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16. Abstract

In order to demonstrate the desirability and feasibility of subcritical cryogenic fluid orbital storage and supply, the conceptual design of a Spacelab cryogen management experiment was performed. The conceptual design includes a description of the experimental apparatus, definition of supporting requirements, procedures, data analysis, and a cost estimate. The experiment was conceived as a LH_2 tank 1.06 m (41.7 in.) in diameter with a screen device and helium pressurization system for LH_2 supply, and a high-performance thermal control system consisting of a vapor-cooled shield thermodynamic vent system, multilayer insulation, and vacuum jacket. The experiment could be mounted on the ESA pallet and flown with Spacelab in the STS Orbiter payload bay, or alternatively, could be mounted in the bay next to the Spacelab ingress/egress tunnel. The complete experiment package in the payload bay, including fluids and pallet mounting supports, weighs 162 kg.

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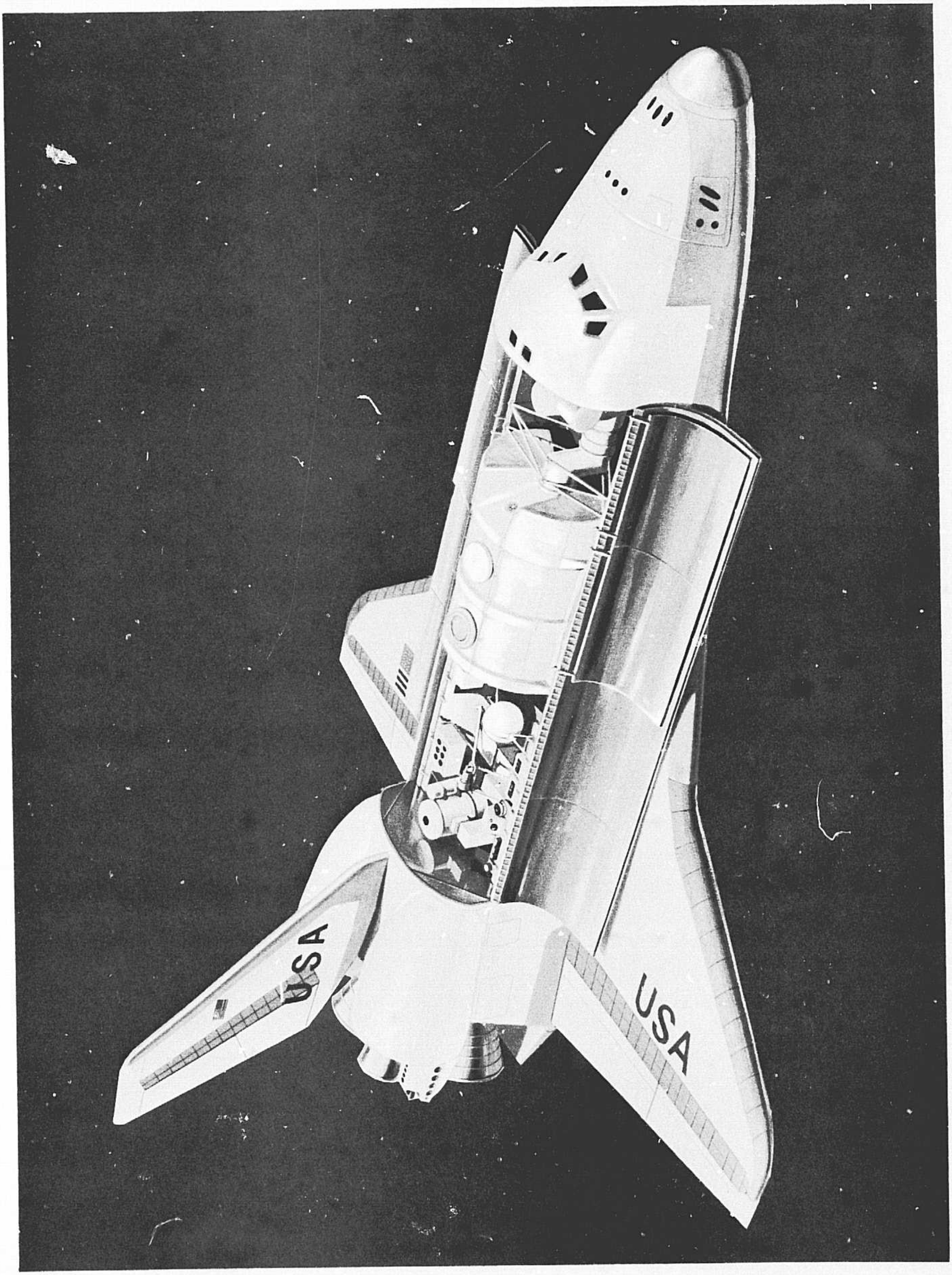

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PREFACE

This report was prepared by McDonnell Douglas Astronautics Company under Contract NAS 3-19719. The contract is administered by the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio. The NASA Project Manager for the contract is Mr. John C. Aydelott. This is a special report which summarizes the technical effort on contract Tasks VII and VIII which were performed from June 1976 through November 1976.

CONTENTS

Section 1
INTRODUCTION

The use of fine-mesh screen devices to exploit surface tension forces and provide fluid control in low gravity has come of age. Such devices are now flying in some satellites, and are being developed for use in the orbital maneuvering and attitude control systems of the Space Transportation System (STS) Orbiter vehicle. However, all such recent uses for screen devices have been restricted to storable fluids such as hydrazine or nitrogen tetroxide. For cryogenic fluids, such as liquid hydrogen (LH_2) or liquid oxygen (LO_2), the integration of the necessary thermal protection and vent systems with the screen device has not been developed to a sufficient level to confidently allow use of such screen devices with cryogenic liquids. Instead, for smaller-scale cryogen systems, storing the cryogen at supercritical pressures is common practice to provide historically proven (e.g., Apollo) single-phase fluid expulsion in low gravity. Supercritical cryogen storage systems currently under development include the STS Orbiter power reactant storage assemblies (PRSA) which supply hydrogen and oxygen reactants to the fuel cells for on-board power generation (Reference 1). The initial storage conditions for the PRSAs are at cryogenic temperatures, thus a sophisticated thermal protection system is used to reduce external heat leak over the 7- to 30-day Orbiter mission duration. This thermal protection system, consisting of a vapor-cooled shield, multilayer insulation (MLI), and a complete vacuum jacket, also provides for ground-hold thermal protection. This high-performance thermal protection system concept was thoroughly developed some years ago (References 2 and 3) and is being proposed for long-duration (years) liquid helium storage in space (Reference 4).

Storage of cryogens at supercritical pressures has as its principal drawbacks the requirements for heavy high-pressure storage vessels and substantial (electric) power input to maintain constant tank pressure during supercritical fluid withdrawal. A recent study (Reference 5) indicated that replacement of the Orbiter supercritical PRSAs by lightweight subcritical tanks with screen devices would save about 540 kg (1190 lb) of inert weight and 156 kW-hr of heater energy consumption for a 30-day mission.

Many fluids, such as nitrogen and oxygen, used for atmosphere supply or leakage makeup for Spacelab, Space Stations, etc., are stored as warm high-pressure gases. These fluids could be stored as subcritical cryogenic liquids with weight savings (even with the addition of a thermal control system) of up to 79% of the inert storage system weight (Reference 5). Many other current or potential NASA missions could use cryogenic fluids in relatively small quantities for life support, electrical power generation, and in the saturated or subcooled state for instrument cooling, auxiliary propulsion, and attitude control, and for cryogen supply for experimental payloads. A survey of all such missions was conducted (References 6 through 13) and the results, shown in detail in Appendix A, included 5 space systems, 9 automated payloads (satellites), and 18 sortie payloads (experiments flown with Spacelab or in the Orbiter payload bay).

Representative systems from each category were analyzed in terms of weight and power savings, for subcritical liquid storage/transfer compared to either supercritical fluid or high-pressure gas storage, as appropriate. The PRSA thermal protection system was extrapolated to the appropriate sizes to provide baseline weights for the cryogenic storage systems. The results are summarized in Table 1. It can be seen that subcritical liquid storage/transfer offers substantial weight and power savings, even for very-long-duration missions.

In view of the potential performance gains available from, and the many potential applications of small-scale subcritical cryogenic liquid storage/transfer systems, together with the modest technology extrapolation from storable propellant screen devices and the availability of high-performance thermal control technology, a system demonstration of orbital subcritical cryogenic fluid management appears both feasible and appropriate. Accordingly, the conceptual design of a cryogenic fluid management experiment, to be flown with the Spacelab in the STS Orbiter payload bay, was undertaken.

Table 1

SPACE SYSTEM PERFORMANCE COMPARISON

			Storage System Inert Weight			Benefits	
	Mission Duration (days)	Fluid Weight (kg)	Hi-Pressure Gas (kg)	Super-Critical Fluid (kg)	Sub-Critical Liq/Screen (kg)	Weight Savings (kg)	Power Savings (kW-hr)
STS Orbiter PRSA (H_2, O_2)	30	3169.6	--	1484.8	947.2	537.6	156
Spacelab Atmosphere (N_2, O_2)	30	163.6	442.0	--	95.0	347.0	--
Space Station Atmosphere (N_2, O_2)	120	471.0	1039.8	235.7	150.1	889.7	16.6
Satellite ACS (N_2)	730	115.6	168.4	61.5	38.9	129.5	0*
Spacelab Instrument Cooling (N_2)	30	50.0	80.2	--	29.2	51.0	--

*Heater not needed for supercritical system; External heat leak maintains constant tank pressure

In order to provide a convincing experimental demonstration and provide technology applicable to a wide spectrum of potential users, the experiment fluid and size were carefully evaluated. An evaluation of the fluid applications, mission storage times, and vessel size, based on the survey data of Appendix A, appears in Table 2. The results indicate that most applications are of a size equal to or less than the H_2 PRSA size of 1.06 m (3.5 ft) diameter, most missions (because of the preponderance of sortie payloads) run from 7 to 30 days, and LN_2 has the largest number of potential applications.

In order to further evaluate appropriate fluids, the fluid applicability and the experiment demonstration aspects based on the fluid properties were analyzed. The results are shown in the simple unweighted rating chart of Table 3, which indicates that LH_2 is slightly better than LN_2 which in turn is better than either LO_2 or LHe. With LH_2 selected as the experiment fluid, the following advantage would accrue: demonstration of a qualified high-performance storage system using a hard cryogen with immediate applicability to PRSA performance improvement. Liquid hydrogen has low density, hence lighter experiment weight; it also has the highest screen head retention capability. By scaling the experiment to the PRSA H_2 tank size, it may be possible to use directly the PRSA thermal control system (vacuum jacket, vapor-cooled shield, etc.) as well as many qualified components (fill, drain, relief, etc.). Finally, it will be possible to directly compare the weight and power usage with that of the PRSA in order to demonstrate directly the benefits of subcritical versus supercritical cryogen storage/transfer.

Therefore, the experiment was conceived as a LH_2 tank of PRSA size (1.06 m [41.7 in.] diameter pressure vessel) with a screen device and helium pressurization system for fluid transfer, and a high-performance thermal control system comprised of a vapor-cooled shield thermodynamic vent system, multilayer insulation, and vacuum jacket. The basic experiment objective is to demonstrate the feasibility and desirability of subcritical cryogen orbital storage and supply, specifically:

- Weight and power saving compared to supercritical systems
- Tank pressure control using a thermodynamic vent system
- Low-gravity LH_2 liquid supply using a fine-mesh screen device

Table 2

MISSION REQUIREMENTS FOR FLUID, STORAGE TIME, AND SIZE

Fluid	Application (Number of Missions)	Total
LH_2	APS (1), PRSA (3), Thermal control (1)	5
LO_2	APS (1), PRSA (3), Atmosphere (3)	7
LN_2	Atmosphere (3), ACS (8), Instrument cooling (6), Freezer (2), Purge (4)	23
LHe	Instrument cooling (9)	9

Storage Time (Days)	7	30	120	180	365	730	1825
No. of Missions	22	1 or 2	1	1	1	7	1

Size				No. of Missions				
Diameter		Volume						
(m)	(ft)	(m^3)	(ft^3)	LO_2	LN_2	LH_2	LHe	Total
<0.6	<2.0	<0.12	<4.2	2	14		2	18
0.6-1.07	2.0-3.5	0.12-0.62	4.2-22	4	11	4	4	23
>1.07	>3.5	>0.62	>22	1	1	1	3	6

Table 3
FLUID APPLICABILITY/DEMONSTRABILITY RATING

		Demonstrability								
Fluid	Applicability	Safety	PV Wt Savings	Power Savings	Storage Difficulty	Experiment Weight	1-G Screen Perf	TVS Design	Pressurant	Rating
LO_2	2	3	1	1	3	2	2	1	1	16
LN_2	1	1	1	1	3	3	2	1	1	14
LH_2	2	2	2	2	1	1	1	1	1	13
LHe	2	1	3	3	1	1	3	3	3	20

1 — Best
2 —
3 — Worst

- Ground-servicing and 1-g performance capability
- Development of technology applicable to potential system users.

If a more advanced experiment configuration using two interconnected tanks were deployed, many additional experiment objectives could be achieved:

- Performance evaluation of two different screen device configurations
- Multiple expulsion cycles from each device
- Evaluation of low-gravity screen device refill with cold tank and wet screen device
- Evaluation of low-gravity refill of evacuated (warm) tank and dry screen device.

However, the conceptual experiment design described in the next section will concentrate on the baseline one-tank experiment configuration.

Section 2
EXPERIMENT DESIGN

The conceptual design of the Spacelab cryogenic fluid management experiment consists of the following: (1) experimental apparatus, including hardware, instrumentation, data transmission descriptions, schematics, drawings, and volume/weight estimates; (2) supporting requirements, including electrical power, consumables, and data recording equipment; (3) procedures, including ground test and orbital experiment procedures and astronaut/payload specialist requirements; (4) data analysis, including a discussion of the experimental measurements to be obtained and their relationship to the experiment objectives; and (5) cost estimates, including potential costs of hardware and instrumentation, identification of applicable available or existing equipment, and application of cost-effective design.

APPARATUS CONFIGURATION

The configurational aspects of the experiment concept which were evaluated included the screen device, subcritical pressure vessel, thermal control system, and instrumentation/control components. The overall arrangement of the experiment apparatus is shown schematically in Figure 1. The screen acquisition device uses surface tension forces to supply liquid and prevent the helium pressurization gas from escaping the tank. The thin-wall pressure vessel is surrounded by the thermal control system, which includes a vapor-cooled shield thermodynamic vent system, a multilayer insulation (MLI) blanket, and a vacuum jacket. The vapor-cooled shield thermodynamic vent system uses liquid from the screen device for zero-gravity venting and supports the MLI blanket. The vacuum jacket consists of vacuum shells and a girth ring which provides external support and pressure vessel support. Details of each of the apparatus subsystems follow.

