance and refurbishment have been excluded in this estimate as were any reflights or payload update or modifications. No required facilities were identified chargeable to this experiment.

As may be seen, experiment hardware (component) development may be expected to cost about \$13M, and the flight hardware production and/or procurement cost is estimated at about \$4.5M. The remaining cost elements bring the development and flight unit cost to \$19M and \$4.8M, respectively, for a total acquisition cost of

Table 5-3. PMTE Program Cost Summary

COST ELEMENT	COST (FY '80 M\$) DEVELOPMENT	UNIT PRODUCTION	OPERATIONS
PMTE EXPERIMENT PROGRAM	19.04	4.75	32.95
PMTE PAYLOAD	19.04	4.75	1.19
FLIGHT HARDWARE	(13.06)	(4.52)	—
SYSTEMS ENG. & INTEGRATION	(1.56)	—	—
SYSTEM TEST	(3.17)	—	—
GSE	(.34)	—	—
OPERATIONS	—	—	(.63)
MAINTENANCE & REFURB.	—	—	(.50)
FACILITIES/STE	(0)	(0)	(TBD)
PROGRAM MANAGEMENT	(.91)	(.23)	(.06)
STS USER CHARGE	—	—	31.76
T/DA USER CHARGE	—	—	TBD

Table 5-4. PMTE Cost Estimate

	COST ELEMENT	COST 1980 M$ DEVELOPMENT	PRODUCTION	OPERATIONS
0000	PMTE EXPERIMENT PROGRAM	19.04	4.75	32.95
1000	PMTE PAYLOAD	19.04	4.75	1.19
1100	FLIGHT HARDWARE	13.06	4.52	-
1110	STRUCTURE	1.81	.75	-
1111	PRIMARY	1.62	.71	-
1112	SECONDARY	.19	.04	-
1120	TANKAGE/INSULATION	6.10	1.85	-
1121	SUPPLY	3.18	1.27	-
1122	RECEIVER (LG)	2.40	.48	-
1123	RECEIVER (SM)	.52	.10	-
1130	FLUID SYSTEM	2.25	.55	-
1131	He STORAGE	.02	.13	-
1132	LINES/VALVES	1.15	.22	-
1133	DUMP MANIFOLD	1.08	.20	-
1140	CONTROL SYS/AVIONICS	2.80	.87	-
1141	CONTROL UNITS/RAU	2.06	.48	-
1142	CONTROLS/DISPLAYS	.08	.02	-
1143	INSTRUMENTATION	.26	.26	-
1144	HARNESS/CABLES	.40	.11	-
1150	SOFTWARE	.10	-	-
1160	FINAL ASSY, INST. & C.O.	-	.50	-
1200	SYSTEM ENG. & INTEGRATION	1.56	-	-
1300	SYSTEM TEST	3.17	-	-
1310	SYSTEM TEST ART (TANKS)	1.85	-	-
1320	SYS TEST OPS & SUPPORT	.87	-	-
1321	TANKS	.19	-	-
1322	FLIGHT EXPERIMENT	.68	-	-
1330	TEST ARTICLE REFURB.	.45	-	-
1400	GSE (PECULIAR)	.34	-	-
1500	OPERATIONS	-	-	.63
1510	GROUND OPERATIONS	-	-	.42
1520	MISSION OPERATIONS	-	-	.07
1530	OPERATIONS SUPPORT	-	-	.14
1531	TRANSPORTATION	-	-	.08
1532	TRAINING	-	-	.03
1533	LOGISTICS	-	-	.03
1600	MAINTENANCE & REFURB.	-	-	.50
1610	SPARE AND REPAIR PARTS	-	-	.45
1620	MAINTENANCE & REFURB.	-	-	TBD
1630	UPDATE EQUIPMENT	-	-	TBD
1640	EXPENDABLES & CONSUM.	-	-	.05
1700	FACILITIES AND STE	-	-	-
1710	FACILITIES	0	0	TBD
1720	SPECIAL TEST EQUIPMENT	0	-	-
1800	PROGRAM MANAGEMENT	.91	.23	.06
2000	STS USER CHARGE	-	-	31.76
	BASIC	-	-	28.28
	ADDITIONAL 4 DAYS	-	-	3.30
	ENERGY KIT	-	-	.18
3000	T/DA USER CHARGE	-	-	TBD

about $23.8M. The flight mission will cost about $1.1M per flight exclusive of Shuttle transportation charges. The user charge for a dedicated Shuttle flight will vary upward from $31.8M depending on flight time and other optimal services required. The total program cost is then about $56.7M. The confidence limits on this estimate are judged to have an uncertainty of about -10 percent to +20 percent for the PMTE payload portion depending upon the design requirements imposed. These cost uncertainties are shown in Table 5-5.

