



Contract NAS 9-17852  
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DRD MA-183TJ  
F88-04

# SUPERFLUID HELIUM TANKER (SFHT) STUDY

## Final Report

1 October 1988

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(SFHT) STUDY (Ball Aerospace Systems Div.)  
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Approved by:

A handwritten signature in cursive script that reads "Richard Hopkins". The signature is written in black ink and is positioned above a horizontal line.

Richard Hopkins  
Study Manager



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## FOREWORD

This report documents results of the Superfluid Helium Tanker Study performed for NASA Lyndon B. Johnson Spaceflight Center by Ball Aerospace Systems Group in Boulder, Colorado. The NASA technical manager for this contract, NAS 9-17852, is Mr. William C. Boyd of the JSC Propulsion and Power Division. As required by the Statement of Work, the study effort included: Task 1 - Collection of Requirements, Task 2 - Fluid Subsystem Conceptual Design, Task 3 - System Analysis and Design, Task 4 - Commonality Assessment and Technology Development Recommendations, and Task 5 - Development Program Plan.



## ACRONYMS AND ABBREVIATIONS

AFD	AFT Flight Deck
AP	Attached Payload
AUM	Automatic Umbilical Mechanism
AXAF	Advanced X-Ray Astrophysics Facility
BASD	Ball Aerospace Systems Division
CCTV	Closed Circuit Television
CF	Centrifugal
CITE	Cargo Integration Test Equipment
COBE	Cosmic Background Explorer
CRT	Cathode Ray Tube
CT	Cryogen Tank
CWEA	Caution and Warning Electronics Assembly
EGSE	Electrical Ground Support Equipment
EL	Electro-luminescent
ELV	Expendable Launch Vehicle
EPROM	Erasable Programmable Read Only Memory
EVA	Extravehicular Activity
GPC	General Purpose Computer
GSE	Ground Support Equipment
IRAS	Infrared Astronomical Satellite
J-T	Joule-Thomson
JSC	Johnson Space Center
LAD	Liquid Acquisition Device
LCD	Liquid Crystal Display
LM	Lab Module
LTV	Low-thrust Vent
MLI	Multilayer Insulation
MMS/FSS	Multimission Modular Spacecraft/Flight Support System
MMPS/CPFF	Microgravity and Materials Processing Facility/Critical Point Phenomena Facility
MRMS	Mobile Remote Manipulator System
O&C	Operations and Checkout Building
OMV	Orbital Maneuvering Vehicle
OPF	Orbiter Processing Facility
OSCRS	Orbital Spacecraft Consumable Resupply System
PGHM	Payload Ground Handling Mechanism
PHSF	Payload Hazardous Servicing Facility
PPF	Payload Processing Facility
RCS	Reaction Control System
RMS	Remote Manipulator System
RSS	Rotating Service Structure
RV	Relief Valve
SAEF 2	Spacecraft Assembly and Encapsulation Facility, No. 2
SCS	System Control Station
SEE	Standard End Effector
SfHe	Superfluid Helium
SFHT	Superfluid Helium Tanker
SHOOT	Superfluid Helium On-Orbit Transfer
SINDA	Systems Improved Numerical Differencing Analyzer
SIP	Standard Interface Panels
SIRTF	Space Infrared Telescope Facility
SMRM	Solar Maximum Repair Mission
SRV	Short Range Vehicle
SS	Space Station





SSF	Satellite Servicing Facility
SSP	Standard Switch Panel
STE	Special Test Equipment
STICCR	SIRTF Telescope Instrument Changeout and Cryogen Replenishment
STS	Space Transportation System
TDRSS	Tracking and Data Relay Satellite System
TM	Thermomechanical
TPDM	Three Point Docking Mechanism
VCS	Vapor-Cooled Shield
VPF	Vertical Processing Facility
VPHD	Vertical Payload Handling Device
XRS	X-Ray Spectrometer



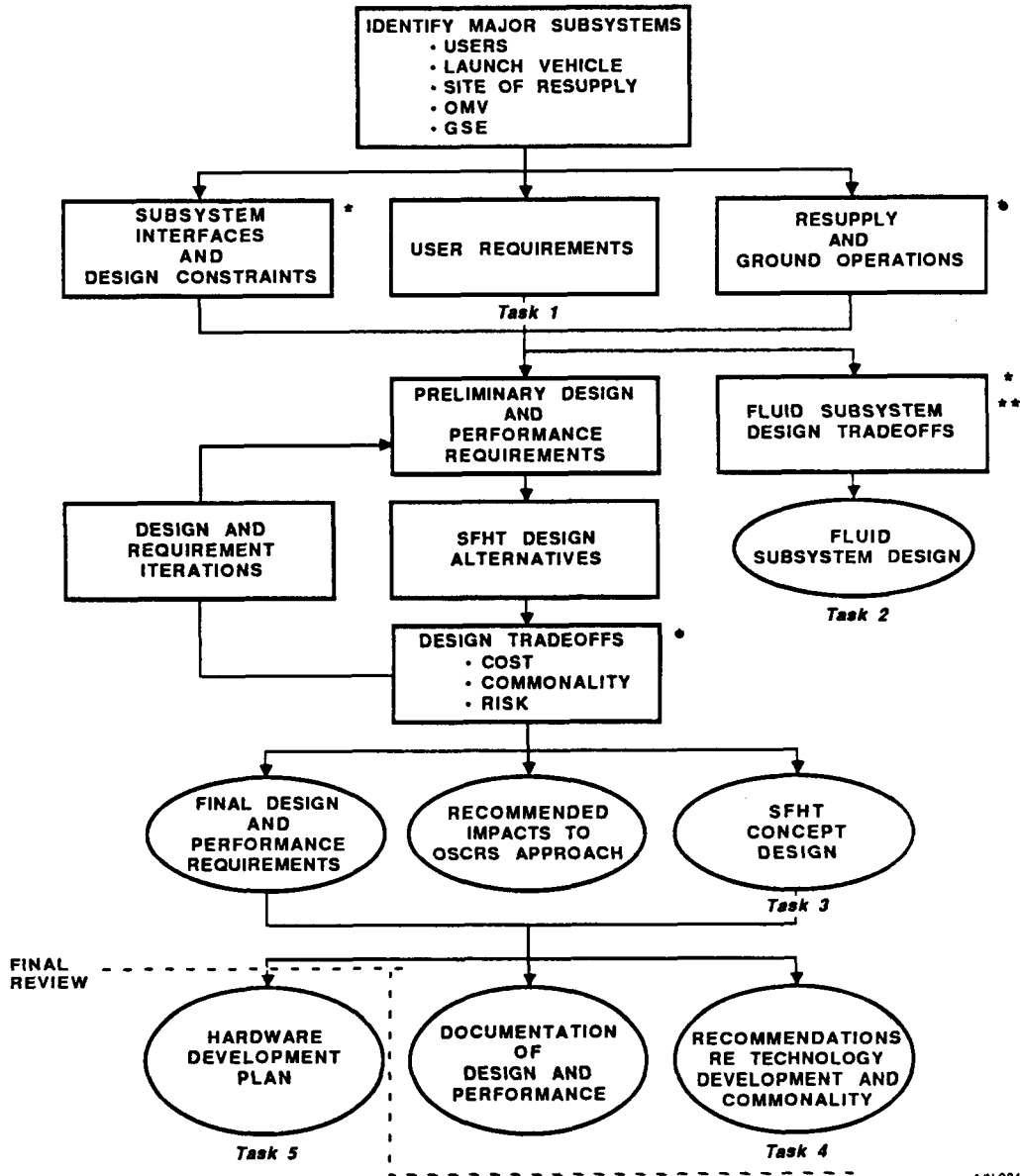
Section 1  
SUMMARY

On-orbit fluid resupply is an economical approach to several aspects of the United States space program in the near future. The first is providing propellants, primarily hydrazines in the near future and eventually also liquid hydrogen, to extend satellite lifetimes by replenishing their station-keeping fuel and to refuel orbital maneuvering and transport vehicles needed to support manned presence in space. The second is replenishment of consumables at the space station (SS), such as nitrogen needed for the life support system. The current baseline is to carry nitrogen to the SS in the form of supercritical (cryogenic) nitrogen. This can be done with current technology. Launch mass and cost can be reduced by carrying liquid (two-phase), rather than supercritical, cryogen into space. For that approach technology development in the areas of liquid acquisition and liquid/vapor phase separation is needed. The third major application for fluid resupply is to replenish instrument systems using stored cryogens for cooling. Lifetimes of these systems are limited by the amount of cryogen that can be carried into orbit within mass and envelope constraints. This third application, specifically helium resupply, is addressed by this study.

Development of helium resupply technology is most urgent compared to resupply of other fluids because the potential applications are more immediate. The nearest and highest priority applications are the Particle Astrophysics Magnet Facility (Astromag), under development at NASA Goddard Space Flight Center, and the Space Infrared Telescope Facility (SIRTF), under development at NASA Ames Research Center. Resupply of these systems is scheduled to occur about the year 2000. SIRTF is the major driver in designing the Superfluid Helium Tanker (SFHT) because it requires the greatest quantity of helium. To maximize the value of this study, effort was focused on those issues and design features that impact cost (development and operations), risk (technical and programmatic), and interface parameters. This includes items such as dewar size, transfer system, and fluid operations. Minimal effort will be spent on the detailed definition of items that require straightforward technology and don't significantly impact the design of any other parts of the system.

This report documents accomplishments and recommendations of the two-phase SFHT study. During the first phase of the study, the emphasis was on defining a comprehensive set of user requirements, establishing SFHT interface parameters and design requirements, and selecting a fluid subsystem design concept. During the second phase, an overall system design concept has been constructed based on appropriate analyses and more detailed definition of requirements. Achieving commonality with the orbital spacecraft consumables resupply system (OSCRS) design has been a consideration, especially related to the avionics. Modifications needed to extend the baseline for use with cryogens other than S<sub>f</sub>He have been determined, and technology development needs related to the recommended design have been assessed.

Figure 1-1 shows the logic flow of the study. Some cost estimates have been made in support of configuration and operation tradeoffs; these are shown. During the final study phase, analysis of the on-orbit transfer system has been conducted in greater detail than originally planned to verify concept feasibility, identify design drivers, and establish performance parameters. This was advisable since the major design uncertainties and technology development issues are related to this aspect of the system.



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\* USING RESULTS FROM STICCR STUDIES  
 \*\* USING RESULTS FROM SHOOT PROGRAM

Figure 1-1 Study logic flow



Major system design requirements are summarized below:

- Provide 8,900 ℓ (based on resupply of warm SIRTf) of SfHe after 9 months of orbital standby (at the SS).
- Launch on STS with Titan IV as an alternative.
- Perform resupply in the shuttle bay with the SS as an alternative.
- Resupply a variety of users, with primary consideration given to Astromag, SIRTf, AXAF XRS, MMPF/ CPPF, and Lambda-point Experiment.
- Perform host and user mating functions by EVA in the initial concept, but consider extension to automatic mating.
- Be compatible with all associated interface and design constraints imposed by other involved systems.
- Emphasize low-risk, low-cost approaches.