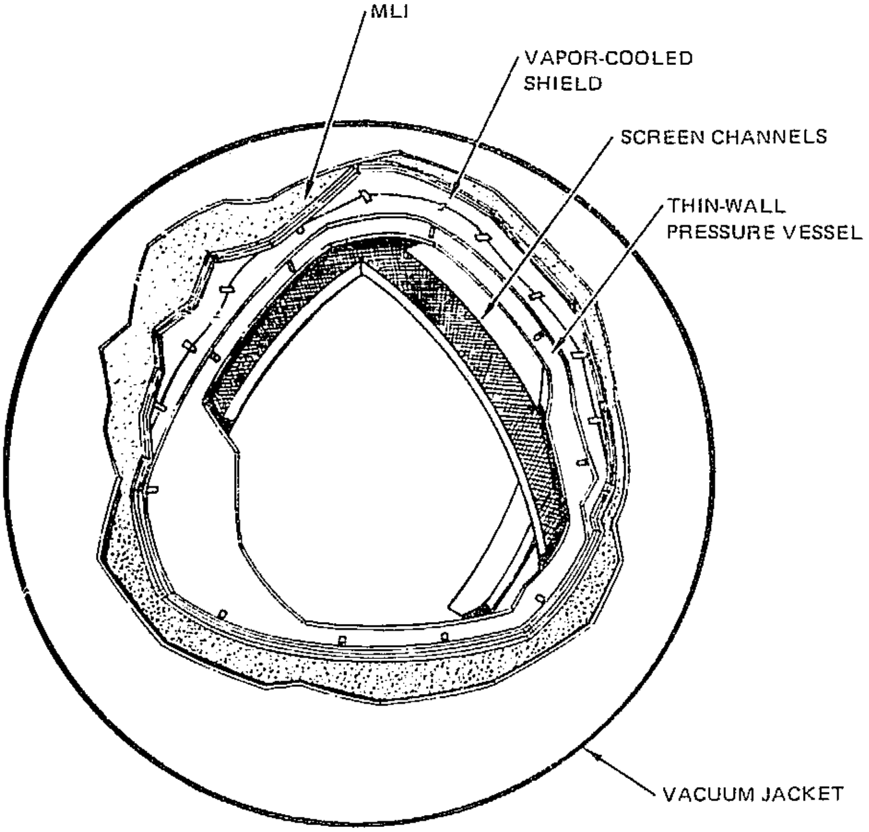

Figure 1. Experiment Apparatus Arrangement

Screen Device

Two screen device configurations were evaluated: (1) a complete spherical pleated screen liner (Figure 2a shows a liner developed by Western Filter Inc. for a previous NASA program) and (2) a multiple screen channel configuration (Figure 2b). The spherical pleated liner was thoroughly evaluated from a fabricability and performance standpoint (see Reference 5), while the screen channel configuration is similar to the Orbiter OMS device and that flying in the satellite hydrazine ACS. The positive and negative aspects of the two configurations are compared in Table 4. Since both types of screen devices have significant positive aspects, both were carried through the conceptual design phase; indeed, both types of screen devices could be used in the advanced two-tank experiment configuration mentioned earlier.

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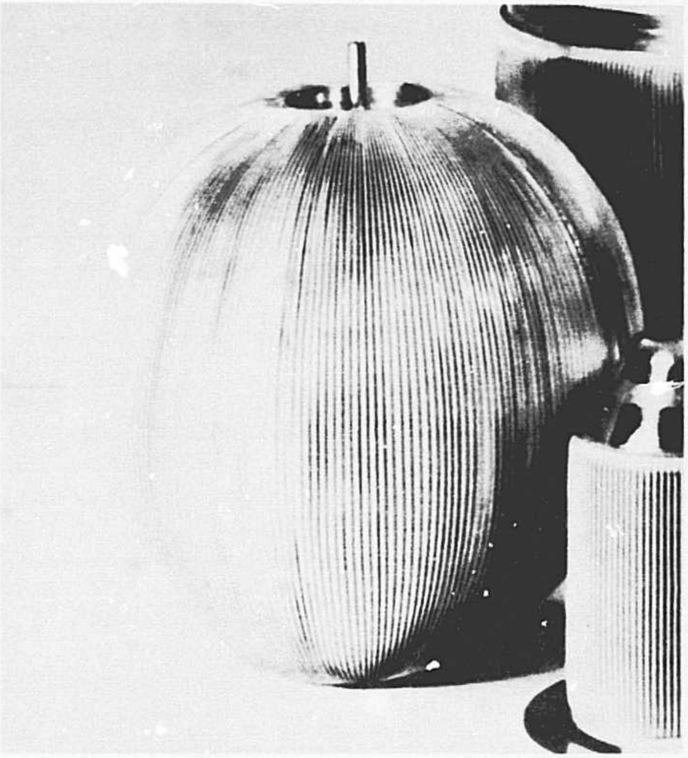

Figure 2a. Pleated Screen Liner

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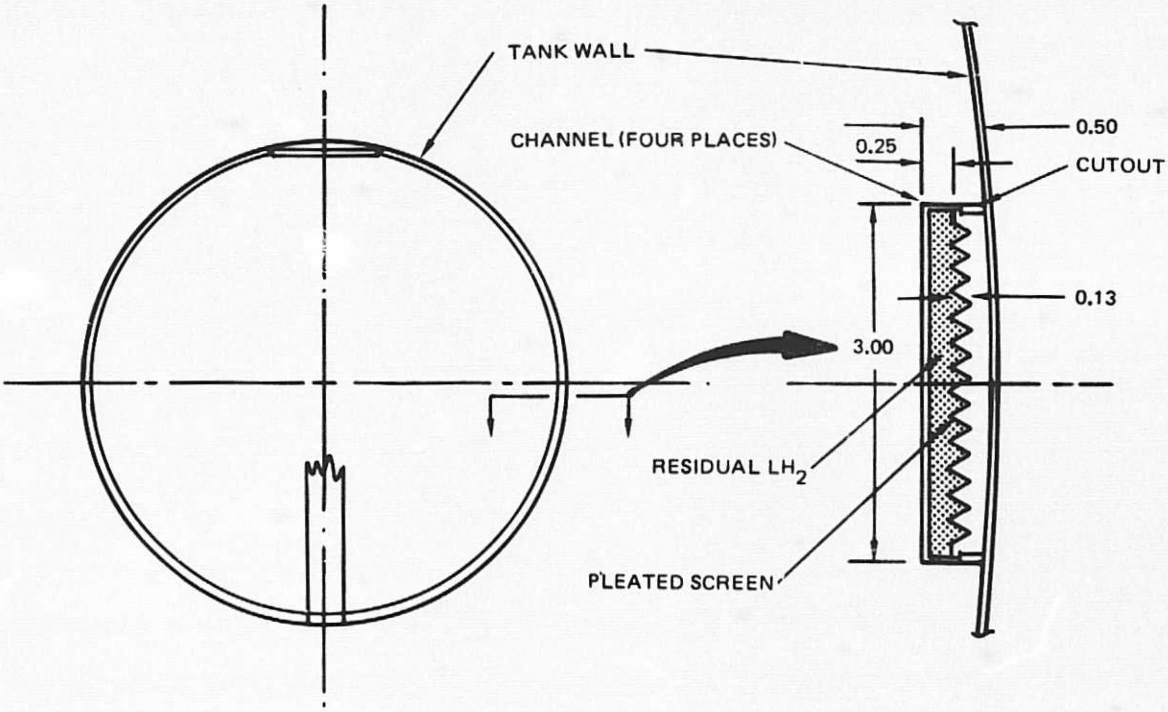

Figure 2b. Screen Channel Configuration

Table 4

SCREEN DEVICE COMPARISON

Pleated Screen Liner

Positive	Negative
• Liner structurally sturdy.	• Fabrication complex and costly.
• Liner highly resistant to effects of sloshing, vibration, and dynamic stresses.	• Liner integrated with pressure vessel; must be same material.
• Liner residual well-defined (1.8%); puddle residual essentially zero.	• Aluminum 200 x 1400 screen used, requires 9.3 m^2 (100 ft^2) of screen: costly.
• Large screen area minimizes flow-through pressure drop, reduces blocking effects of contamination, and enhances expulsion reliability	• Heat flux to tank through supports and plumbing must be eliminated
	• Pressurization line cannot pass through screened annulus volume.

Multiple Screen Channel

Positive	Negative
• Minimum screen device residual (0.5%)	• Undefined puddle residual could be located between channel arms; maximum of 2.3% at 10^{-3} g's.
• Fabrication much less costly	• May be less structurally stable; 1 m^2 (11 ft^2) of screen may be more susceptible to adverse affects of sloshing, vibration and contamination.
• Screen could be different material than pressure vessel, but 200 x 1400 aluminum recommended.	
• Elimination of pressure vessel heat leak (except to screen device plumbing) not essential.	

In order to provide a small ullage volume in the tank and yet withstand the high g levels encountered during launch with a reasonable screen retention safety margin, the finest mesh screen generally available was selected for the screen devices. To be compatible from a thermal contraction standpoint with the aluminum pressure vessel, 200 x 1400 mesh Dutch-twill-weave aluminum screen, with a 1-g LH_2 bubble point (head) of about 43 cm (17 in.) was selected.

Pressure Vessel

The subcritical lightweight pressure vessel was designed in accordance with the STS Safety requirements and guidelines of References 14 and 15.

The pressure vessel design pressure was defined as 41.4 N/cm^2 (60 psia) so that the experiment unit could potentially be used to supply propellant to the STS Orbiter fuel cells, and thus allow a direct system comparison with the supercritical PRSA. In accordance with STS design criteria (Reference 15), the pressure vessel design safety factor was defined as 1.5 on the material yield stress for 0.2% elongation at 21°C (70°F).

The pressure vessel design parameters are shown in Table 5. The pressure vessel halves would be spun from 2219-T42 aluminum alloy (selected for high strength and to assure reliable welding) and then machined and chem-milled to a minimum gage of 0.074 ± 0.008 cm (0.029 ± 0.003 in.). After the pressure vessel girth joint (shown in Figure 3) is welded, the vessel would be aged at 163°C to the T62 condition.

Pressure Vessel Supports

The pressure vessel support method was modified from that used for the PRSA. The S-glass/epoxy supports used for the PRSA are bolted into bosses on the heavy-walled supercritical pressure vessel (and attached to trunnions on the girth ring); bolting would clearly not be suitable for the lightweight thin-walled subcritical pressure vessel. Accordingly, a more suitable tank support method was defined, consisting of ultra-high-strength Dupont Kevlar-49 cables attached to collars around the tank as shown in Figure 3. The collars to which the supports are attached are 7.6 cm (3.0 in.) wide by 0.15 cm (0.06 in.) thick and are not physically attached to the

Table 5

PRESSURE VESSEL DESIGN PARAMETERS

Spherical — Maximum efficiency and thermal performance

PRSA Size — 1.06 m (41.7 in.) ID

Material — 2219 Aluminum alloy

- Compatible with 6061-T6 aluminum vapor-cooled shield and 2219 aluminum vacuum jacket
- Minimum weight — 8.6 kg (19.0 lb)
- Excellent LH_2 properties
- Design pressure — 41.4 N/cm^2 (60 psia)
- 1.5 safety factor on 0.2% yield stress at 21°C (70°F)
- Minimum gage of 0.074 ± 0.008 cm (0.029 ± 0.003 in.)
- Machine-welded; Aged after welding to T62 condition

tank. The support cables would be preloaded in tension with trunnions attached to the girth ring as shown in Figure 3, which also shows how the supports are thermally shorted to the vapor-cooled shield with copper wire.

The cable design loads were based on the most severe accelerations at launch, reentry, and crash-landing for a fully loaded tank with safety factors as specified in Reference 16. The support system is shown in Figure 4 and consists of 12 Kevlar-49 cables 0.069 cm (0.027 in.) in diameter which resist the ±X, ±Y, and +Z loads, and four 0.043 cm (0.017 in.) diameter lateral cables which resist the -Z crash loads. The anticipated heat leak down the cables, based on room temperature conductivity, is 0.002 watts (0.006 Btu/hr).

Thermal Control System

The thermal control system for the experiment is based on and similar to that of the PRSA, and is shown schematically in Figure 5. The vacuum shells and girth ring provide a vacuum annulus which allows effective use of high-performance MLI which is required for 7- to 30-day storage time and allows

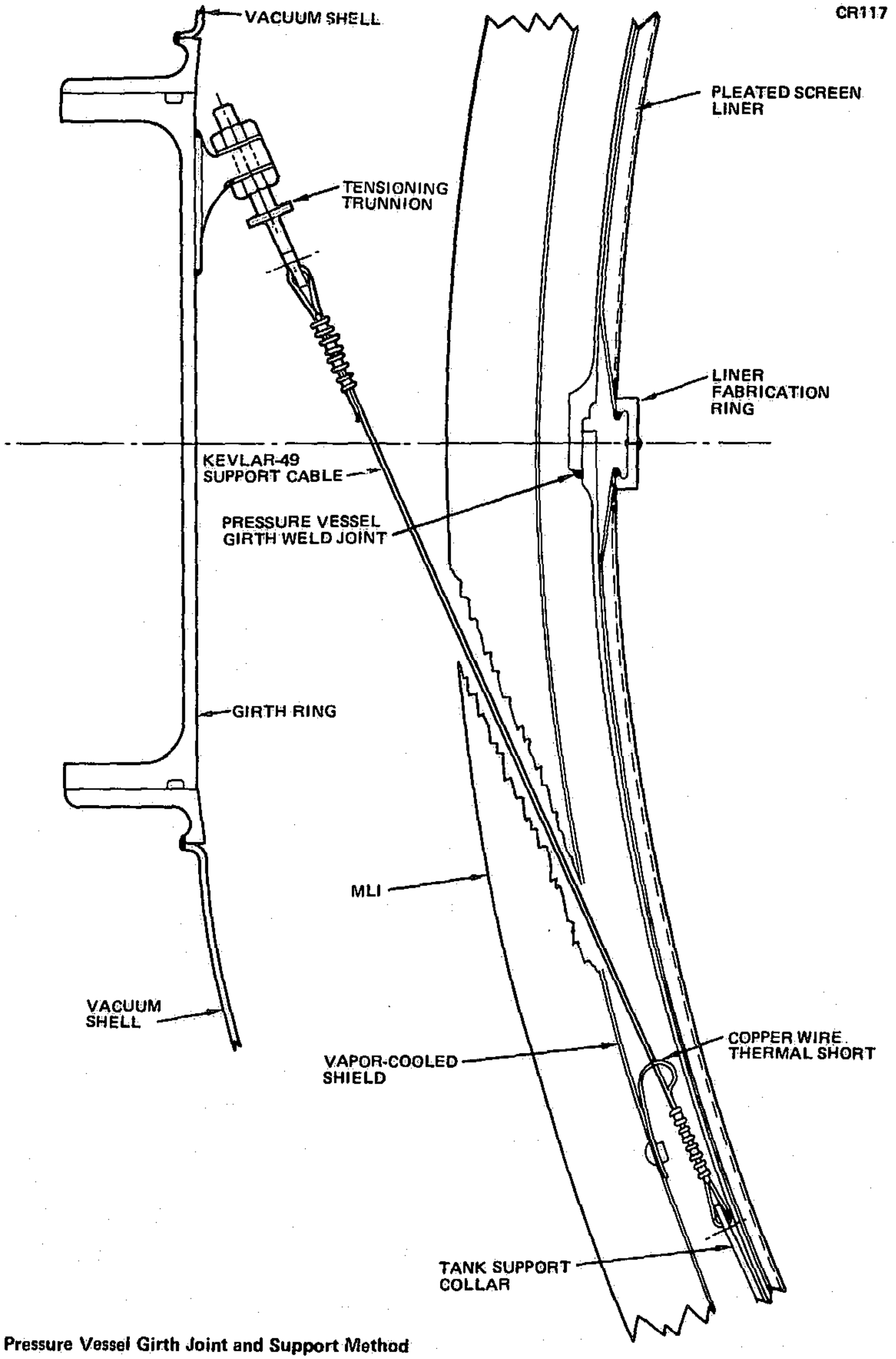

Figure 3. Pressure Vessel Girth Joint and Support Method

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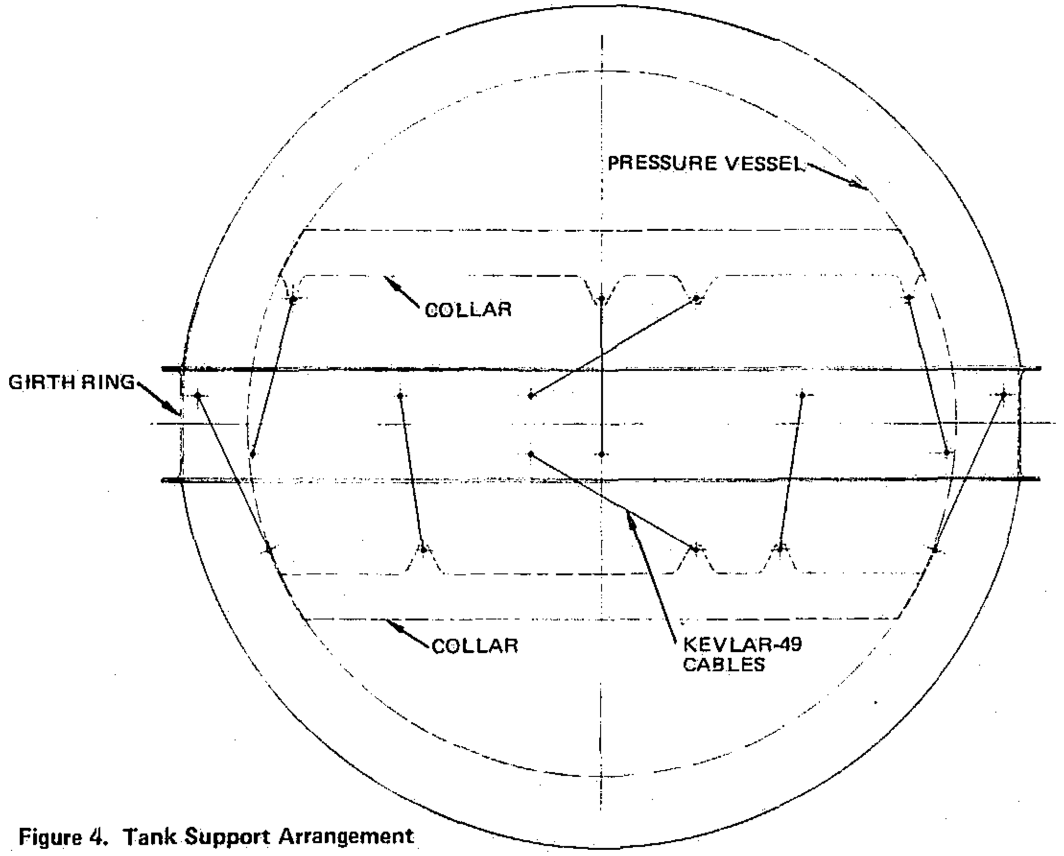