Table 5-5. Cost Uncertainties for PMTE Payload

Estimate	Development	Unit
High	$15.67M	$5.42M
Nominal	$13.06M	$4.52M
Low	$11.75M	$4.07M

5.2.5 ANNUAL FUNDING REQUIREMENTS. The annual funding requirements for the PMTE phase C/D program are shown in Figure 5-9. These funding estimates are shown individually for the development phase, the production phase wherein the flight payload is fabricated, and the operational period including the preparation for and conduct of the flight mission. As may be seen, the STS user charge for Shuttle transportation is also shown separately.

These funding requirements were obtained by accumulating the costs for each WBS element estimated (Table 5-4), properly spread over time in accordance with the program development as presented in Figure 5-2.

The STS user charges are spread in accordance with the schedule of reimbursement required by the "Space Transportation Systems Reimbursement Guide" dated March 1979. A nominal schedule is assumed, i.e., the STS is contracted for more than 33 months before launch.

As may be seen, the total funding is nearly constant between $15M to $20M per year for the three principal years of the program when STS funding is included. Initial year funding (FY 82) is low since ATP (Authority to Proceed) is not assumed until the last quarter of the year and team buildup then proceeds. (If phase C/D were to follow the phase B Definition study without a gap, an accelerated buildup would be possible, increasing the funding for FY 82 and a corresponding decrease of development funds in FY 83).

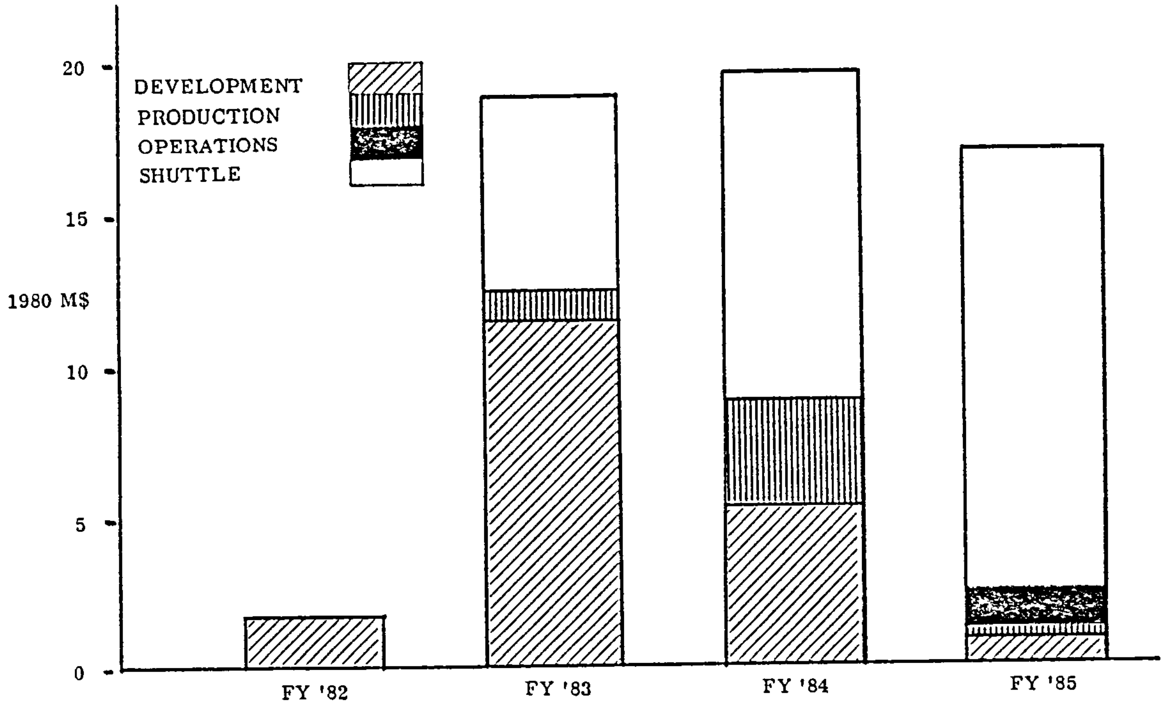


Figure 5-9. PMTE Annual Funding Requirements

6

CONCLUDING REMARKS

The propellant management technology experiment area, under the direction of NASA/LeRC, has systematically investigated experiment designs from the small Spacelab rack mounted experiment to the large Shuttle payload bay installation of this current study.

The "In-Space Cryogenic Fluid Management R&T Ad-Hoc Planning Committee" composed of various NASA center technical and management personnel recommended in December 1979 to focus the propellant management technology and demonstration program on a mid-sized experiment. This approach presently plans the use of the Martin Marietta designed CFME tank as the basic LH_2 supply source to support a series of pallet mounted experiments in Shuttle payload bay.

The present General Dynamics study describes the largest scale experiment configuration considered for in-space propellant management experimentation. Figure 6-1 indicates some of the basic characteristics of this 11.5m (37.7 ft) by 4.42m (14.5 ft) experiment package. The total wet weight including an energy kit is 8993.6 Kg (19831 lb). The support requirements for this experiment concept are all well within the Shuttle capabilities and constraints.