The baseline design concept is shown in Figure 1-2 for resupply at the SS. For shuttle-based resupply, the configuration is essentially identical except for deletion of the mechanical coolers and associated electronics. Design features are as follows:

- A dewar of 10,000-ℓ capacity containing SfHe at launch (this capacity is adequate for resupply of a warm SIRTf or for resupply of several smaller users).
- A spherical dewar configuration to minimize mass, launch cost, and development cost.
- A TM pump and a porous medium distributed within the tank that uses the thermomechanical effect driven by heat from the pump to accomplish liquid acquisition.
- A state-of-the-art insulation system using carefully-constructed, double-aluminized mylar MLI and alumina/epoxy tension strap supports.
- A plumbing system that provides operational flexibility and meets all safety-related requirements.
- Four Stirling cycle mechanical coolers to provide a mass-optimized system (and cost-optimized program) for a mission including 9-month standby.
- An interfacing approach (mechanical, electrical, fluid, and avionics) that is compatible with resupply either in the shuttle bay or at the SS, using EVA-assisted electrical and fluid hookups.
- A "smart" avionics subsystem that uses a three-string, majority-voting approach for control of the SFHT.



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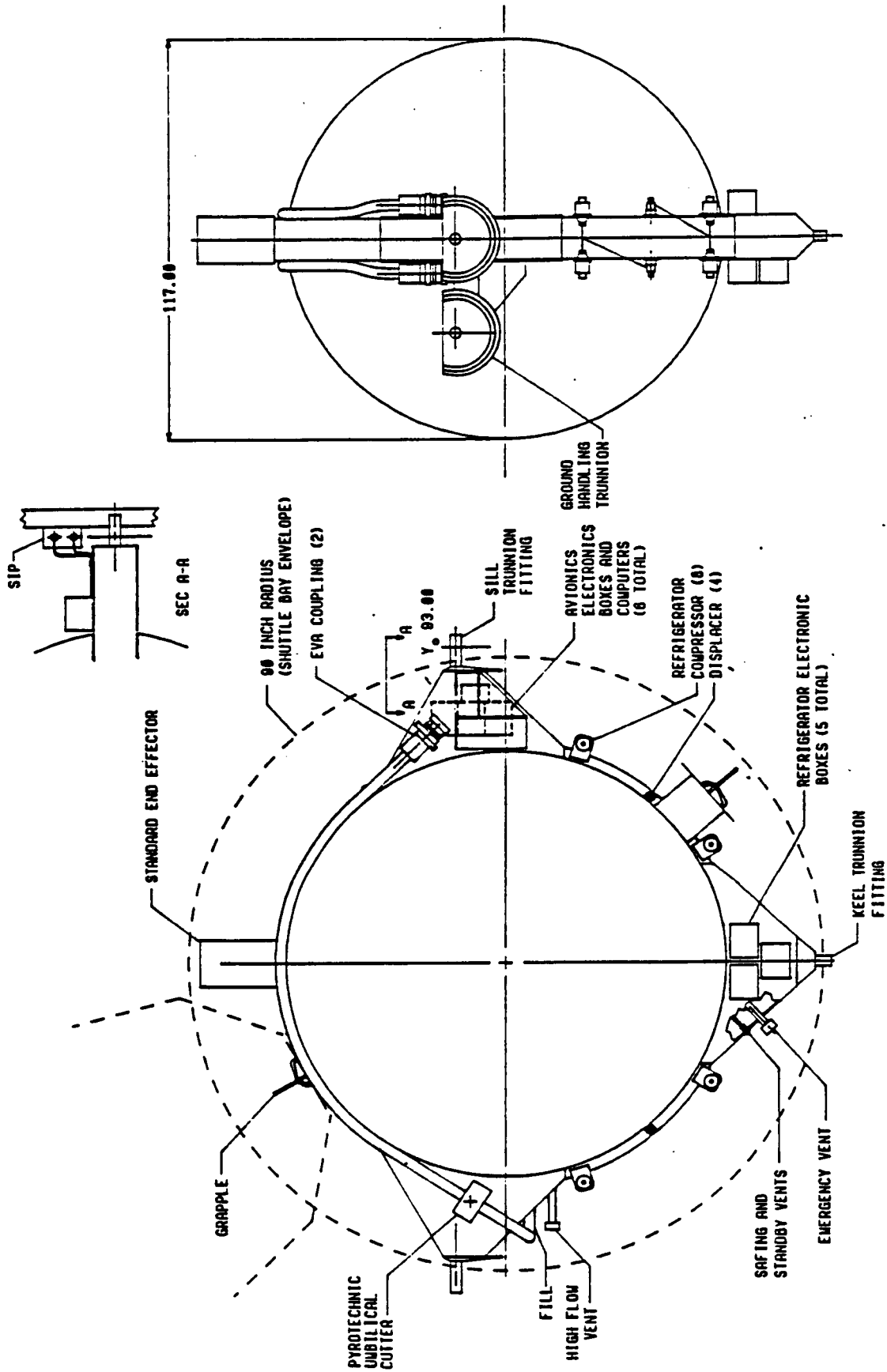


Figure 1-2 Dewar configuration for SS-based resupply



A SFHT design concept has been recommended that meets all mission requirements using low-cost and low-risk approaches. The all-aluminum, 10,000 lb spherical dewar will perform a warm SIRTf resupply at either the shuttle or the space station (after a 9-month standby). The insulation system design is optimized to provide minimum launch mass based on the 9-month standby requirement; mechanical coolers are used to cool the dewar outer VCS during the extended SS standby.

An oblate spheroid configuration was investigated to see if it would reduce shuttle launch cost; it has essentially the same launch cost and thermal performance as the spherical dewar, which is 1,600 lb lighter. It requires about 19 in. less shuttle bay length, providing better manifesting flexibility. Although the spherical shape has been selected as the baseline, there is not a strong preference.

The study has emphasized the areas of technology risk, which center around the fluid subsystem design and operations. Technology development is needed for the follow-on automatic system, but only a cursory evaluation of those items was appropriate within the scope of this study. When the SFHT hardware is developed, state-of-the-art, space-qualified technology will be used for the avionics. Therefore, little study effort was spent on this topic. Regarding avionics, the study was more concerned with assuring that SFHT power and data requirements are compatible with shuttle and SS resources. Considerable software development will be required for the avionics "smart" computer system.

BASG has a proven capability for designing and fabricating spaceborne dewars with high thermal performance. Although this is not a technology risk area, considerable study effort was spent on providing valid mass and thermal performance estimates for the dewar. This was necessary to make legitimate configuration tradeoffs and plan operations, both ground and flight. Also, minimizing the parasitic heat input to the cryogen tank will minimize the Sfh<sub>2</sub> bath temperature and maximize the transfer efficiency.

The primary technology development area for the SFHT is the transfer system, consisting of the liquid acquisition device, thermomechanical pump, SFHT plumbing, flexible transfer line, and user plumbing. Demonstration of this system is the main function of the SHOOT experiment. However, there are important scaling factors and detailed design impacts that can only be determined through a rigorous analytical understanding of the system. Regardless of ground component testing and SHOOT flight testing, a valid analytical model of the entire transfer system is required to establish the SFHT design with any confidence. That analytic capability does not yet exist.

Our approach has been to take a very careful end-to-end look at a point transfer system design based on the fundamental physics involved, therefore verifying the feasibility of performing on-orbit superfluid helium resupply. We conclude that it can be done within the imposed design constraints, but the system design and operation must be very carefully planned and verified. The next step is to construct a comprehensive analytic tool for understanding the system better, particularly the transient aspects of the resupply process.



## Section 2 DESIGN DESCRIPTION

The SFHT consists of two major subsystems: the dewar and the avionics, as seen in Figure 2-1. There is also a large complement of GSE needed to handle and transport the SFHT and to prepare the dewar for launch.

The dewar is a 10,000  $\ell$  spherical configuration with the cryogen tank and vacuum shell made of aluminum (Figure 2-2). Mounted on the vacuum shell for SS-based resupply are four Stirling cycle coolers, which provide 9 W of cooling at the outer VCS. Also mounted on the vacuum shell are the electronics associated with the coolers, the dewar-based portion of the avionics, and the redundant transfer lines, shown in the stored position for launch. The dewar mounts into the shuttle bay with standard sill and keel fittings, which are adaptable for launch on a Titan IV. Not shown in the figure is the avionics remote control station, consisting of computers, displays, touch panels, and manual switches.

Figure 2-3 shows the configuration for shuttle-based resupply with the mechanical coolers and extra grapple deleted.

This section describes the major configuration trades conducted and the recommended design concepts for the dewar, avionics, and GSE.

### 2.1 DEWAR SUBSYSTEM

The dewar is divided into structural/mechanical, thermal, fluid, and instrumentation/cabling subsystems. Because of the importance of the pump and LAD, these are discussed in a separate section even though they are part of the fluid subsystem.

#### 2.1.1 Major Configuration Trades

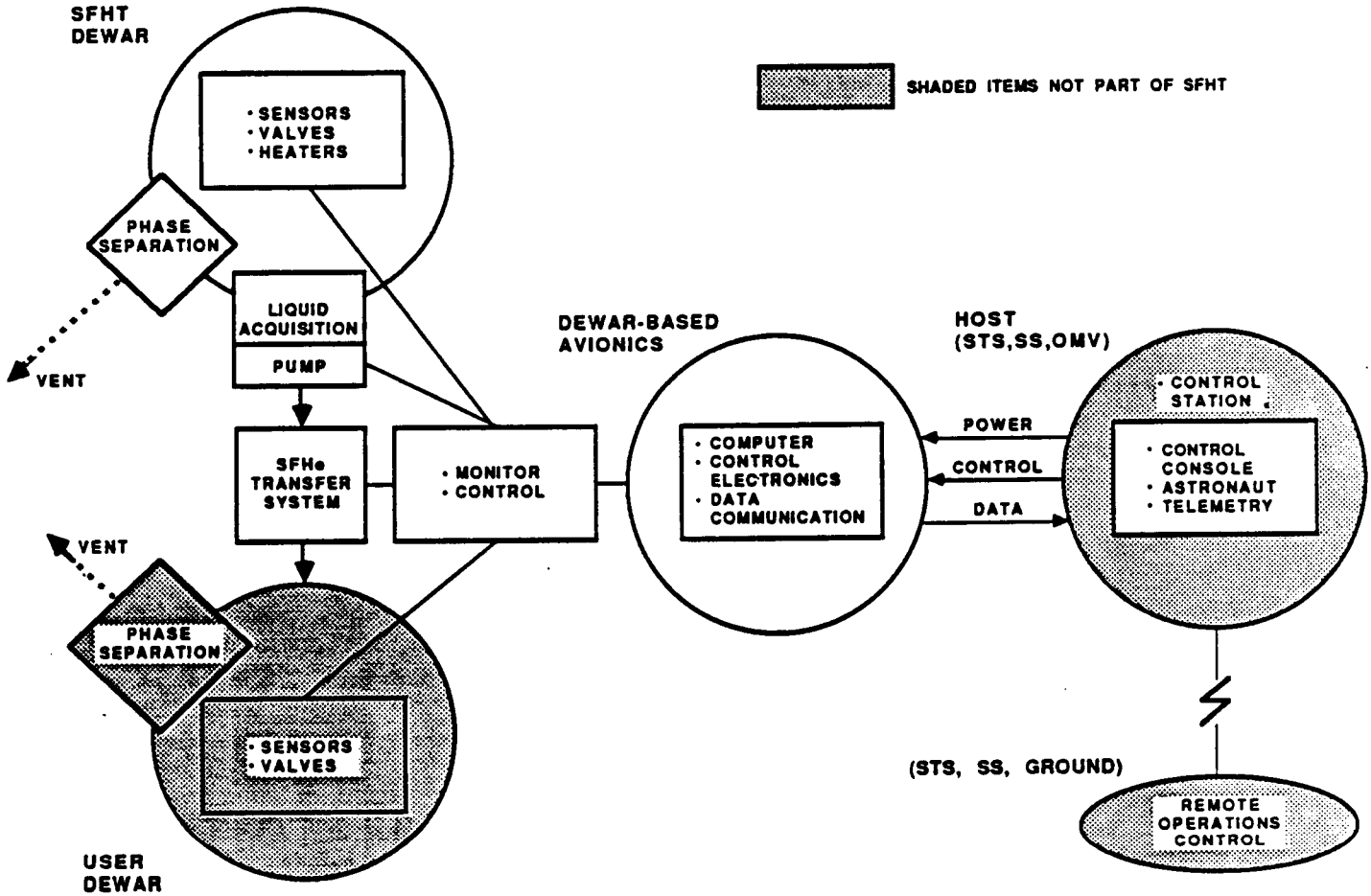
Analyses used to predict system performance characteristics and to aid the configuration trades are discussed in Section 4. Most of the trades relating to the fluid subsystem were performed during the first phase of the study and documented in the Interim Progress Report; the most notable trade results are selection of the thermomechanical pump, the helium is superfluid at launch, and the system must land with a full helium load.