Figure 4. Tank Support Arrangement

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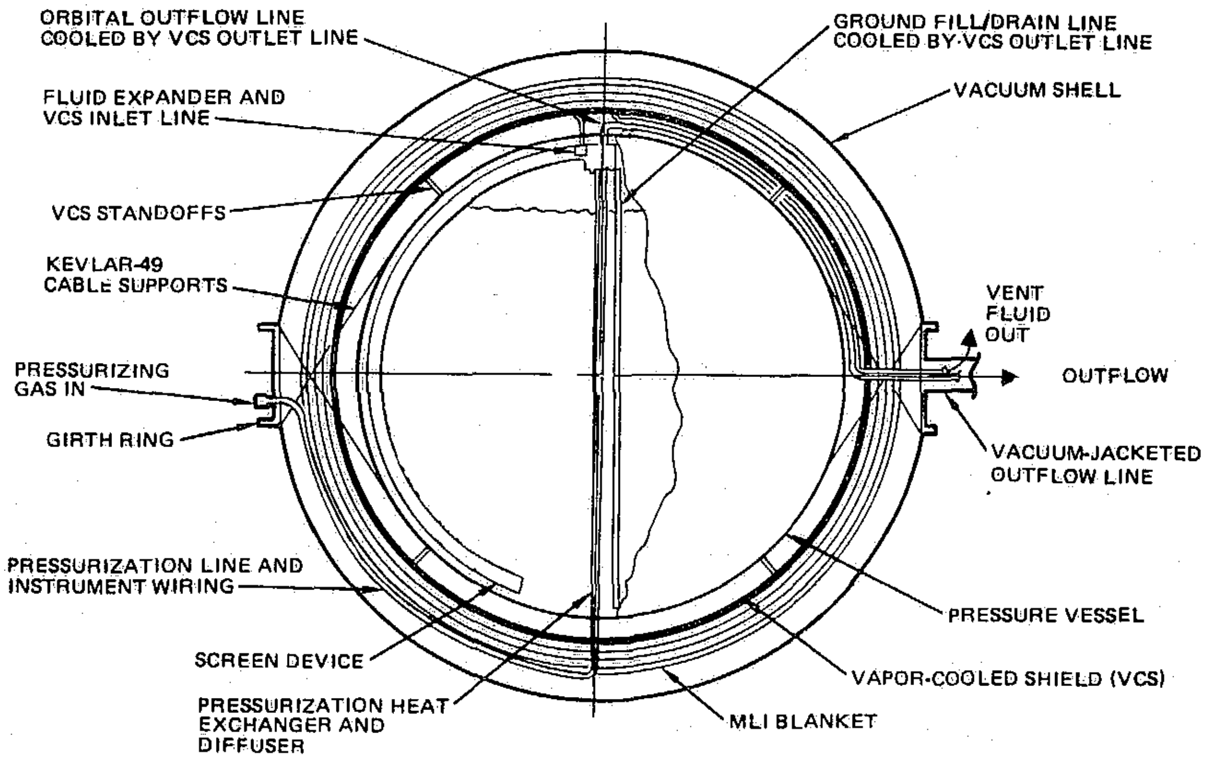

Figure 5. Thermal Control System Schematic

ground fill/hold capability. The girth ring provides a convenient mounting support (both for external mounting and pressure vessel mounting) and fluid inlet/exit points.

The LH_2 storage system operates at essentially constant pressure, and the tank must be vented to prevent pressure rise from heat leak to the LH_2. To operate effectively in low gravity where the liquid-gas phase separation regions are not readily definable, a thermodynamic vent system (TVS) is utilized which uses the heat leak (e. g., through the MLI) to boil vented LH_2 (taken from the screen device) in a vapor-cooled shield (VCS) integrated with the MLI. In order for the pressure vessel to remain at constant pressure while fluid is being vented, energy must be supplied to the pressure vessel, either in the form of leaked heat or pressurizing gas. It is much more efficient (and perhaps unavoidable) to allow heat to leak to the tank rather than pressurize the tank.

Numerous components tend to leak heat to the tank: tank supports, pressurization line, vent and outflow/fill lines, and instrumentation wiring. If this heat is allowed to enter the tank, it must be directed into the tank such that the heat can vaporize LH_2 without affecting the screen device. Clearly, the pressurization line would transmit large quantities of heat to the tank during LH_2 outflow and pressurizing gas inflow, and the screen device must be shielded from this large heat influx. Thus the static heat leak through the pressurization line would also be shielded from the screen device so this heat leak can be used to maintain constant tank pressure during venting. The same is true of the substantial amount of heat entering the tank through the instrumentation wiring and, in fact, these wires could enter the tank along with the pressurization line (or inside it). On the other hand, the vent line and outflow/fill line provide a direct path for heat leak into the screen device during storage, and this heat leak must be eliminated to preclude boiling within the screen device and potential retention loss. This heat leak can be eliminated by cooling these lines with the vent flow after it leaves the VCS. For the full pleated screen liner, the heat leak through the tank supports (although small) should be eliminated by shorting the supports to the VCS.

Given the existence of a heat leak, $\dot{Q}$, into the tank, the required LH_2 venting mass flow-rate ($\dot{W}$) to maintain constant tank pressure (assuming no vapor superheat) is:

$$\dot{W} = \frac{\dot{Q}}{h_{fg}} \frac{\rho_{LIQ}}{\rho_{VAP}}$$

where ρ_{LIQ} and ρ_{VAP} are the densities of liquid and saturated vapor, and h_{fg} the heat of vaporization at constant pressure.

The LH_2 vent flow (taken from the screen device) is expanded to lower pressure and temperature in the VCS. The heat capacity of the vent flow depends on the difference between the enthalpy after expansion and the enthalpy at transition of the vent flow regime from annular to mist flow (where the vent tube heat transfer coefficient drops sharply). This difference defines the allowable heat leak through the MLI (and thus the MLI thickness) plus the heat leak shorted to the VCS. The remaining heat capacity of the vent fluid after annular-mist transition can be used to cool the outflow/fill line.

Vapor-Cooled Shield

Analysis of the VCS indicated that with proper material choice, thermal performance did not control the VCS design; rather the design of the VCS was mainly based on handling and structural considerations. The design details of the VCS construction are shown in Table 6, and the VCS configuration is shown in Figure 6. The predicted performance of the VCS at nominal conditions and at two off-design conditions, MLI heat flux doubled and tank heat short heat leak doubled, are also shown in Table 6. It is clear that the nominal performance of the VCS gives reasonable vent rates and that controlling the vent flow could compensate for off-design heat flux through MLI or tank heat shorts. In addition, analysis indicated that monitoring VCS outlet temperature rather than tank pressure would give more effective control of vent flow in the case of off-design MLI heat flux. A possible control system is shown in Figure 7. The system uses a microprocessor to control the downstream VCS flow control valve which modulates to set the VCS fluid pressure (temperature) and, hence, flow rate through the fixed Viscojet orifices.

Table 6

VAPOR-COOLED SHIELD CONSTRUCTION AND PERFORMANCE

VCS Construction (Two hemispheres, each made of four octants joined together with rivets and standoffs)

Shield Material	6061-T6 aluminum
Thickness	0.41 cm (0.016 in.)
Thermal conductivity	190 W/m-°K at 22°K (110 BTU/hr-ft-°R at 40°R)
Single-Pass Tubing Material	6061-T6 aluminum
Size	0.318-cm dia x 0.038-cm wall (0.125 in. dia x 0.016-in. wall)
Attachment	1.27-cm (0.5-in.) wide clips spot-welded at 15-cm (6-in.) intervals
Standoffs — number, material:	32, nylon
Size	0.64-cm dia x 0.038-cm wall x 1.27-cm length (0.25-in. dia x 0.016-in. wall x 0.5-in. length)

VCS Performance

Nominal:
Vent flow rate: 0.0193 kg/hr (0.0426 lb/hr)
7-day vent loss: 3.25 kg (7.16 lb)
Viscojet P/N: VDCA 1815243K
Viscojet pressure drop: 17.2 N/cm^2 (25 psia)
VCS fluid pressure: 24.1 N/cm^2 (35 psia)
VCS fluid temperature: 23.6°K (42.5°R)
Maximum shield temperature gradient: 1.67°K (3.0°R) at 10% tube contact

Double MLI Heat Flux:

- At nominal vent rate
  Maximum VCS temperature: 41.6°K (75°R)
  Heat transfer to tank: 0.0076 W (0.026 BTU/hr)
- At maximum vent rate of 0.0287 kg/hr (0.0632 lb/hr)
  Maximum VCS temperature: 26.7°K (48°R)
  Heat transfer to tank: zero
  VCS fluid pressure: 3.45 N/cm^2 (5 psia)
  VCS fluid temperature: 17.1°K (30.8°R)

Double In-Tank Heat Flux:
Pressure rise in 7 days at nominal vent rate: 3.83 N/cm^2 (5.55 psia)
Pressure rise in 7 days at maximum vent rate: zero

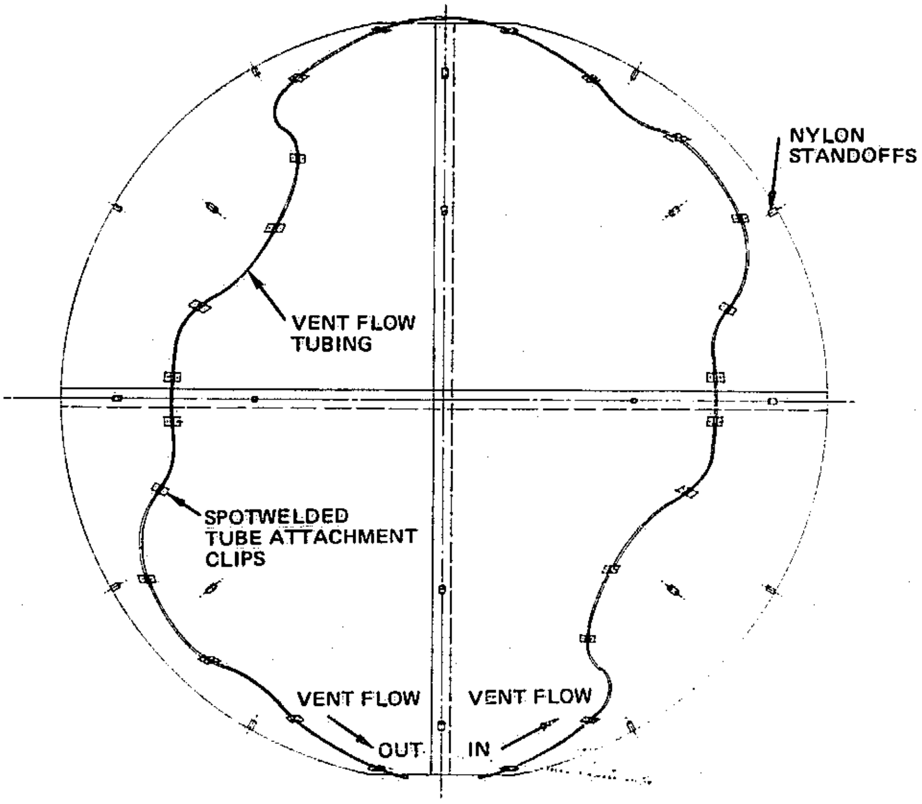

Figure 6. Vapor-Cooled Shield Layout

It was found that a similar microprocessor-controlled pressure control system has already been developed by Marotta Controls and that the system of Figure 7 is a straightforward modification of the Marotta system. The system operation is as follows: The shield outlet temperature is measured with a platinum resistance thermometer (PRT), as are the shield inlet temperature and tank temperature. These temperatures are measured at a sampling rate (e.g., once a minute) established by the multiplexer. The PRT outputs are digitized by an analog-to-digital converter and read into the microprocessor. The microprocessor uses a control algorithm to command the dual flow control valves to adjust the vent flow to keep the shield outlet temperature between the shield inlet and tank temperatures within an adjustable bias value. The shield temperatures are more sensitive to heat flux variations and are therefore used as the primary control parameters; however, as a backup mode, the tank pressure (which changes very slowly) is also monitored, and the vent flow adjusted to keep tank pressure within an estimated ±0.07 N/cm^2 of a preset value, e.g., 41.4 N/cm^2 (60 psia). This preset value, the temperature control bias, and the sampling rate could all be altered during testing or operation through keyboard entries.