The estimated cost and funding spread to support the design, development, and operation of the experiment program is shown in Figure 6-2. All costs are in FY 1980 dollars and are for planning use only. The total cost estimate is $56.7M, of which about $32M are Shuttle user costs.

The fundamental aspects of the entire study are summarized in Figure 6-3. The conceptual design has addressed the broad needs of propellant management for the future. This future includes a family of OTVs and their operational interfaces which have provided the basis of the experiment design features. The primary experiment objectives have been satisfied with a design that also provides the flexibility needed to be responsive to new and unforseen requirements of the future.

EXPERIMENT ELEMENT	WEIGHT KG	(LBS)
SUPPLY TANK SYSTEM	752.3	(1652)
1/2 SCALE RECEIVER TANK	131.9	(291)
1/4 SCALE RECEIVER TANK	49.4	(109)
PRESSURIZATION SYSTEM	725.6	(1600)
INSTRUMENTATION & WIRING	181.4	(400)
SUPPORT STRUCTURES	1097	(2419)
CONTROLS, RAU, DISPLAYS	145.1	(320)
TOTAL DRY WEIGHT	3082.7	(6791)
TOTAL WET WEIGHT (LH_2 & He)	8253.5	(18199)
PLUS ENERGY KIT (840 KWH)	740.1	(1632)

SUPPORT ELEMENTS	
RCS PROPELLANT	725.6 Kg (1600 LB)
ELECTRICAL ENERGY	47.4 Kw-h
ORBITAL EXPERIMENT TIME	3 + DAYS
SECONDARY EXPERIMENTS	6