#### Mechanical Cooler

Fluid loss during the 9-month orbital standby and pressure rise rate during ground lock-up are minimized by cooling the dewar outer VCS with mechanical coolers. The British Aerospace Stirling cycle machine is chosen for this purpose. A unit producing 1 W of cooling at 93 K has been qualified for the ISAMS instrument to be flown on the Upper Atmosphere Research Satellite. This same cooler is baselined as part of the AXAF X-ray Spectrometer, under development at NASA/GSFC. The cooling power achievable by simple extension of the existing technology is 3-4 W<sup>1</sup>. Our baseline uses a cooler producing 3 W at 93 K; the system includes four of these operating simultaneously. As shown in Figure 3-7 of the Interim Program Report, the mass savings achieved by using a mechanical cooler continues to increase up to a cooling power of



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Figure 2-1 SFHT system block diagram





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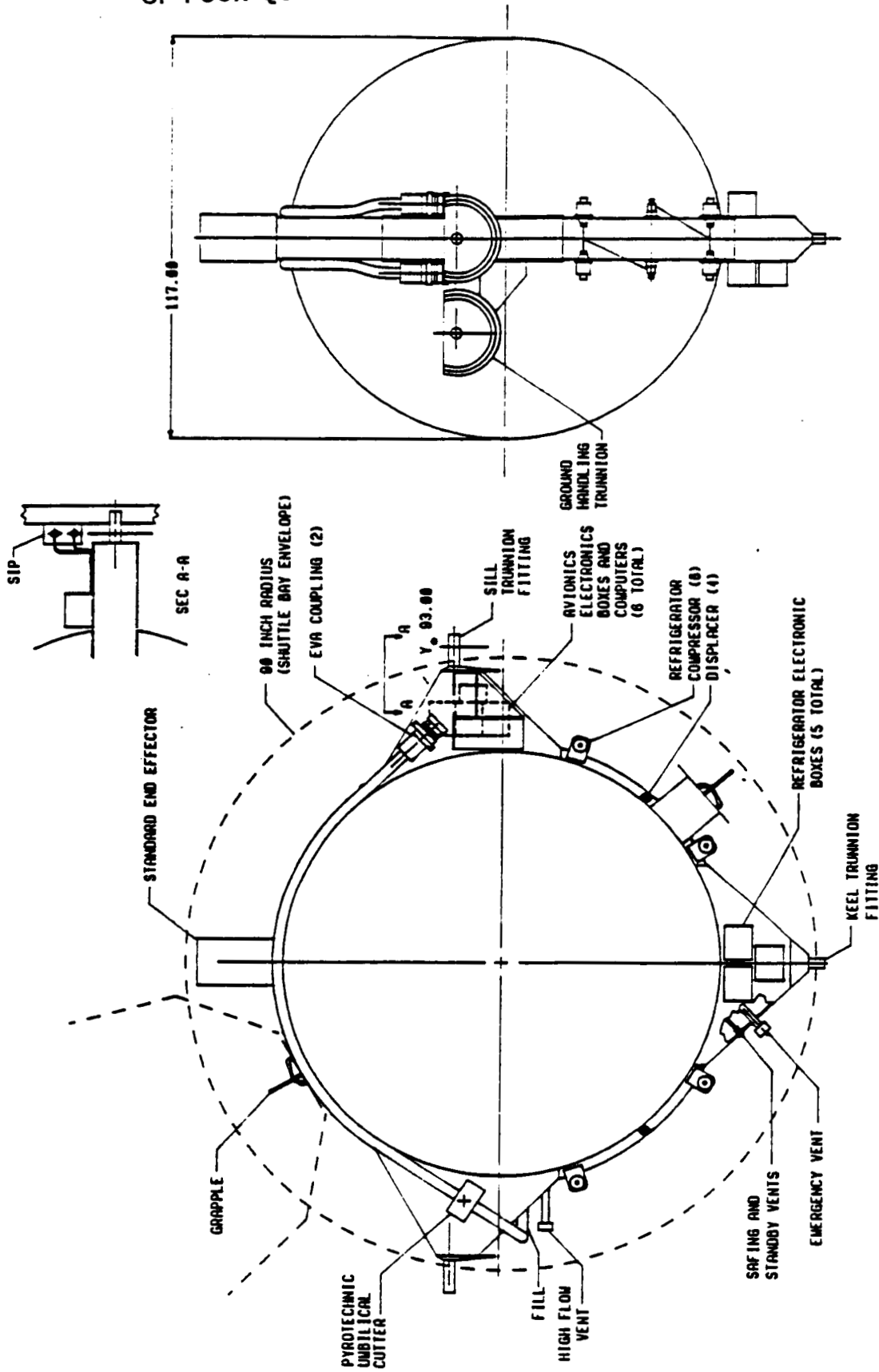
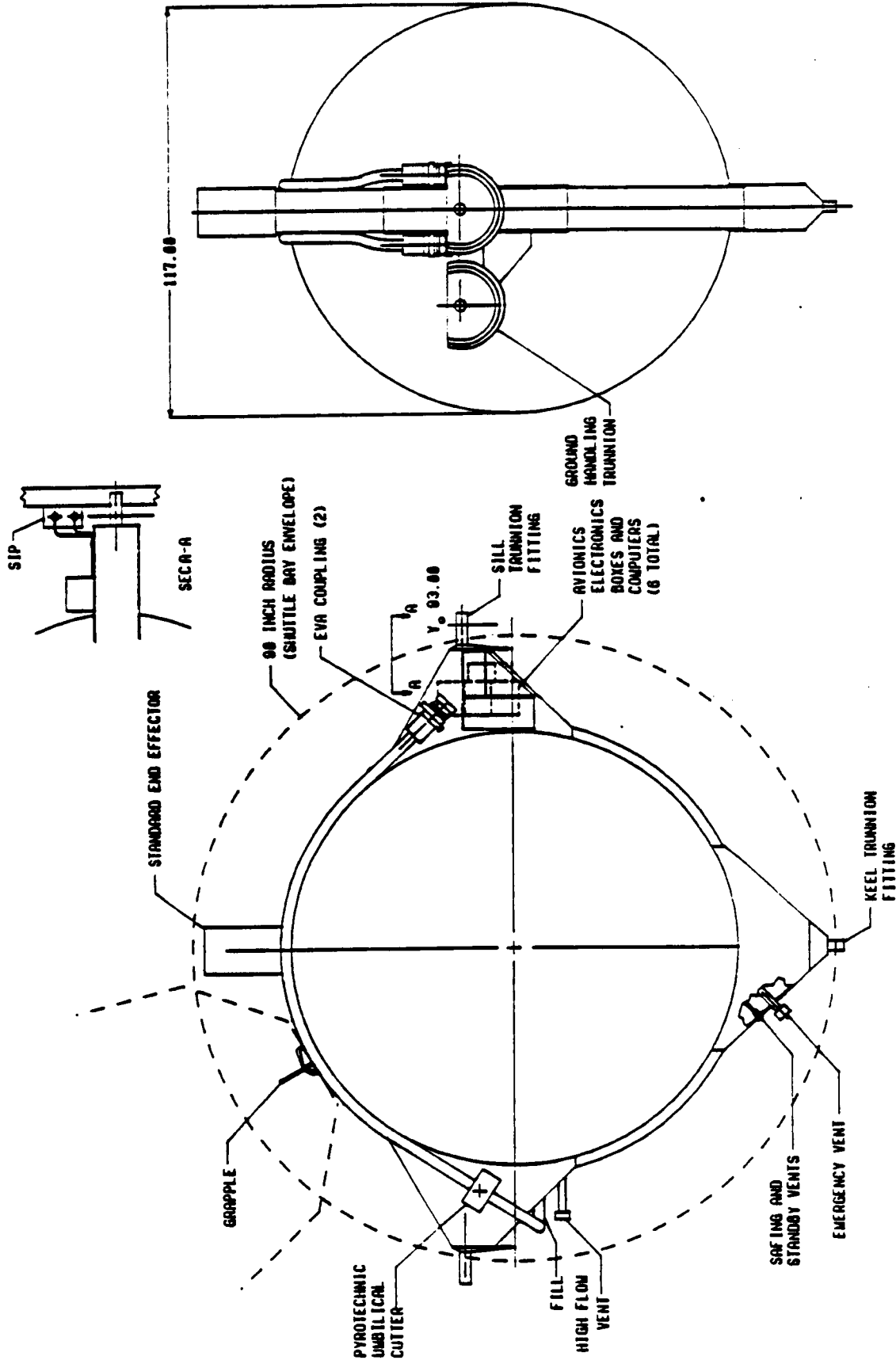


Figure 2-2 Dewar configuration for SS-based resupply



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Figure 2-3 Dewar configuration for shuttle-based resupply



at least 12 W. The optimum number of coolers may indeed be greater than four. They are costly items, and four were chosen for the baseline without pursuing the optimization further.

As discussed in 4.2.4, the estimated SFHT launch mass savings resulting from use of the coolers is about 600 lb. At a cost of \$5,000/lb per launch, this is a savings of \$3 M per launch. The estimated development program cost impact (through delivery of the first flight system) resulting from the mechanical cooler approach baselined is therefore approximately compensated in the first three launches. Since the system is designed for 50 launches, the cost advantage of using the coolers is clear.