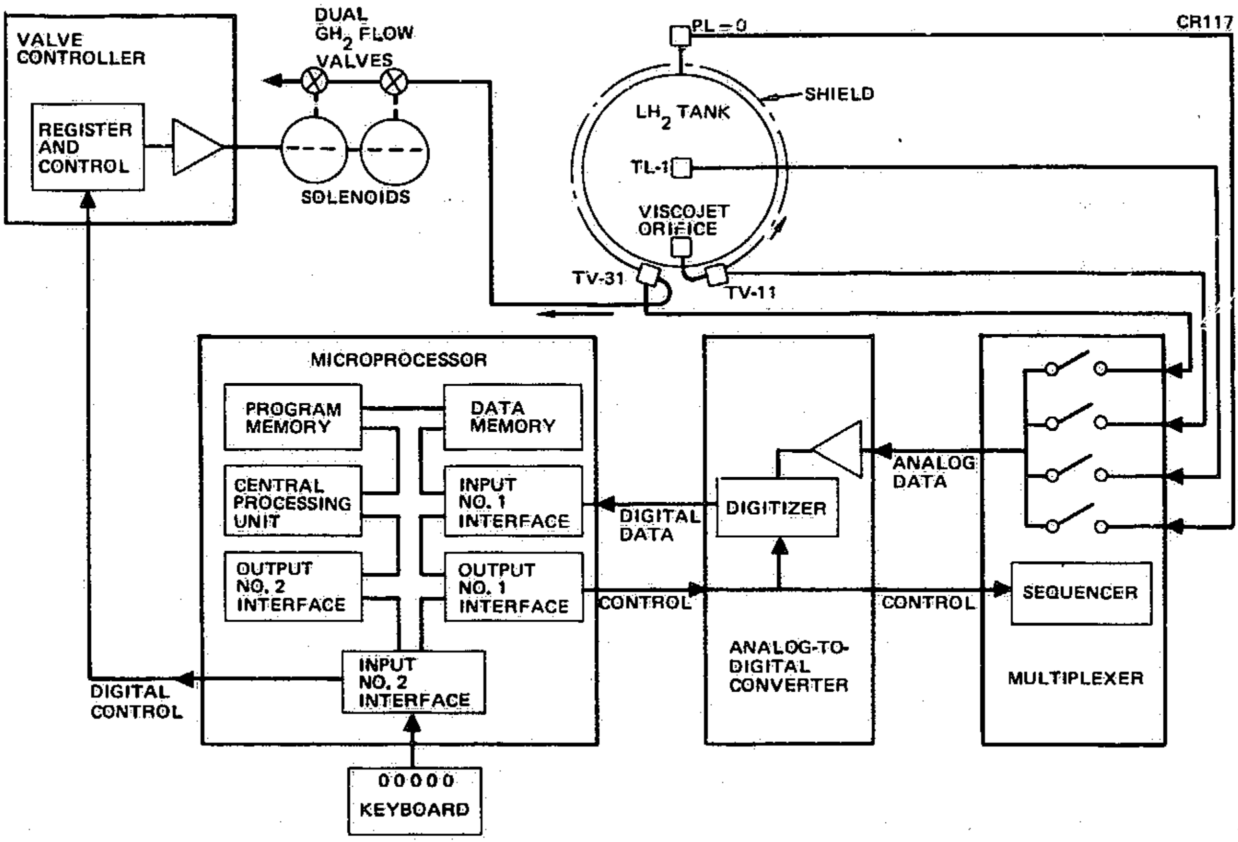

Figure 7. LH_2 Vent Control System Schematic

Multilayer Insulation

The VCS provides a convenient support for the MLI blanket, as shown in Figure 8. The PRSA MLI system is still under development, so an MDAC design was assumed for concept development. The MLI material assumed is 0.15-mil double aluminized mylar with dacron B4A net spacers which are formed in gore sections and laid up on the hemispherical VCS (supported by tooling) with the edges overlapped and taped. The heavier face sheets used top and bottom (Figure 8) provide support for the blanket. There are perforations in both the MLI and the VCS for depressurization of the MLI during evacuation. A heavy dacron net is placed next to the VCS to provide an outflow path during depressurization. The blankets are held to the VCS with nylon thread/buttons at the hemisphere edges, and a lap joint is provided at these edges (Figure 8) which is laced up after the VCS hemispheres are mated together. The access openings at the top and bottom of the VCS are filled with lap-joint plugs taped in place similar to the method shown in Figure 8. This kind of MLI system has been completely developed by MDAC

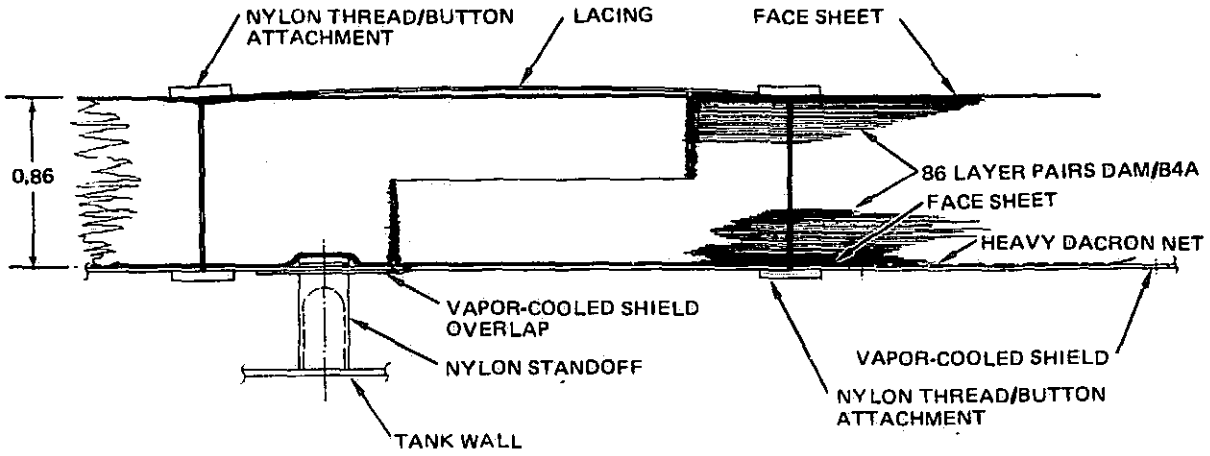

Figure 8. MLI Blanket and Lap Joint Construction

(Reference 17) and has demonstrated an effective thermal conductivity of 3.507×10^{-5} watts/m-°K (2.027×10^{-5} Btu/hr-ft-°R) at LH_2 temperatures at a layer density of 100 layer-pairs per in.

Plumbing

As mentioned previously, the plumbing lines can contribute substantially to the thermal performance of the experiment, and it is desirable that the line sizes be minimized commensurate with the required flow capacity. The PRSA was designed for high flowrate (near mission completion) of warm, low-density H_2 and, hence, required large-diameter (1.59 cm, 0.625-in.) outflow lines. To minimize heat leak, these lines were made of stainless steel and connected to the aluminum pressure vessel with bimetallic joints. Since the experiment is designed to always outflow high-density LH_2, the outflow lines can be made of aluminum and reduced in size, and the bimetallic joints eliminated. The line sizes selected are shown in Table 7 and are based on pressurization and outflow at the maximum PRSA flowrate of 1.48 kg/hr

Table 7

EXPERIMENT TUBING SIZES

Function	Diameter (cm)	Diameter (in.)	Wall Thickness (cm)	Wall Thickness (in.)	Length (cm)	Length (in.)
Thermodynamic Vent 6061-T6 Al	0.318	0.125	0.038	0.015	104	41
Pressurization 5052-0 Al	0.318	0.125	0.051	0.020	104	41
Outflow/Fill 5052-0 Al	0.635	0.250	0.051	0.020	104	41

(3.27 lb/hr). These sizes were also examined for acceptable ground operations (filling, venting relief, etc.) and were found adequate (as described later in the Procedures section).

The ground fill/drain line and the orbital outflow line are cooled by the VCS vent line (after leaving the VCS) and, thus, pass under the VCS/MLI and exit the tank at the girth ring through vacuum-jacketed lines. The pressurization line will be warm during pressurization and outflow, so it, together with the instrumentation wiring, passes outside the MLI. To maximize the conductive length and minimize heat flux during LH2 storage, the pressurization line and instrumentation wiring are insulated with about 20 layer-pairs of MLI. The arrangement of the lines is shown in Figure 9, and the reason for the location of the pressurization line outlet and the arrangement of the inverted tank are consequences of the fill procedures (described later).

The overall predicted thermal performance and heat balance of the integrated VCS/MLI/vacuum-jacketed thermal control system is shown in Table 8.

Fluid Flow Circuits and Control Components

The basic policy for the design of the experiment fluid flow circuitry and control components consists of the following:

- System simplicity with experiment operation flexibility.
- No EVA required to perform experiment.
- No credible failure mode or single point failure will result in personnel hazard.

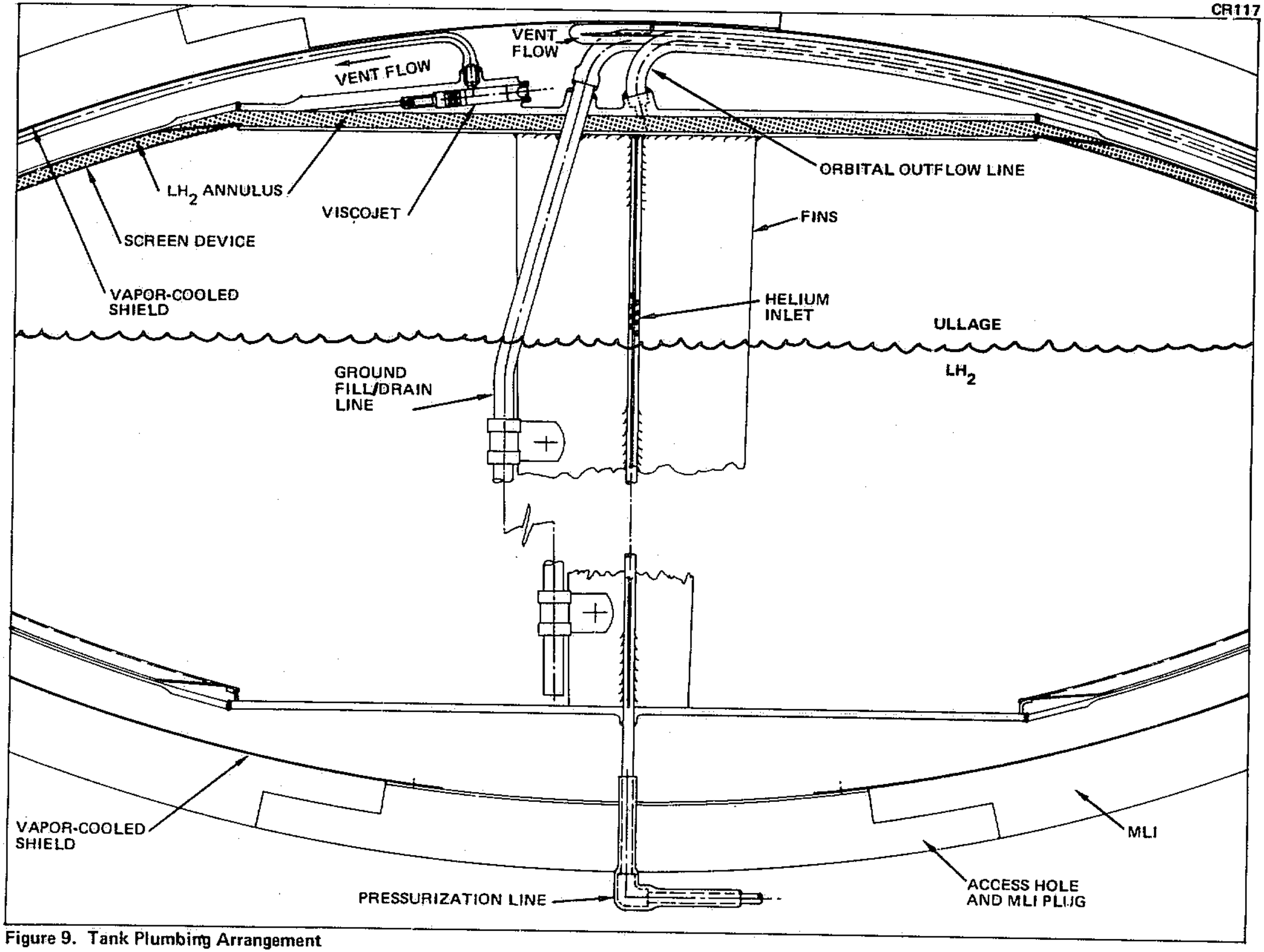

Figure 9. Tank Plumbing Arrangement

Table 8

PREDICTED THERMAL CONTROL SYSTEM PERFORMANCE

	Watts	Btu/hr
Heat Leak Into the Pressure Vessel		
1. Pressurization line	0.094	0.320
2. Platinum resistance sensors (4) wiring	0.242	0.825
Total	0.336	1.145
Heat Transferred From Pressure Vessel to VCS		
1. Conducted around Viscojet	0.103	0.350
2. Radiated from pressure vessel	0.001	0.0035
3. Conducted through VCS standoffs	0.0054	0.0185
4. Conducted through supports and copper heat shorts	0.0576	0.197
Total	0.167	0.569
Net Heat Leak to Tank	0.169	0.576
VCS Flow Heat Capacity (at 0.0193 kg/hr, 0.0426 lb/hr)	1.619	5.525
1. Conducted through supports	0.002	0.006
2. From pressure vessel	0.167	0.569
3. MLI budget	1.450	4.950
MLI Thickness	2.18 cm	0.86 in.
MLI Weight	4.95 kg	10.9 lb
VCS Weight	4.35 kg	9.6 lb

- Relief and ground safety provisions incorporated in GSE when possible.
- Redundant measurements for crucial experiment parameters.
- Use available component technology or simple extrapolations thereof.
- All components will be flight-qualifiable.
- All principal experiment functions will be ground-testable.

The overall experiment flow and control arrangement is shown in Figure 10, and consists of three principal fluid flow subsystems: vent system (described previously), pressurization system, and outflow system.

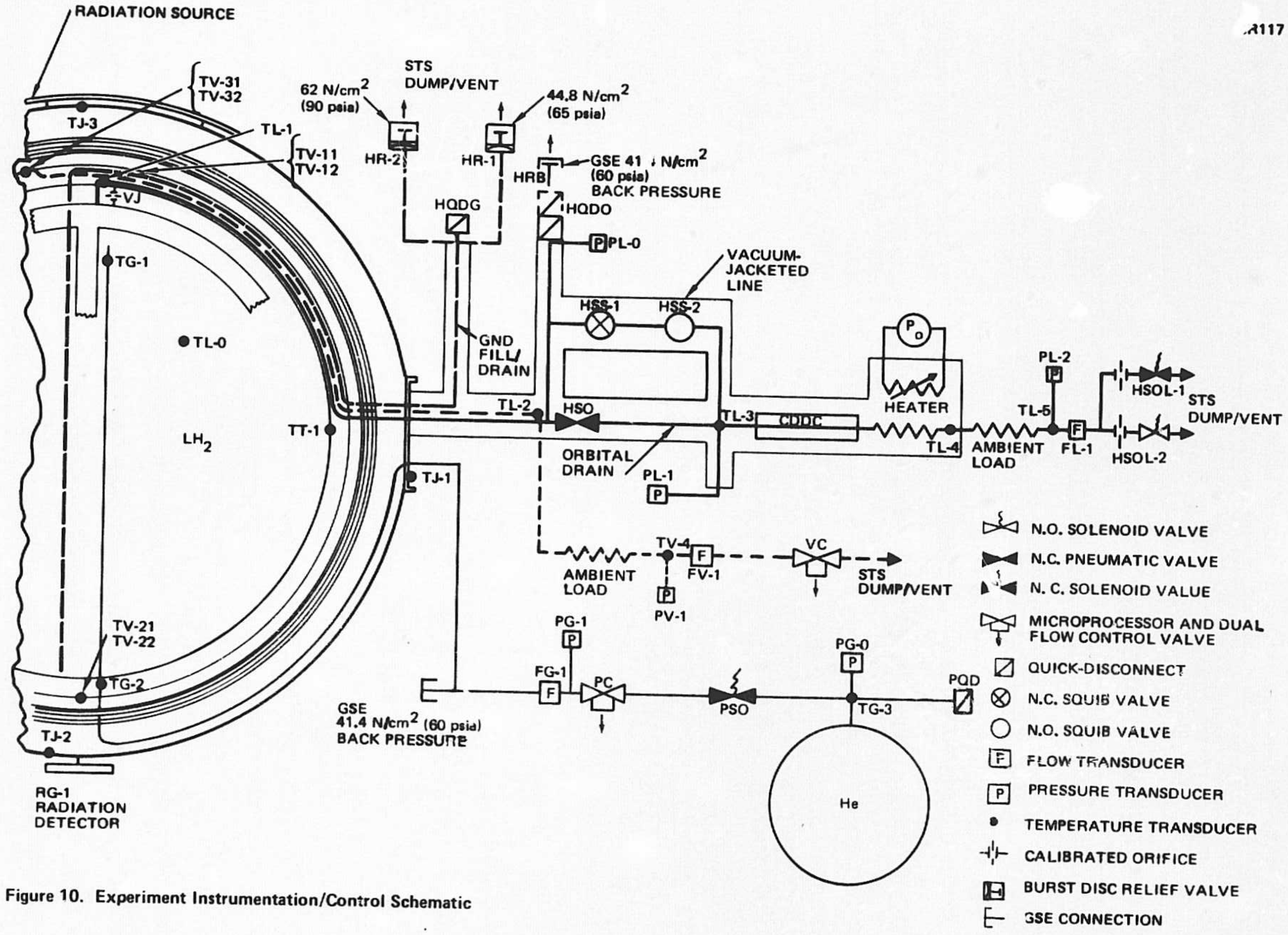

Figure 10. Experiment Instrumentation/Control Schematic

Pressurization System

The STS Orbiter RCS helium storage and pressurization system, including high-pressure bottle, filter, shutoff valve, and quick-disconnect, may be usable for the experiment. The RCS helium storage bottle is 48.3-cm (19.0-in.) diameter fiberglass wound titanium, and one of these bottles would store enough helium at 2620 N/cm^2 (3800 psia) and 256°K (460°R) for the equivalent of 2.7 expulsions. Since the helium is stored in an essentially controlled environment (payload bay), high-pressure relief is not used; rather it is included in the GSE, and the storage bottle would be suitably painted to control solar heating during flight.