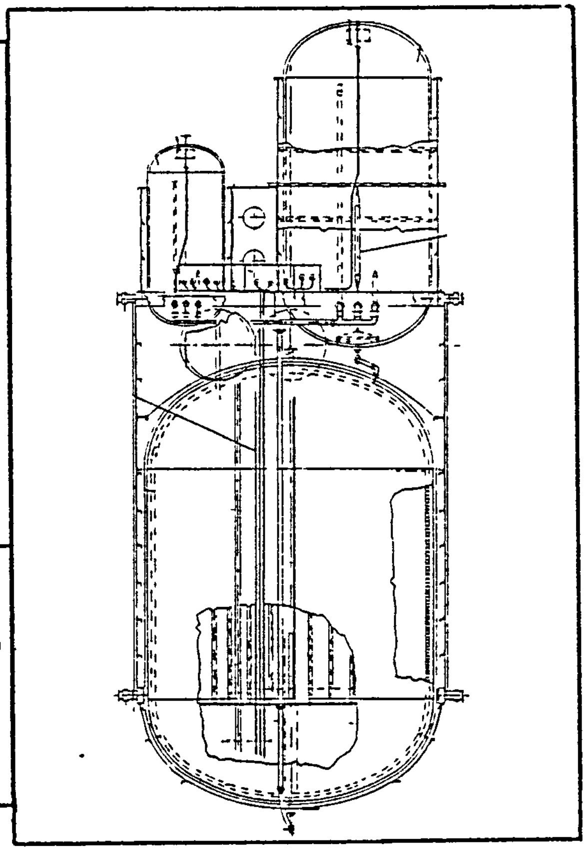


Figure 6-1. Experiment Design Summary

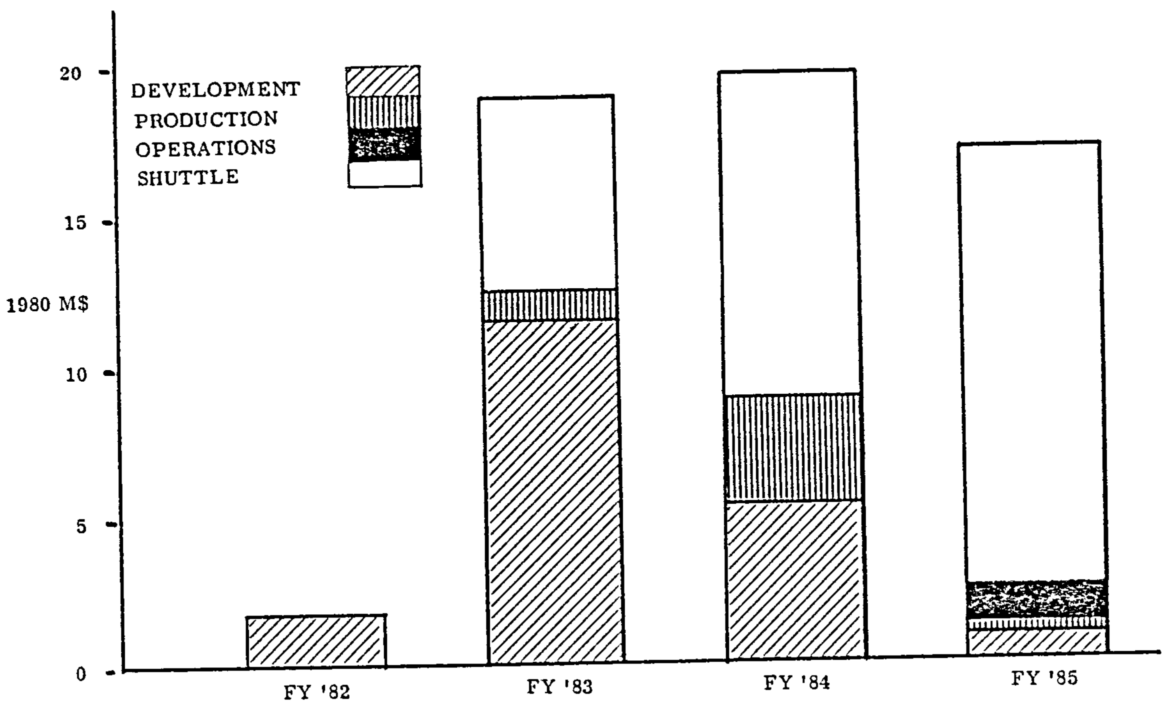


Figure 6-2. Annual Funding Requirements

THE CONCEPTUAL EXPERIMENT DESIGN SATISFIES A BROAD RANGE OF OTV PROPELLANT MANAGEMENT SCENARIOS

- SINGLE STAGE/SINGLE BURN/MULTI-BURN
- MULTI-STAGE/MULTI-BURN
- PROPELLANT TANKS (LH_2 - LO_2) WET OR DRY
- SHUTTLE OR DEPOT REFUELING BASE
- MISSIONS OF SEVERAL DAYS TO SEVERAL MONTHS
- SUBSYSTEM VARIATIONS - PRESSURIZATION, INSULATION, VENTING ACQUISITION, ABORT DUMP

THE CONCEPTUAL EXPERIMENT DESIGN PROVIDES A HIGH DEGREE OF EXPERIMENT FLEXIBILITY

PRIMARY OBJECTIVES	SECONDARY OBJECTIVES	SUPPORTING RESOURCES
FILL LINE CHILLDOWN TANK PRECHILL RECEIVER TANK FILL	PRESSURIZATION (He) PROPELLANT ACQUISITION TANK INSULATION TVS START BASKET REFILL/PERF. ABORT DUMP	– ZERO-G MASS GAUGE – MODIFIED OTV GROUND SUPPORT EQUIPMENT FOR INTERFACE OF EXPERIMENT LH_2 & He REQUIREMENTS

THE CONCEPTUAL EXPERIMENT DESIGN REPRESENTS AN EXPERIMENTAL TOOL TO INVESTIGATE THE PROPELLANT TRANSFER TECHNOLOGY REQUIREMENTS OF A BROAD RANGE OF SPACE-BASED OTVs

Figure 6-3. Summary of Study

7

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APPENDIX A
PROPELLANT MANAGEMENT TECHNOLOGY EXPERIMENT
WBS DICTIONARY

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WBS NO: 0000 Level: 2

WBS Title: Propellant Management Technology Experiment (PMTE) Program

This WBS element summarizes all effort, material, and services required to conduct the development program, flight article fabrication, and the orbital test flight(s) of the PMTE. It includes the payload itself, Shuttle transportation and any tracking and data acquisition user charges incurred during the operational flights.

The following subelements are included:

WBS No.	WBS Title
1000	PMTE Payload
2000	STS User Charge
3000	Tracking and Data Acquisition User Charge

WBS No: 1000 Level: 3

WBS Title: PMTE Payload

This WBS element summarizes all effort and material required for the design, development, fabrication, assembly, test and checkout, and the operation of the PMTE Payload system.

The following subelements are included:

WBS No.	WBS Title
1100	Flight Hardware
1200	System Engineering and Integration (SE&I)
1300	System Test
1400	Ground Support Equipment (GSE)
1500	Operations
1600	Maintenance and Refurbishment
1700	Facilities and Special Test Equipment (STE)
1800	Program Management

WBS No: 2000 Level: 3

WBS Title: STS User Charge

This WBS element summarizes all of the costs incurred by the PMTE program in the form of User Charges for Space Shuttle transportation including optional services.

WBS No: 3000 Level: 3

WBS Title: Tracking and Data Acquisition User Charge

This WBS element summarizes all of the costs incurred by the PMTE program in the form of user charges for Tracking and Data Acquisition functions including TDRSS satellite services.

WBS No: 1100 Level: 4

WBS Title: PMTE Payload

The WBS element summarizes all effort and material required to design and develop and to manufacture the basic PMTE flight vehicle hardware and software.

This vehicle consists of all primary and secondary structure, tankage, and all supporting subsystems necessary for payload functional operation and to provide the necessary resources to the mission payload equipment.