### Dewar Shape

STS launch cost is based on an algorithm accounting for the system mass and the length of bay space used<sup>2</sup>. Cost is determined either by mass or bay space, whichever is the critical parameter according to the algorithm. Approximate mass and launch cost estimates were generated for a variety of dewar shapes, as shown in Table 2-1. These estimates indicate that the special shape is the lightest (as expected), but the  $\sqrt{2}$  oblate spheroid shape may have minimum launch cost. More detailed mass estimates and corresponding launch cost estimates were then made for these two shapes. The oblate spheroid configuration is shown in Figure 2-4. Results indicate essentially equivalent launch costs and a spherical shape mass savings of 1,600 lb.

Table 2-1  
ESTIMATED LAUNCH COST FOR A VARIETY OF DEWAR SHAPES

<u>CONFIGURATION</u>	<u>SPHERE</u>	<u>EL/2:1</u>	<u>EL/1.4:1</u>	<u>TOR/2r</u>	<u>TOR/1.7r</u>
Fluid Mass, lb	3,200	3,200	3,200	3,200	3,200
Dry Mass, lb	3,820	7,290	5,030	9,920	7,810
Total Mass, lb	7,020	10,490	8,230	13,120	11,010
Bay Length, in.	117	88	98	80	86
Launch Cost, \$M	31.9	39.3	31.9	47.9	41.0

The spherical shape is advantageous with regard to mass, center-of-gravity location relative to the shuttle launch axis, and probably fabrication cost. The only advantage of the more compact oblate spheroid shape is potentially superior manifesting flexibility. Thermal performance is only slightly better, especially if mechanical coolers are used, for the spherical shape. Our choice is the spherical shape.

### Mechanical Interfacing

Two docking and berthing mechanical interfaces were evaluated for the SFHT. Both have been successfully used in the space program. The standard end effector, as used on the orbiter RMS, and the three point docking mechanism, as used on the flight support system, were selected to be used on the SFHT. The SEE on the RMS has been used to remove large (as much as 32,000 lb) payload from the orbiter payload bay. The grapple is the mating interface to



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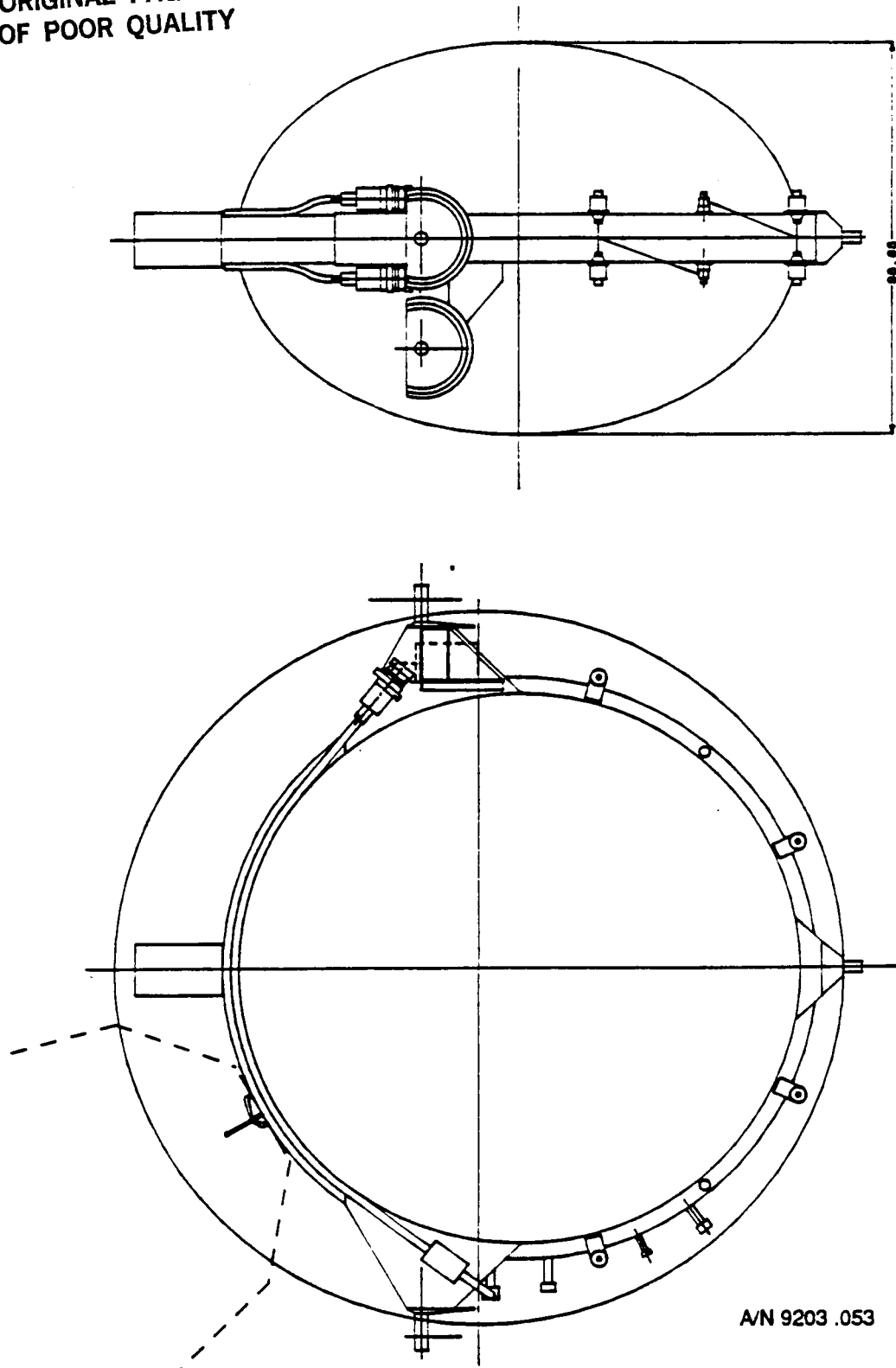


Figure 2-4 Oblate spheroid dewar configuration



the SEE. The Solar Maximum Mission (SMM) program was the first user of the FSS and its TPDM in 1984.<sup>3</sup>

The SEE does not have the capability of providing the forces required to automatically connect and disconnect a number of electrical and fluid connections. Yet it is simple to operate, making it a good choice for earlier SFHT missions where fluid and electrical connections will be made by EVA. One special purpose electrical connector can be provided on the SEE remote connection, but this provides an insufficient number of pins for the SFHT.

The TPDM in its present configuration incorporates two 56 pin connectors, which is sufficient for the user to SFHT interface. There is sufficient space in the TPDM to add the automatic fluid connections. The TPDM is recommended for future missions after development of an automatic fluid coupling.

The SFHT can easily be designed to facilitate the use of either the SEE or TPDM. Both would be easily removed and replaced on the SFHT to accommodate mating with user facilities. Failure tolerance of both approaches should be examined more closely to ensure that SFHT requirements are met.

### Fill Procedure

The recommended fill procedure is the same as that used for IRAS and COBE. This is a proven approach that has minimal impact on the SFHT design. The alternatives considered and the rationale for this choice are discussed in 2.3.1.

#### 2.1.2 Mechanical/Structural Subsystem

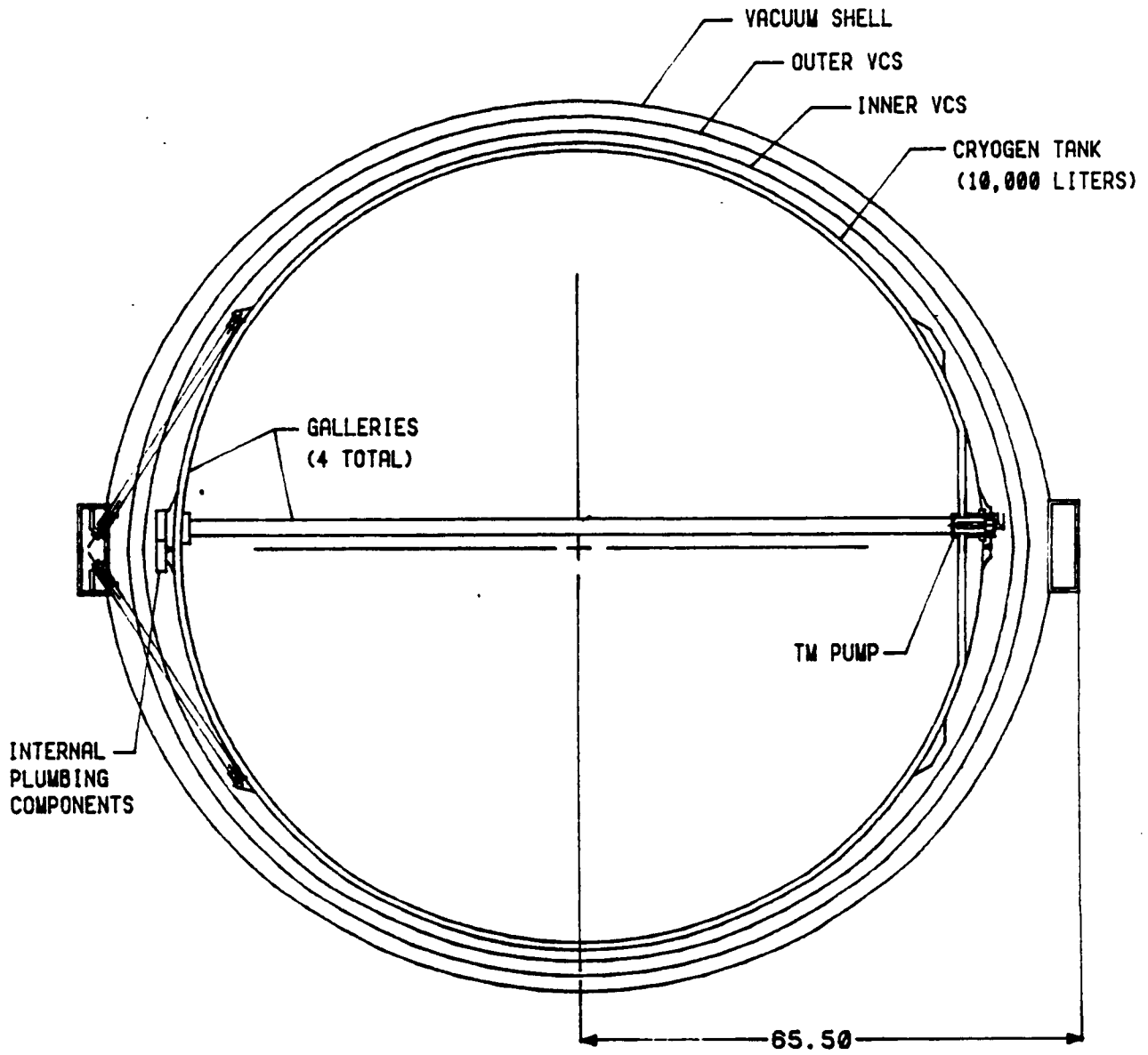
The spherical dewar is mounted in the shuttle bay with standard sill and keel trunnion fittings, as shown in Figure 2-2. There is an additional ground handling trunnion that is removed before flight. Host and user interfaces are discussed further in Section 3.1.