The pressurization system supplies warm (220°K, 400°R) helium and employs the sensible heat of the incoming pressurant to vaporize LH_2 to reduce GHe requirements. The GHe required depends on the GHe inlet temperature which, in turn, depends on the heat transfer characteristics of the pressurization line. The helium inlet temperature and helium quantity requirements will be experimentally determined parameters.

The pressurization inlet line in the tank passes along the tank centerline, and is 91.4 cm (36 in.) long from where it enters the tank to where the helium is injected into the tank ullage (see Figure 9). This line length acts as a heat exchanger to cool the helium to tank temperature (36.1°K, 47°R) before it enters the ullage. Analysis indicates that at design conditions, the heat exchanger has a performance margin of 6 on length. Because of the indeterminate nature of film-boiling bubble behavior in low-g, fins were added to the pressurization line (see Figure 9) to try to help remove bubbles from the line.

The pressurization system acts in concert with the outflow system in that the pressurization system acts as a "demand" system which supplies helium to maintain constant outflow pressure. The pressurant regulation system not only drops the helium pressure from storage pressure varying from 2620 N/cm^2 (3800 psia) to 207 N/cm^2 (300 psia) to tank pressure (41.4 N/cm^2, 60 psia) but also controls the flowrate required to maintain constant liquid outlet pressure. A second adaptation of the microprocessor-controlled

Marotta pressure control system can be used for helium regulation. The difference between tank pressure PG-1 (or PL-0 as redundant backup, see Figure 10) and PL-2 is sensed and used to adjust the flow through dual solenoid flow control valves to maintain the desired pressure difference at less than 0.05% error. The pressure control system also eliminates conventional regulator lockup pressure overshoot.

The helium pressure control system has been qualified for Naval shipboard use, but additional qualification tests would be required for the STS flight requirements. The helium high-pressure shutoff valve (PSO) is not made redundant since other methods of LH_2 tank outflow could be used if the helium flow system fails. The tank could operate in a "blow-down" mode, although this may have a deleterious effect on screen device performance. With the channel screen device, stopping vent flow through the vapor-cooled shield would increase the heat flux to the tank such that an outflow rate of 0.194 kg/hr (0.428 lb/hr) could be maintained at constant tank pressure without pressurization.

LH_2 Outflow System

The LH_2 outflow system is straightforward in concept. The ground fill/drain and orbital outflow lines are vacuum-jacketed and cooled by the vent flow to stay at essentially LH_2 temperature up to the LH_2 shutoff valves (HSO, HSS-1). A burst disc relief valve (HR-2) set at 62 N/cm^2 (90 psia) is situated in the ground fill/drain line to relieve catastrophic overpressure caused by loss of vacuum around the LH_2 tank. Pressure excursions from potential helium leakage, etc. are handled through the low-pressure relief valve (HR-1) set at 44.8 N/cm^2 (65 psia). The flight-qualified LH_2 relief valves, filters, and Q/D's (HQDG, HQDO) used in the STS PRSA appear suitable for our system. The LH_2 outflow shutoff valve (HSO) appears to be available from the PRSA, or adaptable from a completely developed Parker submergible LH_2 valve.

Bypass valves using squib actuators (HSS-1, HSS-2) could provide the reliability and redundancy required to enable LH_2 tank draining even if the main LH_2 outflow shutoff valve fails. The Pyronetics squib valves meet the

STS safety requirements specified in References 14 and 15, and the actuation sequence will be accident-proofed through the switching circuitry, in accordance with Reference 15, so that the valves cannot be accidently actuated.

The LH_2 outflow system is set up as a single outflow rate design at 1.48 kg/hr (3.27 lb/hr) exhausting to vacuum in the STS hydrogen dump line through a calibrated orifice. Use of a modulating valve instead of the orifice to provide a range of flowrates would add system complexity, but use of a parallel calibrated orifice with ambient temperature solenoid shutoff valves (see Figure 10) could provide a more reliable capability for two lower flowrate options (e.g., 0.48 and 1.0 kg/hr). The LH_2 outflow passes through a controllable heater (used to vaporize the LH_2 and determine its thermodynamic state) and then both the outflow LH_2 and the vent fluid pass through ambient heat exchangers (in thermal contact with a large ambient-temperature mass like the pallet) to warm up the H_2 before it enters the pressure and flowrate instrumentation. All of the components required to perform experiment functions are shown in Table 9. Many of the components have already been developed for the STS and may be suppliable as government-furnished equipment. All components are either flight-qualified or developed from flight-qualifiable designs.

Instrumentation

The instrumentation required to provide the data needed to verify experiment objectives is shown in Table 10. All of the instruments shown are either flight-qualified or qualifiable. Many are already in use or are being developed for STS or spacecraft application. The radiation mass gaging system configuration was developed by Tyco Laboratories and is an adaptation of the hydrazine quantity gaging system (HQGS) flying aboard a Lockheed spacecraft. The radiation source is approximately 5 m (200 in.) of 0.64-cm dia x 0.125-cm wall (0.25-in. dia x 0.049-in. wall) aluminum tube configured to completely map the LH_2 tank with a single HQGS Geiger-Mueller detector assembly. The source contains two curies (8 millicuries gamma equivalent) of Krypton-85 gas at less than atmospheric pressure. The system weighs only 1.6 kg (3.5 lb), is completely qualified, and meets the radiation safety requirements of the State of California, the Atomic Energy Commission, and MIL-O-38338.

Table 9
CONTROL COMPONENT PARAMETERS

Name	Designation	Approx Weight (kg)	Possible Source	Flt-Qual	Approximate Cost ($)
Vent System					
Viscojet	VJ	0.01	Lee Company	No	100
Microprocessor/dual flow control valve	VC	1.4*	Marotta Controls	No	10,000
Pressurization System					
Quick-disconnect, helium	PQD	0.2	Fairchild-Stratos	Yes	1,100 or GFE (Shuttle RCS)
Shut-off valve, helium	PSO	0.6	Consol. Controls	Yes	14,000 or GFE (Shuttle RCS)
Microprocessor (dual flow control valve	PC	1.4*	Marotta Controls	No	10,000
LH_2 Outflow System					
Quick-disconnect, ground fill/drain	HQDG	0.7*	TBD	Yes	GFE (Shuttle PRSA)
Quick-disconnect, orbital drain	HQDO	0.7*	TBD	Yes	GFE (Shuttle PRSA)
Burst disc relief valve	HR	2.6	Parker-Hannifin	Yes	5,200 or GFE (Shuttle RCS)
GSE back-pressure relief valve	HRB	0.5*	Parker-Hannifin (?)	No	1,000
Pneumatic shutoff valve	HSO	1.8*	Parker-Hannifin	No	10,000 + 100,000 NR
Squib valve	HSS	0.9*	Pyronetics	Yes	3,000 + 20,000 NR
Ambient solenoid shutoff valve	HSOL	1.3	Consol. Controls	Yes	8,000 or GFE (Shuttle OMS)

*TBD — Estimated

Table 10 (Page 1 of 2)

INSTRUMENTATION PARAMETERS

Name	Designation	Range	Accuracy	Signal	Sample Rate	Approx Weight	Possible Source	Approx Cost ($)
LH_2 Mass Gauge	RG-1	Full (to) Empty	3% to 0.3% FS	A(a) 0-5.0 Vdc	1/sec	1.6 kg	General Nucleonics	Ship Set 15,000 NR(a) 30,000 QT(a) 20,000
Temperature								
He Diffuser	TG-1	(b) 20-50°K	±0.05°K	A(c)	1/sec	<1.0 g	Rosemount	200
He inlet	TG-2	20-300°K	↓	↓	↓	↓	↓	↓
He storage	TG-3	200-300°K	↓	↓	↓	↓	↓	↓
LH_2 bulk	TL-0	20-40°K	↓	↓	↓	↓	↓	↓
LH_2 outflow No. 1	TL-1	20-40°K	↓	↓	↓	↓	↓	↓
LH_2 outflow No. 2	TL-2	20-40°K	↓	↓	↓	↓	↓	↓
LH_2 outflow No. 3	TL-3	20-40°K	↓	↓	↓	↓	↓	↓
LH_2 outflow No. 4	TL-4	20-40°K	↓	↓	↓	↓	↓	↓
LH_2 outflow No. 5	TL-5	200-300°K	↓	↓	↓	↓	↓	↓
VCS inlet No. 1	TV-11	10-40°K	↓	↓	↓	↓	↓	↓
VCS inlet No. 2	TV-12	10-40°K	↓	↓	↓	↓	↓	↓
VCS half No. 1	TV-21	10-50°K	↓	↓	↓	↓	↓	↓
VCS half No. 2	TV-22	10-50°K	↓	↓	↓	↓	↓	↓
VCS outlet No. 1	TV-31	10-50°K	↓	↓	↓	↓	↓	↓
VCS outlet No. 2	TV-32	10-50°K	↓	↓	↓	↓	↓	↓
VCS overboard	TV-4	200-300°K	↓	↓	↓	↓	↓	↓
LH_2 tank	TT-1	20-300°K	↓	↓	↓	↓	↓	↓
Girth ring	TJ-1	200-300°K	↓	↓	↓	↓	↓	↓
Vac Jkt No. 1	TJ-2	200-300°K	↓	↓	↓	↓	↓	↓
Vac Jkt No. 2	TJ-3	200-300°K	±0.05°K	A(c)	1/sec	<1.0 g	Rosemount	200

Table 10 (Page 2 of 2)

INSTRUMENTATION PARAMETERS

Name	Designation	Range	Accuracy	Signal	Sample Rate	Approx Weight	Possible Source	Approx Cost ($)
Pressure								
He storage	PG-0	(b) 0-2760 N/cm^2	±0.7 N/cm^2	A/0-5.0 Vdc	1/sec	0.13 kg	Statham	1200
He pressurant	PG-1	0-42 N/cm^2	±0.04 N/cm^2	↓	↓	↓	↓	↓
LH_2 tank	PL-0	0-42 N/cm^2	±0.04 N/cm^2	↓	↓	↓	↓	↓
LH_2 outlet	PL-1	0-42 N/cm^2	±0.04 N/cm^2	↓	↓	↓	↓	↓
Ambient H_2	PL-2	0-42 N/cm^2	±0.04 N/cm^2	↓	↓	↓	↓	↓
Vent H_2	PV-1	0-42 N/cm^2	±0.04 N/cm^2	A/0-5.0 Vdc	1/sec	0.13 kg	Statham	1200
LH_2 Density	CDDC	0-72 kg/m^3	1% FS	A/0-5 Vdc	1/sec	0.9 kg	Quantomics-Liu	7,000 NR 3,000 QT 5,000
Flow								
He pressurant	FG-1	(a) 0-10 SLM	2% FS	A/0-5 Vdc	1/sec	0.39 kg	Tylan	5,000
H_2 vent	FV-1	0-10 SLM	2% FS	A/0-5 Vdc	1/sec	0.39 kg	Tylan	5,000
LH_2 outflow	FL-1	0-300 SLM	2% FS	A/0-5 Vdc	1/sec	0.39 kg	Tylan	5,000 NR 10,000
LH_2 Heater Power	P_o	0-200 W	2% FS	(d) A/0-5 Vdc	1/sec	0.05 kg	MDAC	1,000 NR 5,000 QT 5,000

(a) Legend: A — analog; NR — Nonrecurring; QT — Qual-test; SLM — std liters per minute

(b) Orbital flight range

(c) Signal depends on bridge network; Could be 0-5 Vdc over range shown

(d) Signal depends on output bridge network

The platinum resistance sensors for temperature measurement are of two basic types: surface sensors for measuring the temperature of the VCS, tank wall, etc., and immersion sensors for fluid temperature measurement. The temperature sensor used in the Orbiter PRSA is a Rosemount 500 Ω (ice-point resistance) unit, and similar flight-qualifiable sensors are available essentially off-the-shelf.

The pressure tranducers selected are thin-film strain gage units such as made by Statham, which are available as qualified units over all pressure ranges. Special designs of such transducers can be used to near-LH_2 temperature (note that only one transducer, PL-1, actually senses the pressure of flowing LH_2, and it will be mounted on a short standoff).

The LH_2 outflow density is measured by a Quantomics-Liu cryogenic dielectric-to-density converter (CDDC) which is a rugged unit with no moving parts and can apparently be qualified for flight use, although no units of this type have been flown. The mass flowmeters, on the other hand, are currently being developed by Tylan Corporation and qualified for the Spacelab atmosphere revitalization pressure control system. These units measure gas flow at ambient temperatures to accuracies of about 1 to 2% and weigh only 0.38 kg (0.85 lb). Minor modifications of these units to meet the required fluid and flowrate range are necessary.

The power requirements and configuration of the calibrated heater used to determine the thermodynamic state of the LH_2 outflow was determined to be 160 watts at maximum LH_2 flow, using a 53-cm (21-in.) long nichrome wire-wound vacuum-jacketed tube.

Experiment Installation

Installation of the experimental tanks and components is most conveniently done in the European Space Agency (ESA) standard pallet. The ESA pallet provides mounting provisions and data/control/power interfaces for experiments, and is flown in the STS Orbiter payload bay either with the Spacelab module or independently with experiment control from the payload specialist station forward of the bay. The volume of the experiment only requires about one-third of a pallet, and the relatively light experiment tanks can be conveniently mounted with simple tubular tension members from the hardpoints incorporated in the pallet, as shown in Figure 11. An artists conception of a pallet-mounted experiment (with other experiments sharing the pallet) is shown in the frontispiece. As shown in Figure 11, there is ample room for packaging components, instrumentation, and data acquisition/signal conditioning equipment.