PMTE development includes all requirements definition, design and analysis, interface integration, subsystem and component hardware fabrication and procurement for test, and for development and qualification testing thereof, tooling, software, etc. Payload production includes all fabrication, material, parts, and components procurement, sub-assembly, and quality control activities.

The following subelements are included:

WBS No.	WBS Title
1110	Structure
1120	Tankage/Insulation
1130	Fluid System
1140	Control System/Avionics
1150	Software
1160	Final Assembly, Installation, and Checkout

WBS No: 1110 Level: 5

WBS Title: Structure

This WBS element summarizes all of the primary and secondary structural hardware making up the PMTE payload.

The following subelements are included:

WBS No.	WBS Title
1111	Primary Structure
1112	Secondary Structure

WBS No: 1111 Level: 6

WBS Title: Primary Structure

This WBS element consists of the primary basic structure which provides support and protection for the three tanks and provides for mounting accommodations in the payload bay. It consists of the protecting support shells for each of the tanks and the tank supporting beams making up the overall installation assembly.

WBS No: 1112 Level: 6

WBS Title: Secondary Structure

This WBS element consists of all secondary structure required for the PMTE payload. This secondary structure includes mounting bracketry, attachment fittings, etc.

WBS No: 1120 Level: 5

WBS Title: Tankage/Insulation

This WBS element summarizes the three tanks: 1) the supply tank, 2) the 1/2 scale receiver tank, and 3) the 1/4 scale receiver tank.

The following subelements are included:

WBS No.	WBS Title
1121	Supply Tank
1122	Receiver Tank (1/2 scale)
1123	Receiver Tank (1/4 scale)

WBS No: 1121 Level: 6

WBS Title: Supply Tank

This WBS element consists of the assemblies and hardware making up the supply tank. This tank has about (73.62 m^3) capacity and includes the tank shell and bulkheads. MLI insulation and installation components, the acquisition system, the bubbler manifold, tank supports and plumbing/electrical interfaces.

WBS No:	1122	Level: 6
WBS Title:	Receiver Tank (Large)	

This WBS element consists of the assemblies and hardware making up 1/2 scale receiver tank. This tank has about ($14.46m^3$) capacity and includes the tank shell and bulkheads, MLI insulation and installation components, the acquisition system, tank supports, and all plumbing and electrical interfaces.

WBS No:	1123	Level: 7
WBS Title:	Receiver Tank (Small)	

This WBS element consists of the assemblies and hardware making up the 1/4 scale receiver tank. This tank has a capacity of about ($1.81m^3$) and includes the tank shell and bulkheads, MLI insulation and installation components, tank supports and all plumbing and electrical interfaces.

WBS No:	1130	Level: 5
WBS Title:	Fluid Systems	

This WBS element summarizes all of the components and assemblies making up the fluid systems of the PMTE payload including cryogenic as well as gaseous pressurization systems. It includes the helium storage system, all lines and valves for either pressurization or for propellant transfer, and the dump manifold.

The following subelements are included:

WBS No.	WBS Title
1131	Helium Storage
1132	Lines and Valves
1133	Dump Manifold

WBS No:	1131	Level: 6
WBS Title:	Helium Storage	

This WBS element consists of the helium pressurized storage tanks used to pressurize the tanks and transfer propellant. There are three $33.6MN/m^2$ (4,875 psi) tanks of $0.507m^3$ (31,000) cu. in. capacity.

WBS No.	1132	Level: 6
WBS Title:	Lines and Valves	

This WBS element consists of all of the fluid or gas lines and fittings (i.e. plumbing) and all control valves and devices such as shutoff valves, checkvalves, pressure regulators, etc.

WBS No.	1133	Level: 6
WBS Title:	Abort Dump Manifold	

This WBS element consists of the fluid lines, connectors, valves, etc. making up the abort propellant dump system.

WBS No:	1140	Level: 5
WBS Title:	Control System/Avionics	

This element summarizes all of the control system and avionics equipment required for the PMTE payload. It includes control units, RAUs, controls and displays, instrumentation, and the necessary harness and cabling.

The following subelements are included:

WBS No.	WBS Title
1141	Control Units/RAU
1142	Controls and Displays
1143	Instrumentation
1144	Harness and Cables

WBS No:	1141	Level: 6
WBS Title:	Control Units/RAU	

This element consists of all control units, sequencers, microprocessors, remote acquisition units and power supplies required for the proper functioning of the experiment during on-orbit operations.

WBS No:	1142	Level: 6
WBS Title:	Controls and Displays	

This WBS element consists of all of the controls and displays, which will be located in the aft flight deck of the Orbiter, for backup override operation of the payload experiment. It will also include any caution and warning equipment required.

WBS No: 1143 Level: 6

WBS Title: Instrumentation

This WBS element consists of all of the instrumentation sensors necessary for this payload including the measurement of pressure, temperature sensors, flow rate, quality, mass, etc.