The cryogen tank consists of two spun and machined 5083 aluminum hemispheres welded together to make a 10,000 l sphere, as shown in Figure 2-5. A thickened area is provided around the equator for the weld and for simple bolted attachment of internal plumbing components. Thickened rings are provided on each hemisphere at an elevation of about 30 deg for attachment of the twelve straps which support the cryogen tank from the vacuum shell. Aluminum-to-stainless steel transition joints are used where the various plumbing lines penetrate the tank.

The vacuum shell is made of spun and machined 5083 aluminum spherical domes welded to a girth ring. The cryogen tank support straps are attached inside the girth ring. Pins and clevises are used at each end of the straps. The straps are made of alumina/epoxy to provide maximum thermal isolation.

The two vapor-cooled shields are 0.04-in. thick and made of 1100-0 aluminum to provide high lateral thermal conductivity. They are supported by attachment to the support straps, and in turn they cool the straps.

The four trunnions are properly positioned by mounting them on plates bolted to the girth ring. Mechanical interfacing with the Titan IV can be simply



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Figure 2-5 Cutaway view of dewar



accomplished by providing the appropriate interface structure bolted to the girth ring.

All of the external hardware, i.e., the standard end effector, the transfer lines, and the dewar-based avionics, are mounted on the girth ring. If re-supply is to be performed at the SS, there is additional equipment mounted to the girth ring: a grapple for attaching the SFHT to the SS, the four Stirling cycle coolers, and the five electronic boxes for the coolers. Mounting of this equipment is shown in Figure 2-2.

The internal plumbing manifold, consisting of sixteen valves, two burst discs, and three electrical feedthroughs, is attached to the equator of the cryogen tank over a span of about 90 deg. The most critical items for access are the burst discs, although access to the entire manifold is certainly feasible. Providing access to all components of the assembly would result in a small system mass penalty. As shown in Figure 2-6, access is gained by removing a section of the girth ring, folding the MLI back like petals of a flower, and removing bolted sections from the vapor-cooled shields. Sealing of the girth ring removable plate can be by grind-down weld or by "o" ring. To ensure a reliable seal and because the need for access will be infrequent or never, the grind-down weld is the chosen approach. This may seem cumbersome, but it is a well-established technique and is probably a small effort compared to repairing the cause of the loss of guard vacuum and the potential resultant damage to the insulation system. Access to the two warm burst discs located in the girth ring is provided through this same cover.

### 2.1.3 Fluid Subsystem

This section summarizes the required fluid operations and describes the overall fluid subsystem design. Further details regarding the liquid acquisition device and thermomechanical pump are provided in the next section. Detailed configuration trades leading to the recommended fluid subsystem design were performed during the first phase of the study and documented in the Interim Progress Report.

The fluid operations occurring during each phase of the mission are shown in Table 2-2. The fluid management system needed to perform these operations is shown in Figure 2-7. This design is based on the following considerations:

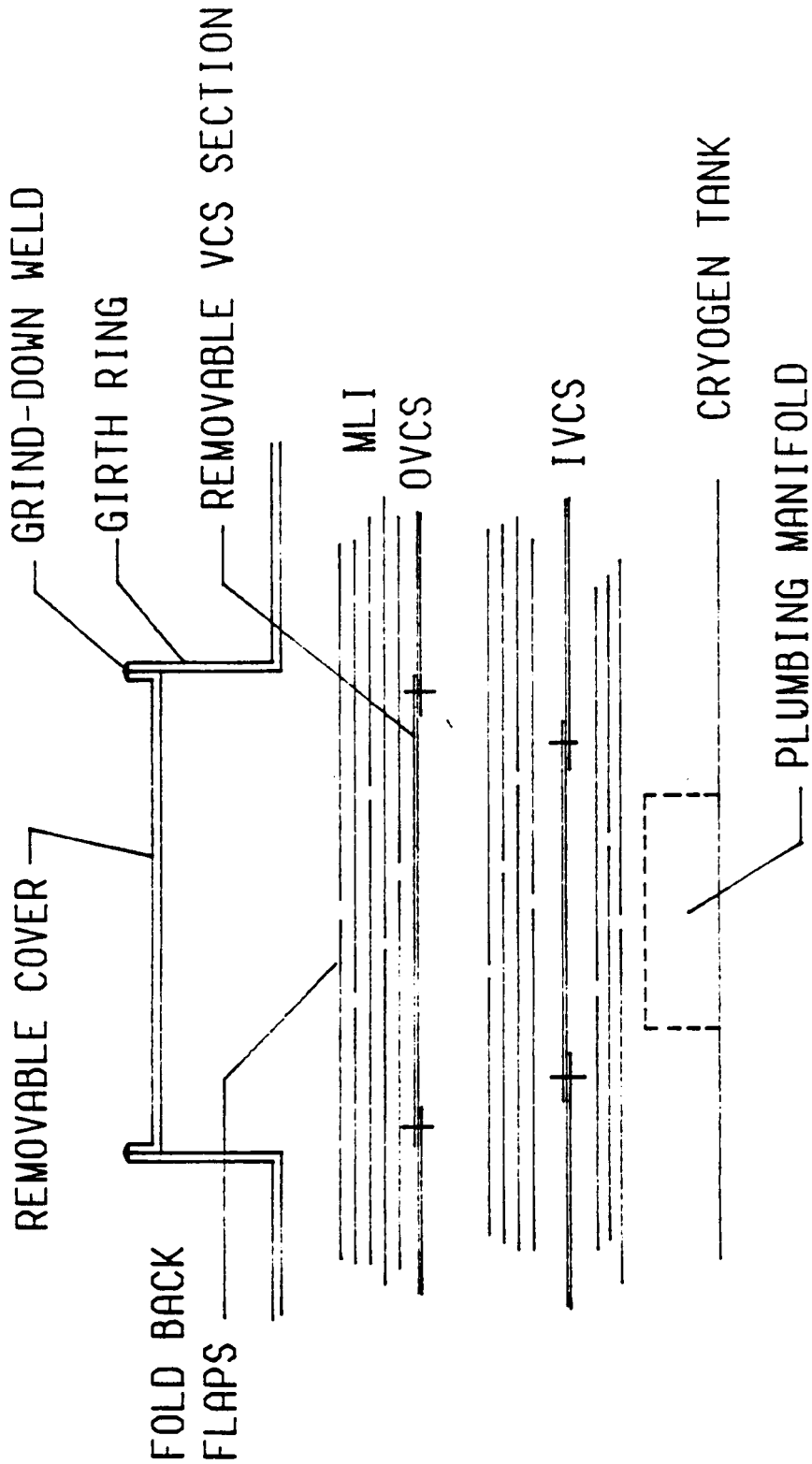
- Two-fault tolerance for safety and one-fault tolerance for mission success
- Maximum use of existing and low-risk technology
- Minimum number of components and valve actuations
- Minimal degradation of dewar thermal performance
- Access to critical components
- All hermetic seals between helium and guard vacuum

The GSE connects to the bayonet couplings at the fill and high-flow vent lines. Valve positions for the various operations are given in Table 2-3.

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Figure 2-6 Access to internal burst discs





Table 2-2  
FLUID OPERATIONS OVERVIEW

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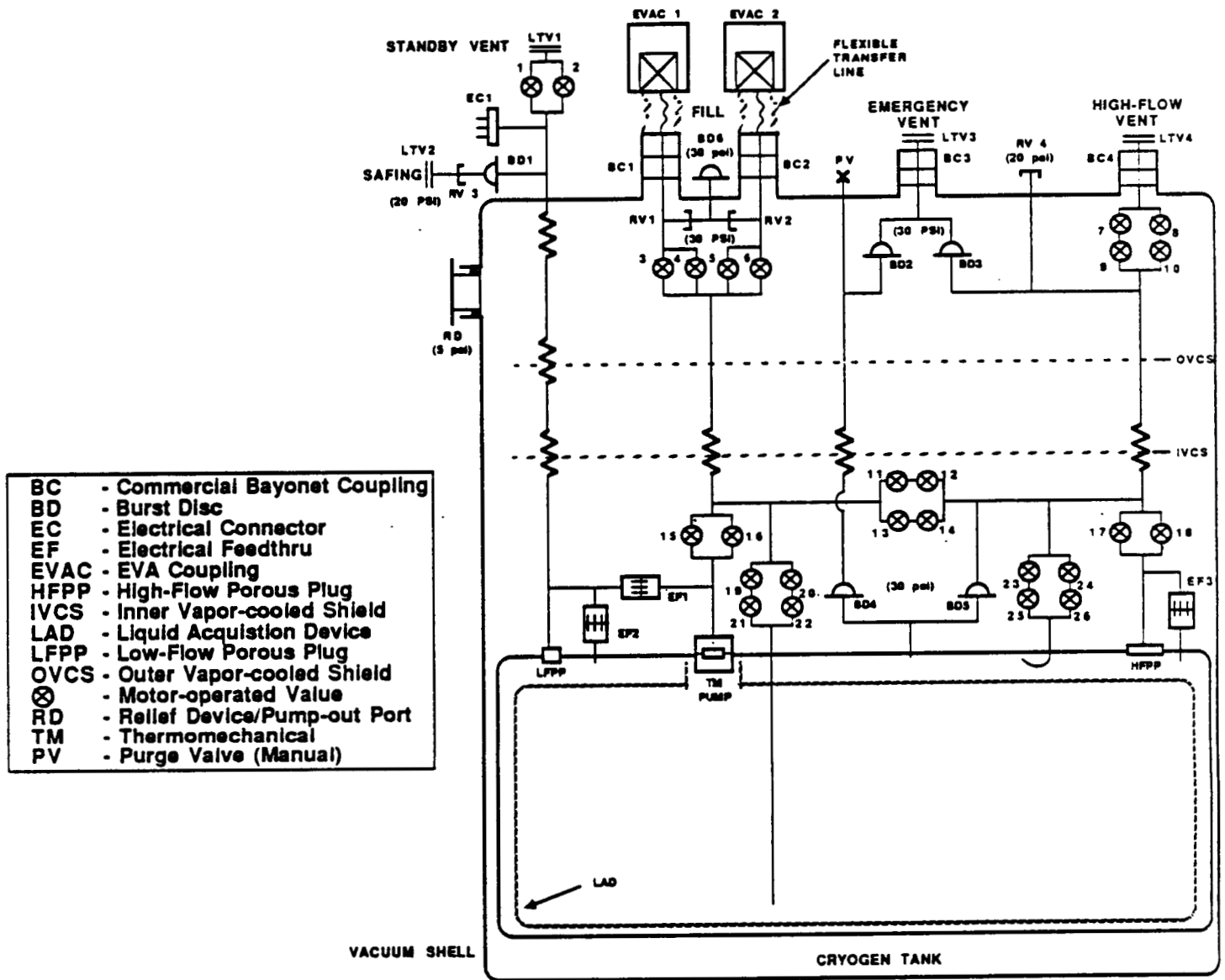
OPERATION	PROGRAM PHASE	TEST AND MAINTENANCE	LAUNCH PREP (BEFORE P/L INTEGRATION)	PRE-LAUNCH (STS OR ELV)	POST-LAUNCH (STS OR ELV)	ORBITAL TRANSPORT (OMV)	RESUPPLY	DESCENT SHUTTLE
SFHT COOLDOWN		✓	✓					
NORMAL FILL		✓	✓ <sup>1</sup>					
BATH PUMPDOWN (ON GROUND)		✓	✓ <sup>1</sup>					
INSULATION COOLDOWN		✓	✓					
LOW-PRESSURE TOPOFF/FILL <sup>2</sup>		✓	✓					
STANDBY VENTING (SFHe BATH)		TO GSE PUMP	TO GSE PUMP		TO AMBIENT	TO AMBIENT	TO AMBIENT	
SAFING (NHe BATH)		TO AMBIENT	TO AMBIENT	TO AMBIENT	TO AMBIENT	TO AMBIENT	TO AMBIENT	TO AMBIENT
EMERGENCY VENTING (GUARD VACUUM FAILURE)		TO AMBIENT	TO AMBIENT	TO AMBIENT OR OVERBOARD	TO AMBIENT OR OVERBOARD	TO AMBIENT	TO AMBIENT OR CONT. VENT	TO AMBIENT OR OVERBOARD
BATH PUMPDOWN (ZERO-g )		✓			✓			
ZERO-g TRANSFER (COOLDOWN/FILL)		✓					✓	