In addition to normal installation of the experiment on a pallet mounted within the payload bay, mounting of the experiment tanks straddling the Spacelab ingress/egress tunnel was investigated. It appears that for many missions, the tunnel area could be a reasonable location for the experiment; there are 19 missions within the first 50 which could accommodate the cryogenic propellant management experiment either in the tunnel area or on a pallet. For all of the Spacelab life sciences missions, no pallets are carried and there are three payload specialists aboard. Since our experiment requires minimal

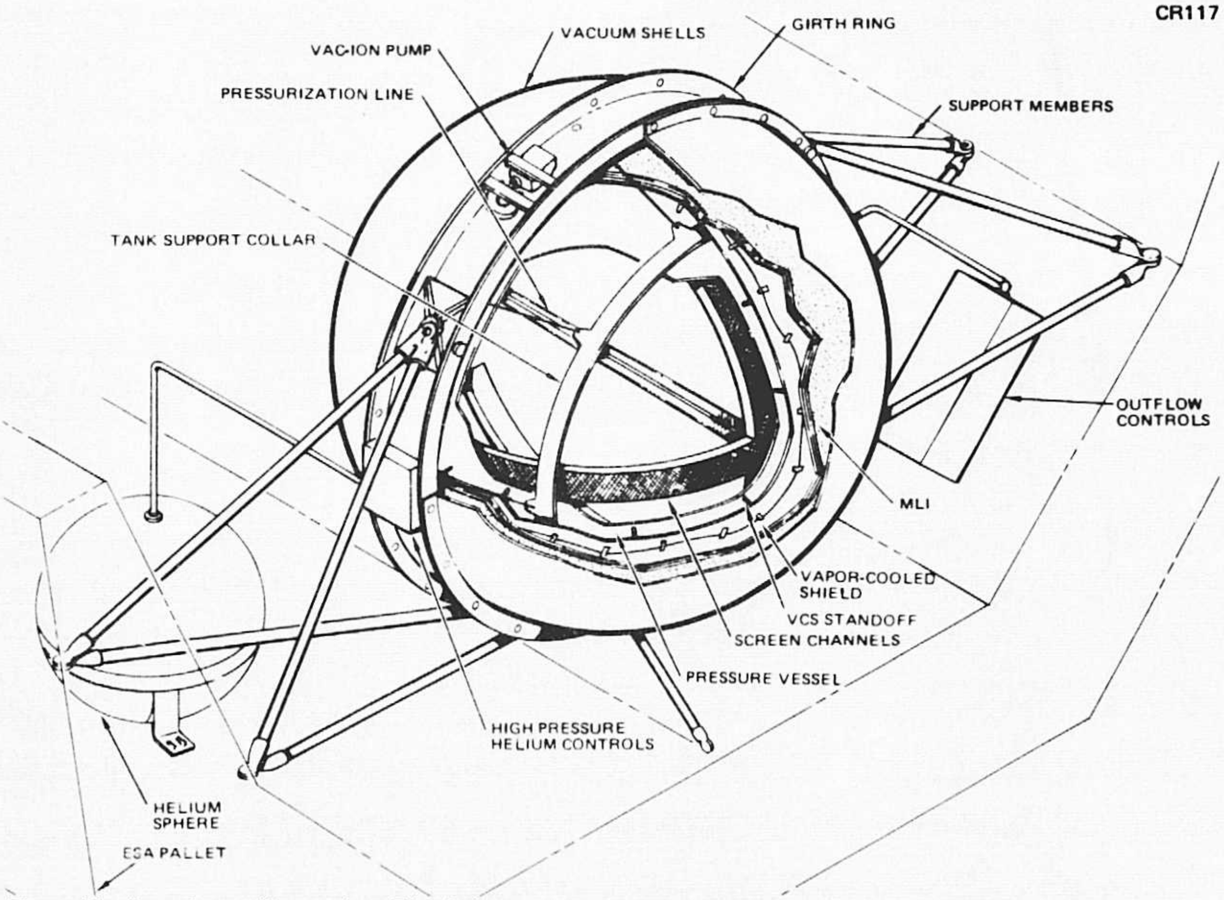

Figure 11. Experiment Mounted on ESA Pallett

payload specialist monitoring, it is possible that these missions would be potentially usable. The experiment tank system is shown mounted beside the "short" tunnel configuration in Figure 12. An artists conception showing two experiment tanks straddling the tunnel is shown in Figure 13. Because of the relatively light weight of the experiment, the payload cg shift is minimal even with two LH_2 tanks: the X-direction cg moves forward only 22.9 cm (9.0 in.) even for the farthest forward minimum-weight Spacelab. This is well within the cg envelope, and less far forward than the worst pallet configuration. The Spacelab cg is biased to the +Y side, so that mounting the experiment tank on the -Y side of the tunnel moves the payload cg 11.7 cm (4.5 in.) back toward the centerline, even with the minimum-weight Spacelab.

Tubular tension supports for the experiment tankage would have to be integrated with the airlock and tunnel supports, since they would share payload bay hard points at Stations 649 and 715. However, the supports would not interfere with airlock EVA operations. The experiment would be controlled

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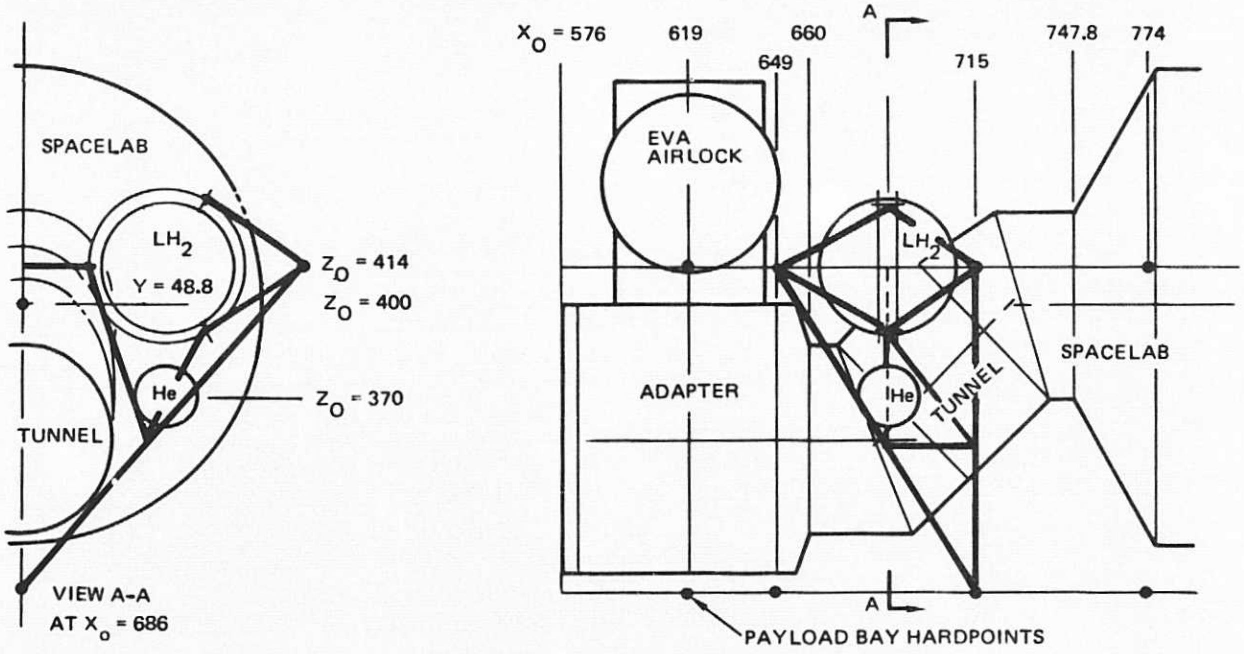

Figure 12. Preliminary Experiment/Spacelab Short Tunnel Layout

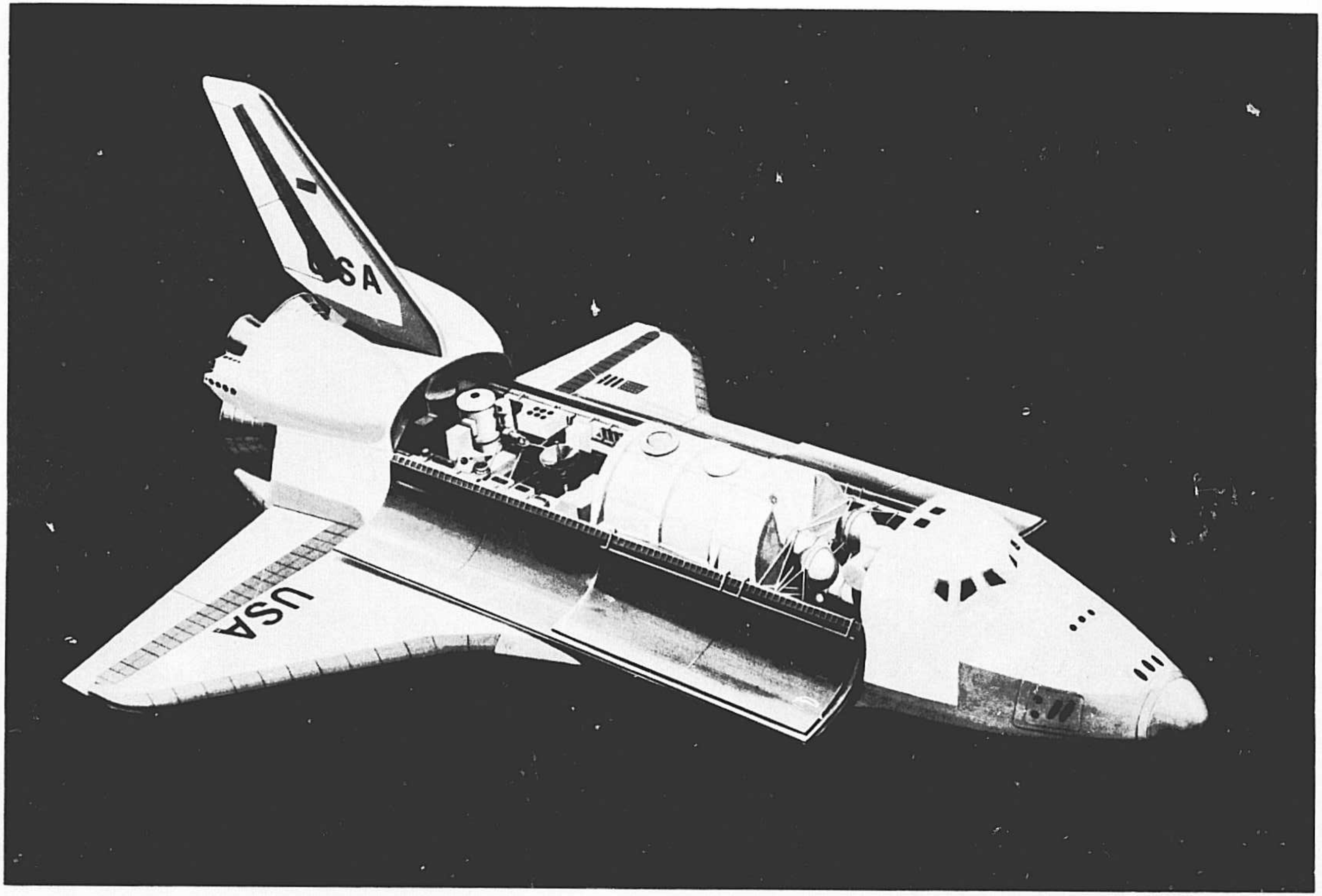

Figure 13. Experiment Installation in Tunnel Area

from the payload specialist station forward of the bay or from the Spacelab. Equipment rack space may be a problem since much of this space is taken up by Spacelab support equipment. However, the minimal experiment requirements for electrical/data interface may be able to be accommodated, resulting in an efficient exploitation of currently unusable area in the payload bay.

The experiment weight and volume breakdown and summary is shown in Table 11. The total experiment package including fluids and supports is about one-fourth the estimated weight of the basic pallet, and volume requirements are minimal. In fact, two tank systems could be accommodated within the same section of pallet occupied by the one-tank experiment shown in Figure 11.

Table 11

EXPERIMENT WEIGHT/VOLUME ESTIMATE

	Weight		Volume	
	(kg)	(lb)	(m^3)	(ft^3)
Experiment Tankage	67.4	148.5	2.05	72.3
Pressure vessel	(8.6)	(19.0)		
Vapor-cooled shield	(4.4)	(9.6)		
Multilayer insulation	(4.9)	(10.9)		
Screen device	(2.3)	(5.0)		
Collars/supports	(1.0)	(2.3)		
Internal hardware/ plumbing	(2.3)	(5.0)		
Vacuum shell	(19.8)	(43.6)		
Girth ring	(20.7)	(45.6)		
Electrical/Vac-ion pump	(3.4)	(7.5)		
Liquid Hydrogen	38.6	85.1	--	--
Helium Storage Sphere	12.0	26.5	0.13	4.6
Helium	2.5	5.5	--	--
Instrumentation	4.6	10.1	0.015	0.5
Controls	16.4	36.1	0.015	0.5
External Plumbing	2.7	6.0	--	0.1
External Heat Exchangers	0.9	2.0	--	0.1
Experiment Tension Supports — Pallet	16.6	36.7	0.03	1.1
Total Experiment	161.7	356.5	2.24	79.2
ESA Pallet (Ref) Approx	632.0	1,393.0	--	--
Additional Tension Supports, Tunnel Location	32.7	72.0	0.06	2.2

SUPPORT REQUIREMENTS

Support requirements for the experiment include data acquisition recording and transmission equipment, electrical power, fluid and cooling interfaces, and the ground support equipment (GSE) required to checkout and perform ground operations, pre-launch operations and provide data/control support functions during flight.

Ground Support Equipment

Because of the relative simplicity of the experiment operations, highly specialized GSE is not required beyond normal cryogenic fluid and high-pressure gas servicing functions. GSE requirements are at three basic levels: (1) ground test GSE to support development of the experiment and verify operational capability, (2) the mechanical and electrical ground support equipment (EGSE) used to support integration and checkout of the experiment pallet and Spacelab (and through the Orbiter Processing Facility, Orbiter integration and checkout), and (3) GSE required for prelaunch, launch, and flight support.

The GSE needed for experiment development and operational verification consists of the usual storage, transfer, vacuum, vent, purge, and disposal equipment required for LH_2 operations. The LH_2 storage supply and GSE back-pressure vent controls must be capable of supplying 41.4 N/cm^2 (60 psia) saturated LH_2 at a flowrate of 45 kg/hr (100 lb/hr). Other GSE requirements are for measured helium gas supply capable of regulation to 41.4 N/cm^2 (60 psia), and up to 200 watts of regulated 28 Vdc power available for component/instrumentation functions. Control and instrumentation development would be supported by the usual GSE data acquisition and FM recording equipment and GSE control consoles. Detailed definition of these requirements would be accomplished during experiment detailed design.

The Spacelab EGSE design is based on the use of computer-controlled automatic test equipment (ATE) augmented by simulators, and is described in currently defined detail in Reference 16. It is designed to support the Spacelab during the integration, prelaunch, launch, postflight, and maintenance and refurbishment phases with its primary purpose to ensure that the Spacelab subsystems are operating within their design limits. In addition, the

EGSE equipment supports experiment integration and the EGSE is used for payload final checkout by interacting with the Spacelab command and data management system (CDMS) and special payload GSE.

Overall test control is implemented via the EGSE computer, checkout software, and CDMS data acquisition capabilities. The EGSE simulates Spacelab interfaces and functions to facilitate payload preparation prior to integration into Spacelab. Integration of the experiment with the pallet is supported by the core segment simulator. Postintegration payload support is provided via the EGSE/CDMS computer link.

The ATE portion of the EGSE configures the test setups, controls the test sequencing, and performs the data acquisition, decommutation, evaluation, recording, and display. It also controls the generation and verification of commands and encoded data.

The Orbiter interface adapter (OIA) acts as the primary Spacelab EGSE interface during all test phases when the Spacelab/experiment is outside the payload bay. The OIA simulates Spacelab-related electrical Orbiter resources. Functions which are generated by the ATE are routed through the OIA to the Spacelab feedthroughs. A simulated Orbiter aft flight deck is included in the OIA for installation of subsystem- and experiment-dedicated equipment.