WBS No: 1144 Level: 6

WBS Title: Harness and Cabling

This WBS element consists of all of the harness and cabling necessary for the controls, instrumentation, and electrical power for this payload.

WBS No: 1150 Level: 5

WBS Title: Software

This WBS element consists of all of the effort and material required to design, code, debug, and validate the software necessary for control and for data management associated with the PMTE payload including programs for operational sequencing control and data acquisition.

WBS No: 1160 Level: 5

WBS Title: Final Assembly, Installation, and Checkout

This WBS element consists of all effort and materials required to accomplish subsystem installation, final assembly, checkout, and acceptance testing of the payload. These are all ground activities and culminate in selloff to the customer (DD250).

WBS No: 1200 Level: 4

WBS Title: System Engineering and Integration

This WBS element summarizes all system level studies, analyses and tradeoffs to support the development of requirements, specifications, and interfaces necessary to direct and control the design of the overall system. It also includes all mission studies and analyses to establish requirements and planning for all phases of the mission, and logistics activities. It also includes all Product Assurance activities consisting of safety, reliability, maintainability quality assurance, and parts, material, processes (PMP) control.

The following subelements are included:

WBS No.	WBS Title
1210	System Analysis and Integration
1220	Mission Requirements and Analysis
1230	Logistics Requirements and Analysis
1240	Product Assurance

WBS No: 1210 Level: 5

WBS Title: System Analysis and Integration

This WBS element consists of all analyses, studies, and evaluations necessary to establish system requirements and specifications (hardware and software), identify and define interfaces (ICDs), establish requirements for design and performance verification (test requirements, etc.), conduct performance and system effectiveness studies and capabilities evaluations, and validate design, performance and interfaces.

It also includes all studies and analysis necessary to ensure the physical, functional (performance), and environmental compatibility of the payload and all interfacing external system elements such as the STS.

WBS No: 1220 Level: 5

WBS Title: Mission Requirements and Analysis

This WBS element consists of all analyses, studies, and evaluations associated with determination and establishment of mission operation requirements, establishment of flight and mission operations plans, and evaluation of associated procedures. It includes payload orbit analyses, payload crew activities planning, real time mission planning, flight crew operations requirements (procedure and training) and flight support POCC analysis for the experiment mission.

WBS No: 1230 Level: 5

WBS Title: Logistics Analysis

This WBS element includes all effort required to plan for, establish requirements, implement, operate and maintain logistics management system for support of the PMTE Program and its related support equipment and systems. This includes identification of spares requirements, analysis of support requirements, inventory, repair requirements, warehousing and storage, and transportation analyses and planning.

WBS No: 1240 Level: 5

WBS Title: Product Assurance

This WBS element consists of all safety, reliability, maintainability, quality assurance and parts, materials, processes (PMP) control for the PMTE Program to assure that these considerations are included in the design, development, and test operation phases in a cost effective manner. This element also includes those efforts associated with planning for, requirements establishment, implementation, and maintenance of these activities to ensure satisfactory hardware/software delivery and operation through procedures, training, analysis, review, and assessment.

WBS No: 1300 Level: 4

WBS Title: System Test

This WBS element summarizes all effort and hardware required to conduct and support all PMTE system level testing necessary to refine and validate the design and verify the accomplishment of the development objectives. They may include but not be limited to full-scale structural tests, integrated avionics tests, all-up cryogenic functional tests, and payload functional and integration testing. This element includes all major test articles fabrication; test article maintenance, refurbishment and reconfiguration; test analysis, preparation and operations; test software and test support activities.

Excluded are the design and analysis of major test articles (WBS 1110 thru 1140) component and subsystem development and qualification testing (WBS 1110 thru 1140) and special test facilities/equipment (WBS 1700).

The following subelements are included:

WBS No.	WBS Title
1310	System Test Articles
1320	System Test Operations and Support
1330	Test Article Refurbishment

WBS No: 1310 Level: 5

WBS Title: System Test Articles

This WBS element consists of all labor, materials, and services necessary to fabricate major system test articles to be used for system level ground developmental or qualification testing. It includes one set of ground test tankage; the supply tank, and two receiver tanks, one large and one small. It includes all fabrication, material and parts procurement, subassembly, final assembly and all quality control activities.

WBS No: 1320 Level: 5

WBS Title: System Test Operations and Support

This WBS element consists of all labor, materials, and services necessary to accomplish the required system test objectives. It includes both test operations for the ground test tanks as well as the ground system level testing conducted using the flight payload. It includes all test planning and design; procedures; preparation, set up, and set up validation; operations; teardown and disposition; data recovery, analysis, and evaluation and finally documentation. It also includes test software and all test supporting activities.

WBS No: 1330 Level: 5

WBS Title: Test Article Refurbishment

This WBS element consists of all labor and materials necessary to maintain, refurbish, or reconfigure the flight article after ground system testing for the subsequent flight test.