1 MAYBE NOT NEEDED IF GSE PROVIDES SUPERFLUID TRANSFER

2 FLUID TRANSFERRED NEAR OR BELOW THE LAMBDA POINT



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Figure 2-7 Fluid management schematic



Table 2-3  
VALVE POSITIONS FOR VARIOUS OPERATIONS

OPERATION	VALVE POSITION (O - OPEN, BLANK-CLOSED)							
	7-10	3-6	1-2	17-18	23-26	11-14	19-22	15-16
COOLDOWN AND NORMAL FILL	0	0			0		0	
PUMPDOWN (GROUND)	0				0			
INSULATION COOLDOWN	0	0				0		
LOW-p TOPOFF/FILL	0	0			0		0	
STANDBY VENTING AND ORBITAL PUMPDOWN			0					
SAFING								
EMERGENCY VENTING								
USER RESUPPLY	0	0		0				0

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Motor-operated valves will be either the 3/4-inch design or 1/2-inch design developed for the SHOOT program. In most valve locations the greater flow conductance of the 3/4-inch valve is needed to achieve desired flow rates and vent system conductance. Although the system mass would be slightly less if 1/2-inch valves were used where possible, the development cost would probably be greater. For the current baseline we assume all valves are 3/4-inch. Relief valves can be the Circleseal design used on the COBE dewar, and burst discs are assumed to be the Ametek-Straza design used on COBE and SHOOT. Suitable electrical feedthroughs are made by Ceramaseal, similar to those used in the COBE dewar. A variety of vacuum tight electrical connectors for room temperature use are available, such as Deutsch and Cannon. The manual purge valve is a simple and readily available item. The combination relief device/pumpout port is a piston and "o" ring arrangement made by Cryolab and used on the COBE dewar.

Currently available bayonet couplings, such as used for the COBE dewar, have a heat leak of about 1 W, compared to an estimated total on-orbit transfer system heat leak on the order of 5 W. The EVA coupling is assumed to be the coupling currently under development by JSC for the SHOOT program. The heat leak of this coupling is estimated by Moog at 1 W<sup>4</sup>; it is unlikely it can be made lower unless requirements, especially the thermal isolator design pressure, are changed. As discussed in 4.4.4, reduction of the coupling heat leaks would be beneficial to the transfer process, but further analysis and testing is needed to adequately determine the importance of this benefit.

Flowrates through the standby vent and safing vent will be low (<8 mg/s) and vapor will exit at room temperature, so that no protective measures are required. Given the relatively large payload thrust allowables of the orbiter and the SS, design of the low thrust vents at these locations will be simple. A "T" is adequate. A low-thrust vent will be installed on the high-flow vent after the dewar is filled for launch. The flowrate out this vent during orbital transfer will be about 1.0 g/s maximum at a temperature less than 10 K. This vent must be located in a protected area to prevent injury to personnel or damage to nearby equipment. The "T" design is still adequate for this vent.

The most critical vent is the emergency vent, which may have a flowrate as high as 250 g/s at a temperature less than 10 K. This vent must be located in a protected area, and the low-thrust vent design may be more complex than the others. This flowrate is small enough that it can be vented directly into the shuttle bay without causing overpressurization; it therefore need not be routed into the overboard cryogenic vent.<sup>5</sup> Analysis of the emergency vent system is presented in 4.3.3. As discussed in the Interim Progress Report, vent collection at the SS is neither necessary nor desirable. A collection system compatible with SFHT operations would be extremely large and costly. Also, helium is inert and the gas cloud formed during transfer operations will dissipate very quickly; local venting of large amounts of helium does not violate SS cleanliness requirements. While on the ground, emergency venting is to ambient via the low-thrust vent.

Since a single failure could prevent mating of the EVA coupling as currently designed, redundant fill lines and couplings are provided. During on-orbit transfer, the interface with the user is at the EVA coupling. It is assumed the mating half of the coupling is welded into the user vacuum shell. For SFHT ground operations, the flexible transfer lines are removed, and the GSE



connects to bayonet BC1 or BC2. The high-flow vent is connected to the GSE vacuum pump for system vacuum purging and bath pumping.

The dewar orientation required for fill and toff operations is dictated by the location of the high-flow vent within the cryogen tank. Three alternatives are possible:

1. The vent can be located so that 100 percent fill is achievable in the given orientation and 50 percent is achievable in the orthogonal orientation.
2. It can be located so that 90 percent fill is achievable in two orthogonal orientations.
3. Four valves (for redundancy) and another plumbing penetration into the cryogen tank can be added to the design to allow 100 percent fill in two orthogonal orientation.

Because of the very long lock-up capability of our design (4 months with mechanical coolers running and 25 days without coolers), fill operations can be performed in a facility where there will be no constraints on dewar orientation. Our approach is to use alternative 1. above; this will minimize cost and operational risk factors.

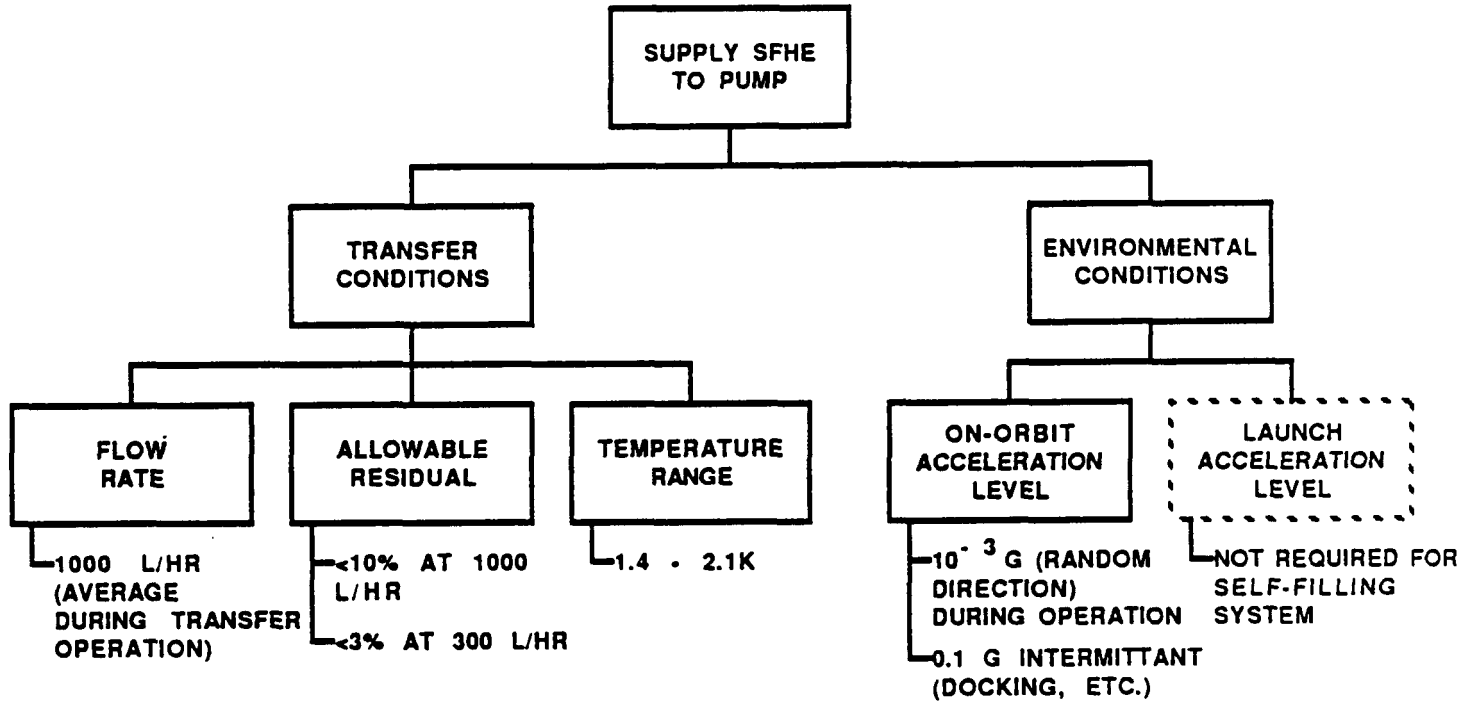
#### 2.1.4 Liquid Acquisition System

Acquisition of superfluid helium (SfHe) in zero gravity for transfer at a high flowrate is a unique requirement with no established technical approach based on flight experience. The unique physical properties and behavior of SfHe make experience gained with other fluids not very useful. We have therefore taken a top-down system design approach to arriving at the conceptual design of this critical SFHT subsystem.

The baseline we have chosen looks very much like a conventional screen-channel liquid acquisition device (LAD), but its design is significantly different. The properties of the SfHe, combined with the heat flux from the thermomechanical (TM) pump, cause the LAD to assist with pumping, and can assure that cavitation in the liquid will not occur. This LAD uses either a fine-mesh metallic screen or a porous material (either porous "plugs" or membranes) with much higher flow impedances than would be acceptable for other fluids.

##### 2.1.4.1 Subsystem Requirements

Figure 2-8 breaks down the fundamental performance required of the LAD into its component parts. The fundamental performance requirement is that liquid be delivered to the pump at 1,000  $\ell$ /hr, or more accurately at a rate such that the overall transfer operation can be completed within the timeline based on a nominal rate of 1,000  $\ell$ /hr. This means that the flow rate can be allowed to fall off near the end of the transfer, or even that occasional interruptions can be tolerated if necessary. Unlike many propulsion applications that involve a high-speed turbine pump, the SFHT can even allow gas or a gas/liquid mix to appear at the inlet of the TM pump occasionally, because this type of pump recovers gracefully without damage.