At the launch site, the EGSE will be used during the prelaunch and launch phase for subsystem preparation, Spacelab-experiment interface verification, and integration and final checkout, and to support Spacelab-Orbiter interface verification, integration, and final checkout.

The existing GSE used at the launch site to provide helium fill of the Orbiter RCS helium system can be used directly to fill the experiment helium system. The LH_2 supply system for filling of the PRSA would have to be modified to provide 41.4 N/cm^2 (60 psia) saturated LH_2 to the experiment, probably by the addition of a separate high-pressure LH_2 storage tank and transfer system.

Data Acquisition

During flight, the basic data acquisition/control interface with the pallet is through remote acquisition units (RAUs) to the CDMS. Although there are provisions for four RAU's on each pallet, our experiment only requires the services of one RAU (capable of handling 64 analog inputs). The other RAUs could support other experiments sharing the pallet.

The CDMS provides services including data acquisition, monitoring, formating, processing, displaying, caution and warning, recording, and transmitting in addition to providing command control capability for Spacelab experiments. An additional set of equipment provides similar services to the Spacelab subsystems.

The equipment provided by the CDMS to Spacelab experiments is listed in Table 12.

Table 12

CDMS-PROVIDED EQUIPMENT

Basic Spacelab	Mission-Dependent
1. Data bus	1. Experiment computer
2. Mass memory	2. Experiment I/O unit
3. Keyboard/data display unit (2)	3. Experiment RAU
4. Intercom	4. Keyboard/data display unit
	5. High-rate multiplexer
	6. Voice digitizer
	7. High rate digital recorder

Experiment outputs, including status and low-speed scientific data, are sampled by RAUs, and transferred to the experiment computer via the experiment data bus and the input/output unit.

The data acquired through RAUs which are to be telemetered are then routed through the Orbiter avionics system to the ground. Data can also be routed to the computer for on-board processing, such as conversion to engineering units, etc. These data can be displayed on a Data Display Unit, as requested by the on-board experimenter via an alphanumeric keyboard.

PROCEDURES

Representative procedures were developed for some phases of experiment development and operations, including ground testing for experiment operational verification and orbital experiment operations. Detailed procedures for these operations and for contingencies depend on the detailed experiment design and are beyond the scope of experiment definition. The following procedures are intended only to indicate the scope of experiment development ground testing and important typical orbital tests.

Ground Testing

As previously shown in Figures 9 and 10, the tank and screen device are "upside down" with draining from the screen device against earth gravity. This is done primarily to assure complete filling of the screen device, in spite of screen wicking, by filling to overflow through the orbital drain line; this assures that no gas bubbles are trapped in the screen device. This also allows demonstration of negative 1-g outflow and verification of adequate screen device performance.

The basic fill level is determined by the position of the pressurization gas inlet since the tank is vented through the pressurization line during filling; this level must provide a screen retention performance margin against launch g-levels if the screen is exposed above this level. For launch accelerations of 3.3 g's, a safety margin of 2.0 on retention head, and for 200 x 1400 mesh screen, the minimum fill level is 6.4 cm (2.5 in.) below the uppermost screen portion (see Figure 9). During ground operations, the experiment tank would be oriented in the launch configuration either on the pallet (on end) or on a suitable mockup.

The typical ground operations for experiment operational verification are shown in Table 13, and are representative of the usual procedures used for

Table 13 (Page 1 of 2)

GROUND TEST PROCEDURES

Operation	Data/Test Objective
1. Annulus Evacuation ● GSE vacuum pump to 10^{-4} Torr ● Vac-ion pump to TBD Torr ● Hold at TBD (max vacuum) Torr	● Outgasing rate ● Pumpdown time ● Vacuum leakage ● Annulus vacuum level
2. LH_2 Tank Evacuation/He Purge Cycles ● GSE vacuum pump, GSE He supply ● Pressurize to 41.4-44.8 N/cm^2 (60-65 psia)	● Purge LH_2 tank ● Check pressure relief ● Vacuum leakage
3. LH_2 Tank Fill, Low Pressure ● ~14 N/cm^2 (20 psia) ● 12-hour hold	● Check thermal cycle ● Check chilldown time/fill schedule/control ● Check vent system operation ● Check gaging/instrumentation ● Vacuum leakage
4. Drain LH_2 Tank Empty ● Use ground fill/drain line ● GSE He supply ● Rapid outflow rate (1 hr)	● Check drain capability ● Check gaging/instrumentation
5. High-Pressure He Fill ● Pressurize LH_2 tank to 41.4 N/cm^2 (60 psia)	● Check He system operation ● Verify GSE relief capability ● Vacuum leakage

Table 13 (Page 2 of 2)

GROUND TEST PROCEDURES

Operation	Data/Test Objective
6. LH_2 Tank Fill, High Pressure • 41.4 N/cm^2 (60 psia) • 24-hr hold	• Thermal performance/stabilization • LH_2 back-pressure system • Childown time/fill schedule/control • Vent system operation/nominal vent rate/temperature distribution • Check gaging/instrumentation • Vacuum leakage
7. Drain LH_2 Tank to Screen Breakdown • Use orbital drain line • Orbital outflow rate (~8.7 hr)	• Check screen performance • Check pressurization system performance • Check gaging/instrumentation
8. LH_2 Tank Refill, High Pressure	• Check screen wickover/fill capability • Check pressurization line vent/relief • Check gaging/instrumentation
9. Drain LH_2 Tank to Screen Breakdown • Use orbital drain line • Orbital outflow rate (~8.7 hr)	• Recheck screen performance • Recheck pressurization system performance • Check gaging/instrumentation
10. Drain LH_2 Tank Empty • Use ground fill/drain line • Use experiment He system • Orbital outflow rate (~16 hr)	• Check pressurization system performance/He usage • Check gaging/instrumentation
11. LH_2 Tank Purge/Evacuate/Warmup/Inert	

cryogenic fluid system checkout. The LH_2 ground fill procedure proceeds as follows. After initial tank evacuation and helium inerting, the tank is first filled through the ground fill/drain line against minimum GSE back pressure (GSE vent system open to disposal lines) of about 14 N/cm^2 (20 psia) with the tank venting through the helium pressurization line and GSE helium connection and at low (vapor) flow through the TVS Viscojet. After approximately 10 minutes chilldown, the tank would start filling and would fill to the level of the pressurization line overflow in about 50 minutes. When the pressurization line overflows, TG-2 (see Figure 10) would show "hard" LH_2 temperature, and the back pressure would rise indicating 99% full and signaling cessation of fill.

At this time, although the tank is chilled down, the VCS and MLI are not, since the vapor vent flow through the Viscojet is much too low. It is estimated that 12 hours would be required to chill down the VCS and MLI through radiation and standoff conduction to the tank and through low flowrate vapor venting (this will be verified during ground testing). During this time, the screen device will wick over (although it may have done so during filling) so that bubbles generated (by VCS heat flux to the tank) in the screen liner annulus or in the tank will be vented through the Viscojet or through the pressurization/vent line. When the VCS reaches a reasonable level of chilldown (as monitored by the VCS temperature sensors), which may be as warm as about 56°K (100°R), the tank would be drained through the ground fill drain line using low-pressure GSE helium supply.

At this point, while the tank is empty but cold, the experiment high-pressure helium storage system is filled to 2620 N/cm^2 (3800 psia) and the tank pressurized to 41.4 N/cm^2 (60 psia). The LH_2 tank is then filled against a 41.4 N/cm^2 back pressure by venting through the pressurization line GSE relief valve until overflow occurs (as before). At this time, the GSE relief valve is closed and the 41.4 N/cm^2 (60 psia) GSE LH_2 back pressure valve in the orbital outflow line is opened and the final screen channel or annulus fill is completed while venting through the orbital outflow line until full (detected by TL-2 showing "hard" LH_2 temperature). At the same time, the TVS would be venting LH_2 through the Viscojet and would show expanded (low) LH_2 temperatures in the VCS inlet sensor (TV-11 or -12) when the annulus is full.

Inflow would be terminated and the TVS control system would then take over thermal control of the tank.

Once the tank has been filled and the TVS control system is functioning, a 24-hour period would allow thermal control system temperature stabilization and verification of proper storage system operation. With the downstream vent flow regulator exhausting to vacuum (through a vacuum pump), it is expected that the thermal performance of the TVS on the ground would not differ significantly from its performance in orbit. The only unadjustable part of the vent system is the Viscojet, which is a fixed series of orifices. However, as shown in Figure 9, the Viscojet is installed from outside the tank and welded in place. If ground testing indicates unacceptable performance requiring increase of the Viscojet flow capacity, the Viscojet welded plug could be drilled out and the Viscojet replaced. Note also that all instrumentation used to control the TVS could be located external to the welded-up pressure vessel, allowing replacement (although with considerable difficulty) if failure occurred during ground testing.

Following the hold period, the pressurization/outflow system would be exercised by draining the tank against negative 1-g through the orbital drain line at design orbital vent rate until screen breakdown (loss of retention capability) occurs. All instrumentation would be monitored during this test and breakdown could be detected by a sharp decrease in outflow density in the CDDC, by a sharp drop in outflow rate as detected by the flowmeter FL-1, by a sharp rise in pressurization flowrate (FG-1), or by changes in VCS temperature.

The screen should break down at about one-third empty and the radiation mass gage should be able to verify the breakdown head within 1 to 2%. Following breakdown, the tank could be refilled through the ground drain/fill line as above, and the screen breakdown test repeated as required. Following the final breakdown test, the tank could be drained through the ground fill/drain line at orbital outflow rate, but using the experiment helium pressurization system to provide baseline helium pressurant requirements. The LH_2 tank and flow system would of course be purged and inerted following ground testing.

Flight Testing

The prelaunch and orbital flight testing would typically follow the same procedures and operations verified by the ground tests, as shown in Table 14. The prelaunch operations of evacuation, pressurization, and fill of the LH_2 and helium systems are essentially the same as described above. In addition, the flight data/control system would be checked for proper operation during the Spacelab/Orbiter/experiment prelaunch checkout. Once the LH_2 storage system is chilled down and topped off to fill the screen device, it is estimated that up to 60 hours of on-pad hold could be endured by the experiment before the LH_2 level drops to where launch g's (at a safety factor of 2.0) could induce screen breakdown for the screen channel device.

The orbital flight procedures are designed to demonstrate the performance of the thermal control system for orbital cryogen storage and the screen device performance for orbital transfer of LH_2. The procedures shown in Table 14 require minimum astronaut/payload specialist involvement. A timeline for astronaut/payload specialist activities would require detailed procedures and integration of activities with other experiments, and is beyond the scope of concept definition. However, the experiment is designed to run automatically except where changes in operating mode or outflow rate are made, so that astronaut/payload specialist operating requirements are minimized.

The data gathered during testing are taken automatically at a rate of about once per seond, and are telemetered through the Spacelab CDMS. Certain data are displayed continuously for experiment control purposes, and all data are available for monitoring. Data (e.g., LH_2 tank and helium sphere pressure) are also used for caution and warning purposes.

The TVS performance is monitored during orbital flight to determine vent rate and tank pressure control performance. After approximately five days in-orbit (the maximum coast time available with a seven-day mission), the orbital outflow procedures would be initiated by the astronaut/payload specialist. Contingency procedures will be available to allow earlier outflow operations in the event of abnormal TVS performance. The nominal LH_2

Table 14
ORBITAL FLIGHT PROCEDURES

Operation	Data/Test Objective
1. Monitor Experiment During Coast • 5 Days	• Verify thermal control system performance • Vent rate/VCS data • Check gaging/instrumentation
2. Initiate Low-G LH_2 Outflow • Orbital outflow rate or rates • 18 hr	• Verify LH_2 condition • Verify pressurization system performance/constant pressure outflow • Check gaging/instrumentation • Check thermal control system during outflow
3. Change to Unvented/Unpressurized LH_2 Outflow • Outflow rate TBD (~12 hr) • LH_2 tank ~ 25% full	• Check outflow rate • Determine VCS thermal response • Check gaging/instrumentation • Check LH_2 condition/screen breakdown (?)
4. Resume Normal Low-G LH_2 Outflow • Orbital outflow rate • Empty tank	• Check LH_2 condition • Determine TVS thermal response • Check pressurization system performance/He usage • Check gaging/instrumentation • Determine residual H_2/He
5. Evacuate/Purge LH_2 Tank • Dump He through LH_2 tank • Evacuate LH_2 tank	• Check thermal control system response • Inert system

outflow rate of 1.48 kg/hr (3.27 lb/hr) could be maintained for up to 18 hours, or other flowrate options (e.g. 1 kg/hr or 0.48 kg/hr) could be exercised, using the microprocessor control on the pressurization/outflow system, to determine system response.

Outflow should be maintained until the tank is about 25% full. The outflow/pressurization mode could then be switched to the unvented/unpressurized outflow mode where the tank heat leak maintains constant tank pressure while outflowing at about 0.194 kg/hr (0.428 lb/hr). This mode could be continued for about 12 hours or until screen breakdown occurs (detected by the CDDC density meter and other instruments as in the ground tests described above). If screen breakdown does not occur after 12 hours, the outflow mode could be switched back to the nominal outflow rate, which would continue to tank depletion/screen breakdown. The final LH_2 residual and helium pressurant usage requirements would be determined.

If screen breakdown does occur due to screen dryout during unvented/unpressurized outflow, venting through the TVS could be resumed, while holding for about one hour to see if wicking reseals the screen. If this occurs, as indicated by normal (LH_2) vent flow, then pressurized outflow could be resumed. If resumption of outflow is not possible, or if outflow is complete, the LH_2 tank would be inerted by blowing the tank down to vacuum and alternately pressurizing with residual helium, until the LH_2 has boiled off and been dumped. The tank would be further inerted after H_2 dumping by alternately evacuating and pressurizing with the remaining residual helium until depleted.

Following the initial one-tank orbital experiment, the apparatus could be refurbished at minimal cost and could be used for further testing as part of the two-tank experiment option. With the optional two-tank experiment configuration, of course, the testing procedures could also include refill of one tank/screen device from the other, and a much more comprehensive and flexible test program could be performed.

DATA ANALYSIS

Analysis of test and design data will determine system performance and verify that the experiment objectives have been met. The basic experiment objective is to demonstrate the feasibility and desirability of subcritical cryogen orbital storage and supply. The desirability of subcritical (compared to supercritical) cryogen storage and supply systems is evident from design aspects of the experiment, i.e. reduced weight and power consumption and ability to deliver saturated or subcooled liquid. If the experiment can meet all of the test objectives of Tables 13 and 14, it will have demonstrated the feasibility of subcritical cryogen storage and transfer in orbit.

The performance of the system will basically be mapped by the ground test program. The baseline thermal performance of the system will be established by ground tests and the proper component selection and operation (e.g. microprocessor TVS, Viscojet, vapor-cooled shield) to achieve tank pressure control will be demonstrated. The basic data used to verify thermal control system performance is tank pressure, which is measured with two redundant pressure transducers (see Figure 10). Many other instruments will supply data to evaluate details of thermal control system performance. The VCS pressure and temperature distribution, together with vent flowrate, will allow determination of system heat flux and verification of VCS design adequacy.

The system heat flux can also be inferred from the unvented, unpressurized outflow tests, since the liquid volume outflow rate will self-adjust, keeping tank pressure constant, until it equals the in-tank vaporization (volume) rate from system heat flux.

It should be noted that with high-performance thermal control systems, changes occur very slowly, and it will take at least a day — perhaps several — for the thermal control system conditions to stabilize. Similarly, outflow at maximum flowrate takes about 25 hours. Thus there will be great quantities of data available for use in correlating events. The largest influence on thermal control system performance will be changes in external environment; for the ground tests, conditions will be rather uniform, while in orbit there may be unknown or periodic variations in payload bay and vacuum jacket temperature. It is anticipated that, for a given vacuum level in the MLI, these external temperature variations will be the principal cause of MLI and other heat flux variations.