WBS No: 1400 Level: 4

WBS Title: Ground Support Equipment (Peculiar)

This WBS element summarizes all effort and material required to define, design, develop, test and qualify, procure, fabricate, assemble and check out all PMTE peculiar new or modified Ground Support Equipment (GSE). It includes all deliverable GSE hardware and its associated software required to support the PMTE System during the development, manufacturing and operations phases, and all effort and material required for GSE maintenance. It includes all necessary handling and transportation equipment; servicing equipment; functional checkout equipment; and maintenance and auxiliary equipment.

Unique test facilities and major test setup/fixtures are excluded from this element and included under Facilities/STE (WBS 1700).

The following subelements are included:

WBS No.	WBS Title
1410	Handling and Transportation GSE
1420	Servicing Equipment GSE
1430	Checkout GSE
1440	Maintenance and Auxiliary GSE

WBS No: 1410 Level: 5

WBS Title: Handling and Transportation GSE

This WBS element consists of all PMTE program peculiar GSE necessary for handling, protecting, shipping, and storage of the flight experiment or equipment items during all phases of development, production, integration, operations and maintenance and refurbishment. This element includes such items as transporters, dollies, handling slings, protective covers, shipping containers, etc.

WBS No. 1420 Level: 5

WBS Title: Servicing GSE

This WBS element consists of all PMTE program peculiar GSE necessary for servicing the payload, experiments, or equipment items during all phases of development, production, integration, operations or maintenance and refurbishment of the platform, and payloads and experiments. This element includes such equipment as fluids servicing equipment for propellants, and pressurized gas servicing equipment for helium.

WBS No: 1430 Level: 5

WBS Title: Checkout GSE

This WBS element consists of all PMTE program peculiar checkout and monitoring GSE necessary for checkout, test and diagnostics, monitoring, and repair and maintenance of the payload or equipment items during all phases of development, production, integration, operations, and maintenance and refurbishment. This element includes such items as automated checkout systems, equipment item test sets, signal stimulus sets, monitoring controls and displays.

WBS No: 1440 Level: 5

WBS Title: Maintenance and Auxiliary GSE

This WBS element consists of all PMTE program peculiar auxiliary GSE necessary for maintenance or training activities. It includes all maintenance equipment other than checkout GSE, such as simulators (signal, power, etc.) special tools, fixtures, or other maintenance aids; all training aids and simulation equipment; and all other special ground equipment as necessary.

WBS No: 1500 Level: 4

WBS Title: Operations

This WBS element summarizes all of the effort and materials required to support the PMTE program during its operational phase. It includes all ground operation and integration activities, flight and mission operations, and all operations support.

The following subelements are included:

WBS No.	WBS Title
1510	Ground Operations
1520	Mission Operations
1530	Operations Support

WBS No: 1510 Level: 5-

WBS Title: Ground Operations

This WBS element consists of all effort and material required for the ground operations and integration phase prior to launch of the experiment and post-mission tasks. It begins with NASA acceptance of the vehicle (DD250) and ends with the shuttle return and demating operations. It includes all integration preparations, installation and integration into the shuttle orbiter, launch operations support and post-mission operations.

WBS No: 1520 Level: 5

WBS Title: Mission Operations

This WBS element consists of all effort and materials required on the ground for support of the on-orbit mission operations phase of PMTE flight. It includes PMTE monitoring (housekeeping) and problem resolution and consists of payload operations control center (POCC) and data acquisition activities.

WBS No: 1530 Level: 5

WBS Title: Operation Support

This WBS element consists of all contractor effort and materials required for transportation, training and logistic system activities during the operational phase inclusing launch, on-orbit operations and post mission activities. Also included is sustaining engineering and support during the experiment operations period for support in problem simulation and resolution and update engineering.

The following subelements are included:

WBS No.	WBS Title
1531	Transportation
1532	Training
1533	Logistics

WBS No: 1531 Level: 6

WBS Title: Transportation

This WBS element consists of all effort, material, and services required for payloan transportation to the cognizant NASA center and/or to the KSC launch site after NASA acceptance (DD 250).

WBS No. 1532 Level: 6

WBS Title: Training

This WBS element consists of all effort, material, and services required for PMTE system unique training of the mission and/or payload specialist, but excludes his basic spaceflight training.

WBS No: 1533 Level: 6

WBS Title: Logistics

This WBS element consists of all effort, material and services required for the PMTE logistics effort and activities including transportation, storage, and accounting for all spare and repair parts.

WBS No: 1600 Level: 4

WBS Title: Maintenance and Refurbishment

This WBS element summarizes all of the effort and material required to procure hardware components and assemblies for maintenance, refurbishment, and capabilities update. This hardware includes all spare and repair parts, maintenance and refurbishment labor, and update replacement equipment, expendables and consumables for the payload systems.