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Figure 2-8 Liquid acquisition requirements



The LAD must drain most of the tank contents to allow replenishing the user system with minimum SFHT launch mass and/or maximum flexibility in servicing other users later. This requirement should be stated in terms of the residual allowed when transferring at the full 1,000 l/hr, plus a smaller allowed residual when "topping off" the user at the lowest practical transfer rate. Based on the SHOOT baseline, we are assuming 10% allowable residual at the full transfer rate, and 3% at the end of the reduced-rate toff.

The SFHT will operate over a range of temperatures during the user cooldown and fill operations, and the LAD must function over this range. The lowest supply tank temperature anticipated is 1.4 K, and the downstream side of the TM pump (and therefore the supply tank) must be kept below the lambda point (2.18 K) to allow the pump to function. The overall SFHT system should be optimized to keep the operating temperature as low as possible to minimize the mass loss associated with the TM pump operation. Therefore, the LAD should be designed to operate from 1.4 K to 2.1 K, with any tradeoffs made to optimize it for the low end of this range.

During the transfer operation, our analysis of measurements made on the orbiter show that we should anticipate random accelerations of up to  $10^{-3}$  g, with impulses up to 0.1 g during docking, etc.<sup>6</sup> When operating on the SS and the OMV, we anticipate the random accelerations to be reduced. The appropriate design requirement is therefore  $10^{-3}$  g. Occasional impulses above this level can be tolerated without design impact because both the TM pump and the selected design approach for the LAD will recover gracefully from any momentary loss of liquid flow.

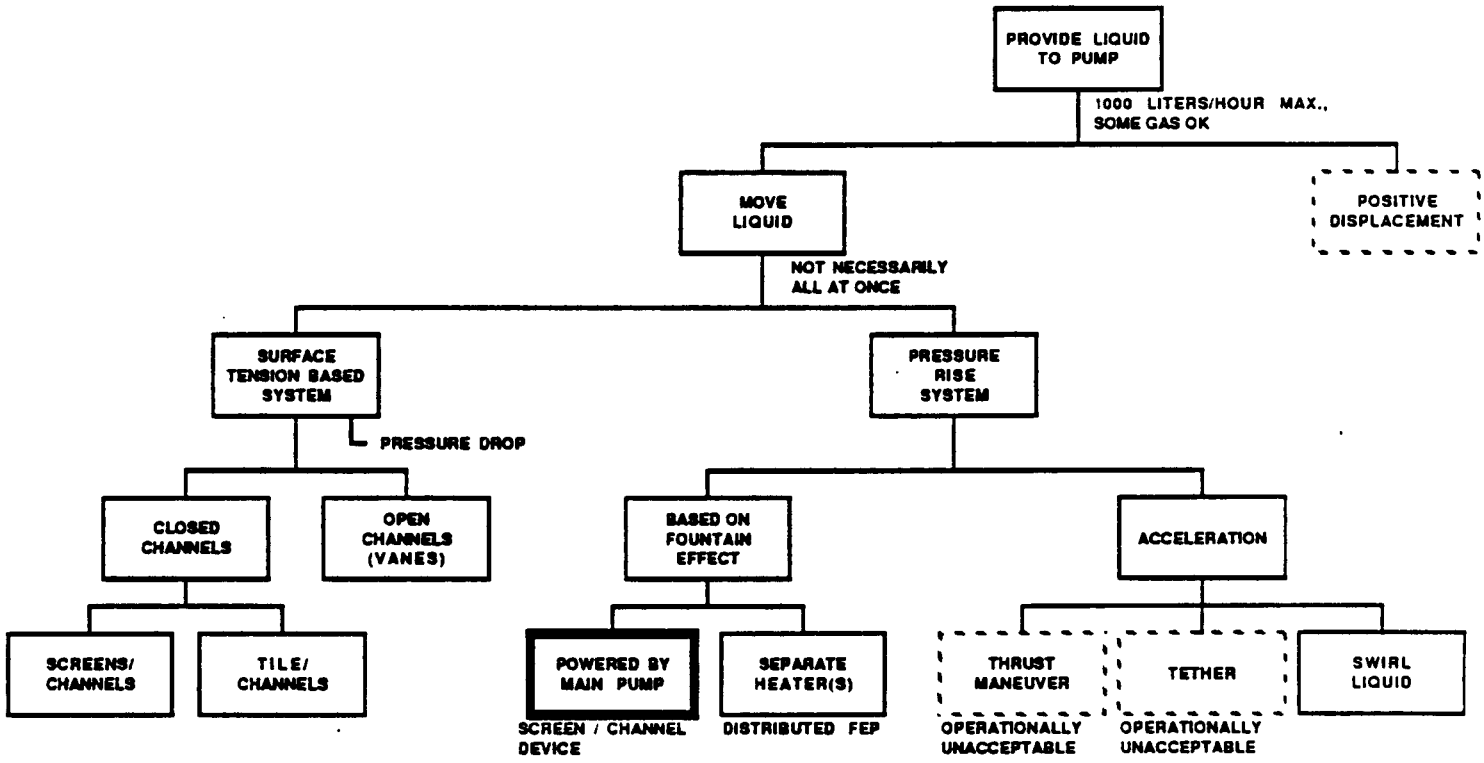
A conventional screen-channel LAD would face the additional requirement that it retain liquid during the launch acceleration because such systems do not recover automatically if vapor is ingested into the LAD. This is frequently a driving requirement for the LAD design. Fortunately, the unique behavior of SfHe causes the selected LAD to refill itself automatically when used.

#### 2.1.4.2 Design Options

Figure 2-9 shows all of the design approaches considered for the LAD, and classifies them in a way which simplifies the selection of the baseline. Positive displacement approaches (bellows, diaphragms, pistons, etc.) can be rejected immediately as impractical at cryogenic temperatures or as having serious weight penalties. The fundamental choice therefore becomes one between LAD approaches which supply liquid to the pump at a pressure either lower or higher than that of the main bath.

Classical LAD schemes which depend on the surface tension of the liquid to retain it in the galleries all cause a finite liquid pressure drop. Open-channel systems (e.g., vane structures) cause very little pressure drop, but analysis<sup>7</sup> has shown them to be capable of only withstanding accelerations in the micro-g range, and therefore unusable by SFHT. Fundamentally this is because the surface tension of SfHe is more than an order of magnitude lower than that of other cryogens.

Analysis of a screen-channel LAD operating by itself in SfHe<sup>7</sup>, even with corrections for the properties of SfHe, predicts a pressure at the pump inlet



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Figure 2-9 Liquid acquisition design options





below the saturation pressure of the liquid. Viscous pressure drop for the normal component of the SfHe (see below) traveling downstream through the impedance of the screens is significant. When the TM pump is considered jointly with the LAD, however, we find that the normal component travels upstream away from the pump, and the viscous drag causes the impedance of the screen to raise the pressure of the fluid inside the LAD slightly. This will be discussed below.

In conventional fluid systems that use screen-channel LADs, the fluid is forced through the LAD by a pressurizing gas. As long as the fluid is kept above saturation pressure everywhere inside the LAD channels, it cannot form bubbles (cavitate). It is possible to pressurize cryogenes other than SfHe because either:

- The pressurant gas is helium, which does not condense at the temperature of the cryogen, or
- It is pressurized with its own vapor, but the low thermal conductivity of the liquid limits the rate at which the vapor condenses

Pressurizing a mixture of SfHe and gaseous helium above the saturation line is impossible because the effectively infinite thermal conductivity of large bodies of SfHe causes the gas to condense almost instantly, returning the system to the saturation line. Any pressure drop in the LAD therefore brings the liquid in the channels below its vapor pressure, and raises the possibility of cavitation.

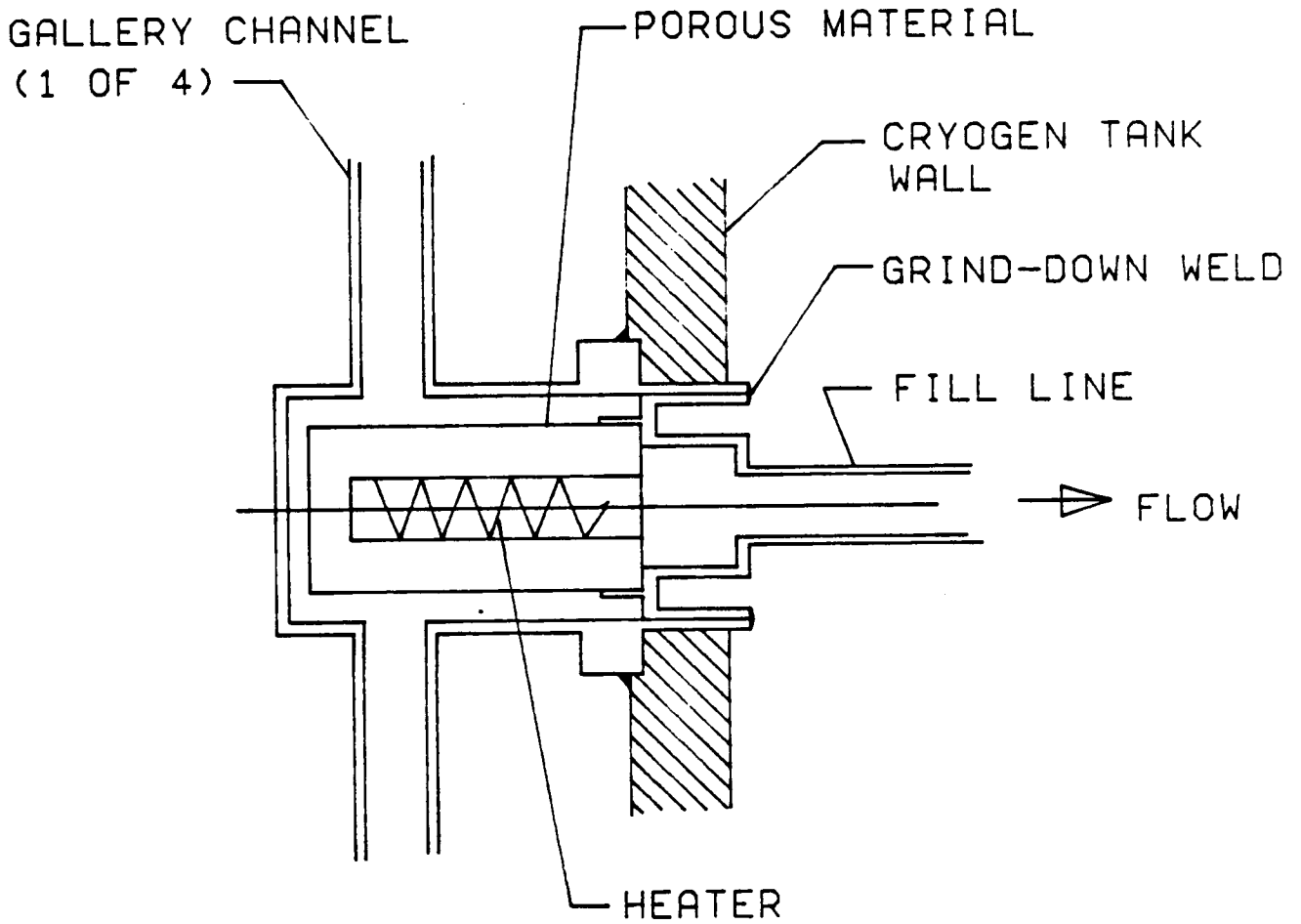
In general, liquids will withstand pressures below their vapor pressure for a short time without forming bubbles because of the time required for random fluctuations of thermal energy to allow creation of a bubble larger than a certain critical radius. Testing has shown that SfHe can withstand a pressure head of about 8 cm below saturation, but that this sustainable pressure falls off at high flow rates. Other work has shown that this sustainable head can fall to near zero under certain high flowrate conditions. The extent to which, or whether, the LAD or SFHT can be allowed to count on operating correctly below the SfHe saturation line is uncertain at this point.