The ability of the screen device to supply saturated or subcooled LH_2 will also be verified first by ground tests. Outflow against 1-g is hydrodynamically a more severe test than low-g outflow and will provide verification of screen device head capability and complete filling. Again, redundant data determine the condition of the LH_2 outflow; the LH_2 density is measured directly by the CDDC and can be compared to predicted values of LH_2 density at the measured LH_2 temperature and pressure. In addition the LH_2 is boiled at constant pressure, and the power needed to supply heat of vaporization will indicate LH_2 quality into the heater. Finally, the existence of LH_2 in the screen annulus can be verified from TVS vent flowrate, which differs markedly for vapor or liquid flow through the Viscojet.

The helium flow requirements compared to the LH_2 outflow rate, and the helium inlet condition data, will verify the performance of the pressurization/outflow system. The major operational differences between ground and orbital testing will occur during pressurization with the in-tank helium heat exchanger.

Since film boiling bubble behavior (and heat transfer coefficient) in low gravity are not well defined, the helium inlet temperature to the tank may vary, and hence the degree of in-tank LH_2 vaporization and consequent helium use is not known. The ground testing will defined baseline requirements, but determination of orbital pressurization system performance is a basic experiment objective.

The helium inlet temperature is measured at the tank inlet and also at the gas injection point. The integrated helium inflow rate (volumetric) subtracted from the integrated LH_2 (volumetric) outflow rate gives the volumetric rate of in-tank LH_2 vaporization and, hence, the equivalent low-g overall heat transfer coefficient.

The overall data verification of experiment objectives are summarized in Table 15.

Table 15

DATA ANALYSIS

Experiment Objective	Data Verification
1. Weight savings compared to supercritical system.	1. Pressure vessel/screen device assembly and pressurization system weight.
2. Power savings compared to supercritical system.	2. Experiment power requirements during coast and outflow with and without LH_2 vaporization heater.
3. Tank pressure control using a vapor-cooled shield thermodynamic vent system.	3. a. Tank pressure maintained constant in orbit by TVS. b. VCS pressure, temperature distribution, and vent flowrate. c. Unvented, unpressurized LH_2 outflow rate. d. Environmental temperature variations.
4. Supply of saturated LH_2 in orbit using a screen device and helium pressurization system.	4. a. LH_2 density during outflow. b. LH_2 outflow rate, pressure, and temperature. c. LH_2 vaporization power requirements. d. Helium flowrate quantity, inlet temperature, and pressure control.
5. Ground servicing and 1-g performance capability.	5. a. Ground chilldown, fill, vent, and system stabilization. b. Negative 1-g outflow screen head verification.
6. Development of technology applicable to potential system users.	6. Applicable existing technology and components.

EXPERIMENT COST ESTIMATE

A cost analysis of the experiment was performed to determine rought-order-of-magnitude (ROM) costs for experiment hardware and instrumentation. The costs determined are approximate, and are only intended to identify especially costly components or subsystems and to indicate available or developable flight-type components which could be made available to the experiment as GFE. For many of the flight components being developed for the STS Orbiter PRSA or RCS, costs were not available; where component costs were available, they were based on a current procurement contract, and there would doubtless be additional nonrecurring costs for future startup, additional qualification paperwork, etc. The ESA pallet was assumed as GFE for experiment integration since other experiments would share the pallet, and the cost distribution is unknown. This is also appropriate since the current estimated cost of the ESA pallet is about $1,800,000 which far exceeds all other experiment hardware costs (Reference 18).

The estimated experiment hardware costs are shown in Table 16. Clearly the dominant costs will not be hardware procurement costs, but rather the presently unknown costs of development, checkout, qualification at subsystem level, and integration with pallet, Spacelab, and STS Orbiter.

Table 16

ESTIMATED EXPERIMENT HARDWARE COSTS (1976 DOLLARS)

Item	Non-Recurring Cost	Unit Cost
Screen Device		
Pleated Liner	30,000	70,000
Channel	1,000	15,000.
Pressure Vessel	50,000	25,000
Vapor-Cooled Shield	10,000	5,000
MLI	5,000	25,000
Vacuum Shells	5,000	GFE*
Girth Ring	5,000	GFE+5,000*
Helium Sphere	5,000	28,000 or GFE*
Control Components	125,000	78,600 and/or GFE*
Instrumentation	88,000	49,200
Checkout Control Console	10,000	5,000
Flight Control Console	30,000	8,000

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*TBD

Section 3

SUMMARY AND RECOMMENDATIONS

In order to demonstrate the desirability and feasibility of subcritical cryogenic fluid orbital storage and supply, the conceptual design of a Spacelab cryogen management experiment was performed. The experiment was conceived as a LH_2 tank 1.06 m (41.7 in.) in diameter with a screen device and helium pressurization system for LH_2 supply, and a high-performance thermal control system comprised of a vapor-cooled shield thermodynamic vent system, multilayer insulation, and vacuum jacket. The experiment could be mounted on the ESA pallet and flown with Spacelab in the STS Orbiter payload bay, or alternatively, could be mounted in the bay next to the Spacelab ingress/egress tunnel. The complete experiment package in the payload bay, including fluids and pallet mounting supports, weighs 162 kg.

It is apparent from the conceptual experiment design that essentially all of the technology and much of the hardware needed to demonstrate successful orbital storage and supply of subcritical cryogens is now available. A successful orbital demonstration will give confidence in the design of cryogen supply systems which will result in substantial performance gains from uprating existing subsystems (e.g., STS Orbiter PRSA) and designs of new systems (e.g., Space Station). This experiment will demonstrate the crucial supply technology half of the problem of in-orbit resupply of propellants, life support fluids, etc., necessary for efficient deployment of future space systems such as Space Station and OTV. Because of the immediate technology applications and substantial performance gains available from subcritical cryogen storage and supply, it is recommended that detailed design and development of the Spacelab cryogenic fluid management experiment be initiated immediately. It is further recommended that detailed analysis and consideration be given to installation of the experiment package beside the Spacelab tunnel to allow mission flexibility and integration on STS flights before 1982.

Finally, it is apparent that two tanks interconnected to provide multiple expulsion and refill capability would provide a much more flexible and interesting experiment program; if successful, this could provide essentially the total technology needed for in-orbit transfer of cryogens. It is acknowledged that technology gaps exist in the area of refill dynamics, therefore it is recommended that a technology program be immediately initiated to study and define the dynamics of tank/screen device refill. It is further recommended that conceptual design be initiated for a future two-tank experiment using the fully developed and refurbished experiment tank from the Spacelab cryogenic fluid management experiment.

The benefits to be gained from the experiment, the technology issues yet to be resolved, and recommendations to resolve these issues are summarized in Table 17.

Table 17

EXPERIMENT BENEFITS, ISSUES, AND RECOMMENDATIONS SUMMARY

Benefits resulting from Spacelab cryogen management experiment:

1. The following experimental operations will be demonstrated for the first time:
   - Orbital subcritical cryogen storage and supply
   - Cryogen thermodynamic vent system technology
   - Use of screen device for low-gravity supply of cryogen
   - Weight and power savings compared to supercritical cryogen storage and supply.
2. Technology for cryogen orbital storage and supply will be proven which will have immediate application in:
   - Uprating performance of existing systems (STS Orbiter PRSA)
   - High-performance subsystem design for future systems (Space Station, OTV, satellites, sorties).

Issues yet to be resolved:

1. Successful integration of cryogen thermal control system and screen device for fluid supply
2. Uncertain behavior of cryogens during refill in orbit
   - Screen device wickover
   - Refill venting
   - Fluid dynamics.
3. Tank-to-tank cryogen transfer in low-gravity

Recommendations to resolve issues:

1. Initiate detail design and development of Spacelab cryogen management experiment.
2. Perform technology study to define cryogen refill behavior.
3. Initiate conceptual design of Spacelab two-tank transfer experiment.

Section 4

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Appendix A

SURVEY OF SMALL-SCALE CRYOGENIC FLUID STORAGE/SUPPLY SYSTEMS (Page 1 of 2)

Reference No.	System Description	Fluid	Quantity (kg)	Thermodynamic State	Fluid Storage Times (days)	Fluid Supply Rate (kg/sec)	Comments
(Ref 6) 1A	Space Tug-dedicated APS (some burns by MPS)	LO_2	130.4	Subcooled liq at 91.7°K and 152 N/cm^2	7	0.1	1 LO_2 tank
		LH_2	42.6	Subcooled liq at 27.8°K and 152 N/cm^2		0.0245	3 LH_2 tanks
1B	(All burns by APS)	LO_2	956.8	Subcooled liq at 91.7°K and 152 N/cm^2		0.1	9 LO_2 tanks
		LH_2	268.2	Subcooled liq at 27.8°K and 152 N/cm^2		0.0245	1 LH_2 Torus
(Ref 5) 2	Spacelab atmosphere makeup	LN_2	68.6	Gas at 300°K and 10.1 N/cm^2	30	2.4×10^{-5}	
		LO_2	96.6	Gas at 300°K and 10.1 N/cm^2		3.1×10^{-5}	May be available from Shuttle PRSA
(Ref 5) 3	Shuttle fuel cell reactant supply	LO_2	708.6	Gas at 145° - 350°K and 41.4 N/cm^2	7	1.75×10^{-3} max continuous	2 LO_2 tanks
		LH_2	83.4	Gas at 90° - 350°K and 41.4 N/cm^2		2.2×10^{-4} max continuous	2 LH_2 tanks
(Ref 7) 4	Space Station atmosphere	LN_2	606	Gas at 300°K and 10.1 N/cm^2	180 (90 Resupply)	9.1×10^{-6} 0.0136	Leakage only Repress.
		LO_2	183.7	Gas at 300°K and 10.1 N/cm^2		2.5×10^{-6} 0.0043	Leakage only Repress.
(Ref 8) 5	Modular Space Station atmosphere makeup	LN_2	231.0	Gas at 300°K and 10.1 N/cm^2	120 (90 Resupply)	5.7×10^{-7} 0.0236	Leakage only Repress.
		LO_2	240.0	Gas at 300°K and 10.1 N/cm^2		6×10^{-5} 0.0085	Metabolic consumption Repress
(Ref 9, 10)							
AS-02-A	Extra Coronal Lyman Alpha Explorer						
HE-07-A	Small High Energy Satellite						
	Propulsion Orbit Adjust	LN_2	90.7	Gas at 273°K and 18 N/cm^2	730	0.070	F = 4.44 N 101 M/S = ΔV
	Attitude Control	LN_2	22.6	Gas at 273°K and 18 N/cm^2	730	0.0007	F = 0.445 N
HE-01-A	Large X-Ray Telescope Facility						
HE-03-A	Extended X-Ray Survey						
HE-08-A	Large High-Energy Observatory A						
HE-09-A	Large High-Energy Observatory B						
HE-11-A	Large High-Energy Observatory D						
	Attitude Control	LN_2	100	Gas at 273°K and 18 N/cm^2	730	0.070	Assume F = 44.4N
HE-09-A	Large High-Energy Observatory B						
	Magnet Cooling	LHe	430	Subcooled liq at 3 ± 1.2°K and 10.1 N/cm^2	730	1.36×10^{-5}	365 Days Supply (Reliquefaction)
AP-04-A	Gravity and Relativity Satellite						
	Gyroscope Cooling	LHe	135	Subcooled liq at 1.6°K and 10.1 N/cm^2	365	4.28×10^{-6}	Accurate Temp Control on LHe
OP-01-A	Geopause						
	Attitude Control	LN_2	115.6	Gas at 273°K and 18 N/cm^2	1825	0.0007	Assume F = 0.445N

SURVEY OF SMALL-SCALE CRYOGENIC FLUID STORAGE/SUPPLY SYSTEMS (Page 2 of 2)

Reference No.	System Description	Fluid	Quantity (kg)	Thermodynamic State	Fluid Storage Times (days)	Fluid Supply Rate (kg/sec)	Comments
(Ref 11)							
AS-01-S	1M Shuttle IR Telescope Facility						
	Instrument Cooling	LHe	150.8	Supercritical?	7	2.5 × 10^{-4}	Tankage Sized for 680 kg He for 30 Days
		LHe	59.7	Subcooled liq at 2 ± 0.5°K and 10.1 N/cm^2		1.0 × 10^{-4}	LH_2 or LN_2, T.C.S.
AS-03-S	Deep Sky UV Survey Telescope						
	Instrument Cooling	LHe	10.5	Subcooled liq?	7	1.7 × 10^{-5}	Self-Contained In Instrument
AS-15-S	3M Ambient Temperature IR Telescope						
	Instrument Cooling	LHe	59.7	Subcooled liq at 2 ± 0.5°K and 10.1 N/cm^2	7	1.0 × 10^{-4}	Tankage Sized for 544 kg He for 30 Days
HE-15-S	Magnetic Spectrometer						
	Instrument Cooling	LHe	18.0	Subcooled liq at 3 ± 1.2°K and 10.1 N/cm^2	7	3 × 10^{-5}	Dewar Around Superconducting Magnet
SO-01-S	Dedicated Solar Sortie Mission						
SO-15-S	Solar Activity Early Payload						
	Instrument Cooling	LN_2	TBD	Subcooled liq?	7	TBD	Self-Contained In Instrument
SO-01-S	Dedicated Solar Sortie Mission						
SO-11-S	Solar Fine-Pointing Payload						
SO-15-S	Solar Activity Early Payload						
SO-17-S	Solar Activity Growth Processes						
	Purge Gas	LN_2	272	Gas at 273°K and 10.1 N/cm^2	7	3 × 10^{-3}	Stored as H. P. Gas
AP-06-S	Atmospheric Magnetosphere and Plasma in Space						
	Instrument Cooling	LN_2	8	Subcooled liq at 77°K and 10.1 N/cm^2	7	1.3 × 10^{-3}	
		LHe	22	Subcooled liq at 4°K and 10.1 N/cm^2		3.6 × 10^{-5}	
LS-09-S	Life Sciences Shuttle Laboratory						
	Freeze Trap	LN_2	41	Subcooled liq at 77°K and 10.1 N/cm^2?	30 or 7	1.4 × 10^{-5}	
EO-19-S	Mark II Interferometer-Solar						
EO-22-S	Mark II Interferometer-Earth						
	Instrument Cooling	LN_2	25	Subcooled liq at 77°K and 10.1 N/cm^2?	7	4.1 × 10^{-5}	
SP-01-S	Space Processing (Biological)						
	Fuel Cell Propellants	LO_2	132	Gas at 145° - 350°K and 41.4 N/cm^2	7	2.8 × 10^{-4}	Uses Shuttle Orbiter PRSA
		LH_2	16.5	Gas at 90° - 350°K and 41.4 N/cm^2		3.5 × 10^{-5}	
SP-14-S	Space Processing (Manned & Automated)						
SP-15-S	Space Processing (Automated Furnace/Levitation)						
	Fuel Cell Propellants	LO_2	398	Gas at 145° - 350°K and 41.4 N/cm^2	7	7.1 × 10^{-4}	60 kg Vented-Uses Shuttle Orbiter PRSA
		LH_2	50.3	Gas at 90° - 350°K and 41.4 N/cm^2		9.5 × 10^{-5}	5.3 kg Vented
SP-31-S	Space Processing (Biological/Furnace)						
	Cryo-Freezer	LN_2?	6	Subcooled liq?	7	6.5 × 10^{-5}	28 kg Stored?
CN-05-S	CO_2 Laser Data Relay Link						
	Experiment Cooling	LN_2	10	Subcooled liq	7	1.2 × 10^{-6}	
P. 3-25, 3-46 V. 2 Ref 12	Cryo-Cooled IR Telescope	LHe	18	Supercritical fluid at 20°K and 30.4 N/cm^2. Also subcooled liq at 4°K and 10.1 N/cm^2.	7	3 × 10^{-5}	