The following subelements are included:

WBS No.	WBS Title
1610	Spare and Repair Parts
1620	Maintenance and Refurbishment
1630	Update/Replacement Equipment
1640	Expendables and Consumables

WBS No: 1610 Level: 5

WBS Title: Spare and Repair Parts

This WBS element consists of the procurement of all required spare and repair parts consumed during the operational period for the experiment. These spare and repair parts, components, assemblies, etc. are primarily for the repair of failed units.

WBS No:	1620	Level:	5
WBS Title:	Maintenance and Refurbishment		

This WBS element consists of all effort, both labor and services, necessary to accomplish post flight maintenance and refurbishment or update modifications as required in case of potential reflights.

WBS No:	1630	Level:	5
WBS Title:	Update/Replacement Equipment		

This WBS element consists of the acquisition of all update and replacement equipment used to refurbish and/or update or change the basic functional capabilities of the experiment. The acquisition of this equipment includes the design, test, and manufacturing thereof.

WBS No:	1640	Level:	5
WBS Title:	Expendables and Consumables		

This WBS element consists of the procurement of all expendables and consumables required during the operational flight of the PMTE payload. It includes all propellant, fluids, and gases.

WBS No:	1700	Level:	4
WBS Title:	Facilities/STE		

This WBS element summarizes all of the effort and materials necessary to acquire or modify and to maintain all of the unique capital facilities and Special Test Equipment (STE) necessary for the total PMTE program during development, manufacturing, and for operations. It includes all planning, design and layout, construction and installation, and activation.

The following subelements are included:

WBS No.	WBS Title
1710	Facilities
1720	Special Test Equipment (STE)

WBS No: 1710 Level: 5

WBS Title: Facilities

This WBS element consists of the PMTE program unique new or modified capital facilities and equipment necessary to develop, manufacture and operate this system. Equipment includes all fixed facility associated equipment not categorized as tooling, special test equipment (STE) or GSE. It may include facilities for development and test, manufacturing, integration, and launch operations.

WBS No: 1720 Level: 5

WBS Title: Special Test Equipment

This WBS element consists of the PMTE system special test equipment, not categorized as facilities or GSE, necessary to conduct the required test program for the flight experiment. It may include special test fixtures, mission operations simulators, etc.

WBS No: 1800 Level: 4

WBS Title: Program Management

This WBS element summarizes all of the effort required to manage, direct, and control the entire PMTE Program. These functional tasks and activities include planning, organizing, budgeting, scheduling, directing, and controlling and other administrative tasks to ensure that the overall objectives of the program are accomplished.

The following subelements are included:

WBS No.	WBS Title
1810	Program Direction
1820	Program Planning and Control
1830	Data Management
1840	Procurement Management
1850	Configuration Management

WBS No: 1810 Level: 5

WBS Title: Program Director

This WBS element consists of all effort of the Program Manager and his staff.

It includes management review and control as well as direction in executive, engineering and scientific areas necessary to assure proper progress and attainment of program goals. It also includes continuous monitoring of all functional management disciplines for central direction and control of the overall project by ensuring timely resolutions of scientific, technical, or programmatic problem areas, and interface with the cognizant customer Program Office.

WBS No: 1820 Level: 5

WBS Title: Program Planning and Control

This WBS element consists of all management effort associated with integrated program planning, scheduling, financial and manpower budgeting, cost control and reporting necessary to provide management visibility and control of overall program activities. This effort includes the preparation and maintenance of a master project schedule and those planning documents associated with definition of the PMTE Program. Also included is a performance management system for monitoring and controlling technical performance of all tasks.

WBS No: 1830 Level: 5

WBS Title: Data Management

This WBS element consists of all overall management activities required to ensure proper program documentation, information control, compatibility, availability, and currency. Included are services to identify, prepare, control, reproduce, distribute and maintain status of the internal and deliverable documentation for the PMTE Program. Establishment, implementation, and maintenance of the data management requirements and procedures are also part of this element.

WBS No: 1840 Level: 5

WBS Title: Procurement Management

This WBS element consists of all management and technical control of effort by subcontractors and vendors. Tasks included are the providing of work direction to subcontractors and vendors; authorizing subcontractor tooling and equipment; analyzing subcontractor reports; conducting subcontractor and vendor reviews; and on-site coordination and evaluation of procurements. Also included is the maintenance of records and submission of required reports relating to the geographic dispersion of minority and small business participation in project procurements and subcontracts.

WBS No: 1850 Level: 5

WBS Title: Configuration Management

This WBS element consists of all management activities associated with planning for and defining, controlling, and accounting for the hardware and software configurations at any point in time throughout the program life cycle. The configuration management system developed will provide identification of configuration and programmatic baselines, control changes to and maintain current status accountability of these baselines, and progressively verify that the as-built configuration agrees with the contract requirements (or that differences are identified). Included in this element are establishment, implementation, and maintenance of specification formats, end item selection criteria; procedures for control and accounting of configurations and changes, provisions for design support; conducting design reviews, audits and analyses; and Class II change control are also included in this element, as well as participation in configuration verification to support CEI acceptance.

APPENDIX B

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