#### 2.1.4.3 Recommended Design Approach

We recommend a LAD design based on the TM principle. Whether or not this system should be designed to maintain the SfHe pressure above saturation under adverse accelerations is a tradeoff we discuss below. The overall LAD concept (Figures 2-5 and 2-10) looks very much like a conventional screen-channel LAD, but the flow impedances (i.e., the screen pore size and open area) are chosen specifically to function with the TM pump and SfHe.

To understand how the SFHT LAD behaves, it is necessary to understand the physical principles governing the behavior of SfHe. The well-established two-fluid model describes SfHe as consisting of two components, a normal component that has viscosity and entropy, and a superfluid component that has neither. The overall SfHe density  $\rho$  is given by

$$\rho = \rho_n + \rho_s,$$



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Figure 2-10 Thermomechanical pump concept



where  $\rho_n$  and  $\rho_s$  are the densities of the two components.

Just below the lambda point (the temperature near 2.18 K where the superfluid transition occurs), the SfHe consists almost entirely of the normal component, as shown in Figure 2-11. As the temperature is reduced to the range around 1.6 K where SFHT will operate, the liquid consists mostly of the superfluid component.

To predict the behavior of the LAD requires analyzing the velocities  $V_n$  and  $V_s$  of the normal and superfluid components separately. Table 2-4 shows the four equations that govern the velocities of the two components. Here  $\dot{m}$  is the mass flow,  $A$  is the cross-section area of the flow channel,  $x$  is the distance down the flow path,  $Q$  is the external heat input, and  $T$ ,  $P$ , and  $S$  are the temperature, pressure, and entropy respectively. The meaning of the mass conservation equation is obvious, and the energy conservation equation is based on the fact that the energy carried by the liquid is given by its enthalpy plus the internal convection described below. The Gorter-Mellink equation is a well-accepted empirical relationship between the temperature and pressure gradients and the mutual friction between the two fluid components, using experimental values for the Gorter-Mellink constant,  $a$ . The pressure drop is tied only to the normal fluid component.

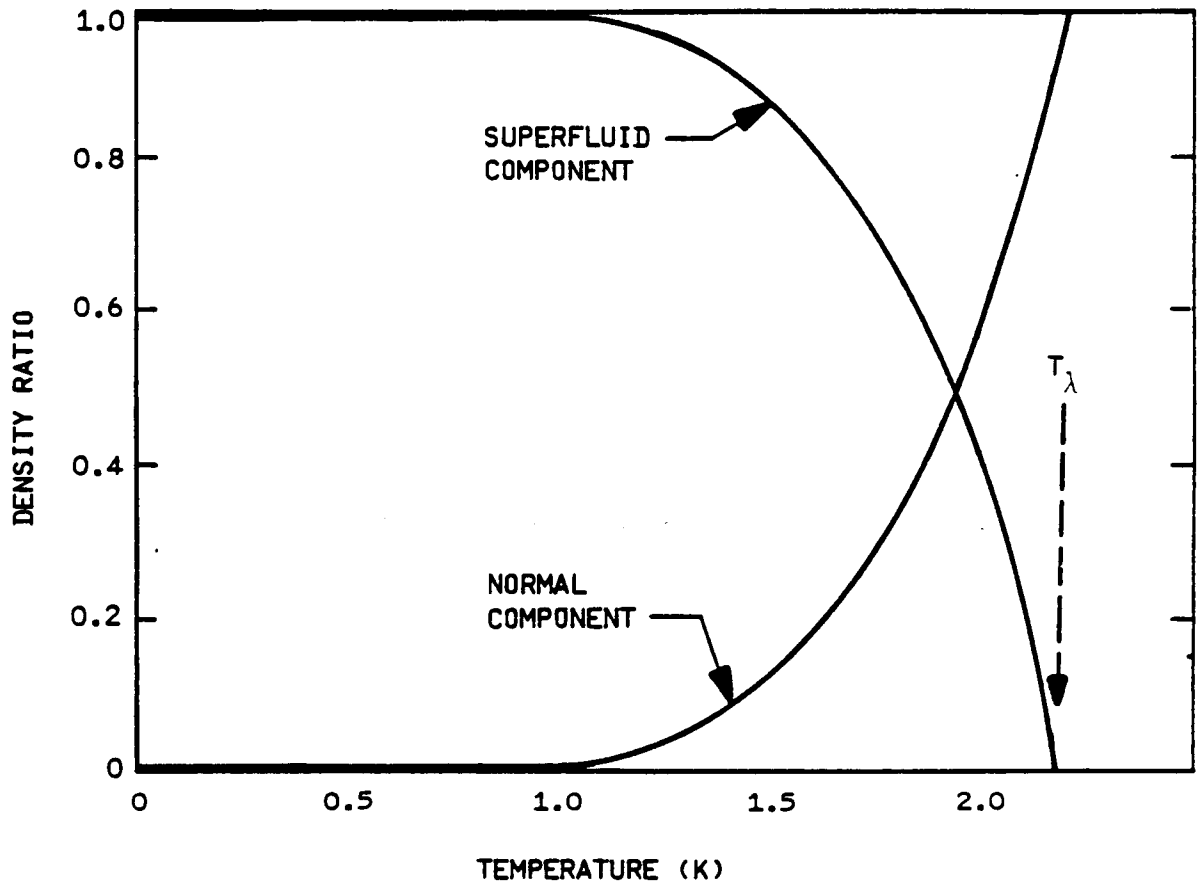
The fifth equation describes the heat flux  $q$ , which is the energy transport within the fluid due to the difference between  $V_n$  and  $V_s$ . This internal convection has no counterpart in normal fluids and is the phenomenon that gives SfHe its anomalously high thermal conductivity.

Figure 2-12 shows why it is that the LAD in the SFHT tends to pump the SfHe. The porous plug of an ideal TM pump would have pores so small that it would allow essentially none of the normal component to be forced back through by the high downstream pressure. In real materials, however, a finite  $V_n$  flows upstream through the LAD channel and screen. The flow impedance of the screen (or other porous material covering over the opening into the channel) therefore causes the pressure to be higher inside the LAD than in the main bath. In other words, the screen of the LAD tends to act as a TM pump, driven by the backflow of the normal component from the main TM pump.

Figure 2-13 shows the design criteria for a conventional screen-channel LAD. The LAD must be able to draw fluid at the rate  $\dot{m}$  from the screen located farthest away from the pump inlet without either causing cavitation or sucking bubbles in through the screen closest to the pump. The pressure  $P_{LOCAL}$  at the pump inlet is

$$P_{LOCAL} = P_{BATH} - P_{SCREEN} - P_{CHANNEL} - P_{ACCELERATION} - P_{BERNOULLI}$$

where  $P_{SCREEN}$  and  $P_{CHANNEL}$  are the viscous pressure "loss" across the impedance of the screen and the channel,  $P_{ACCELERATION}$  is the "static head" that would be caused by an adverse acceleration of the vehicle, and  $P_{BERNOULLI}$  is due to the Bernoulli effect. Note that with normal fluids the viscous pressure drop term causes the pressure inside the screen to be lower than in the bath, but the fact that  $V_n$  is flowing upstream causes these terms to produce a pressure increase.



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Figure 2-11 Two components of He II



Table 2-4  
EQUATIONS GOVERNING SUPERFLUID

Mass Conservation:

$$\dot{m} = A(\rho_n V_n + \rho_s V_s)$$

Energy Conservation:

$$\frac{d}{dx} (\dot{m}h + q) = \frac{dQ}{dx}$$

Gorter-Mellink Equation:

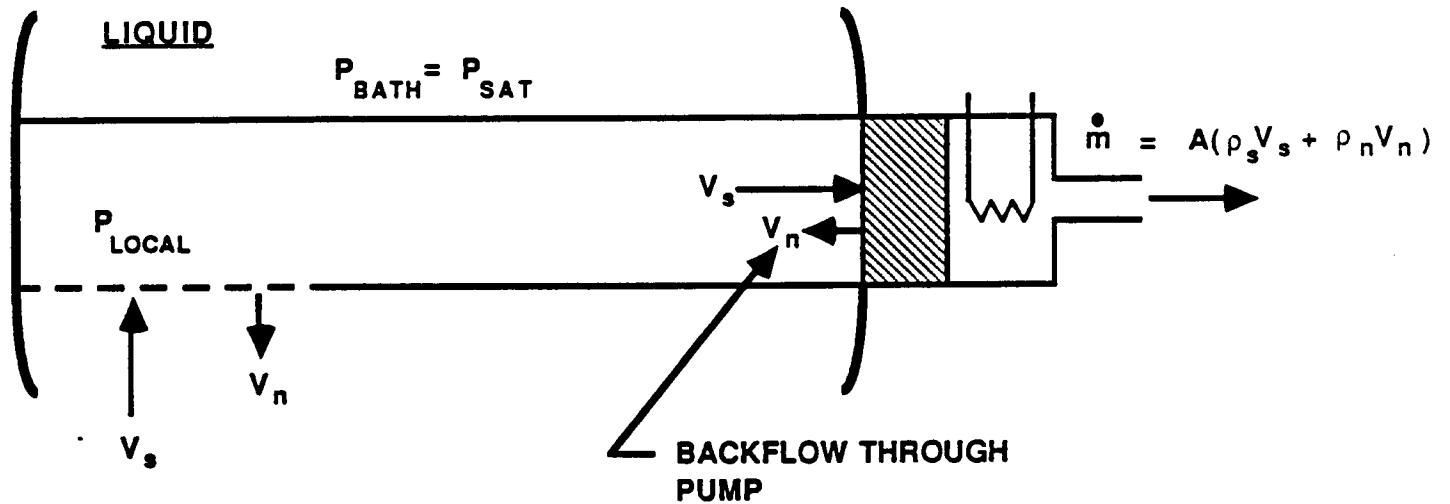
$$\frac{dT}{dx} = \frac{1}{\rho S} \frac{dP}{dx} + \frac{a\rho_n}{S} (V_s - V_n)^3$$

Viscous Pressure Drop:

$$\frac{dP}{dx} = \begin{cases} -\frac{32\eta V_n}{D^2} & \text{(laminar)} \\ -\frac{0.316\rho V_n^2}{2 D Re^{1/4}} & \text{(turbulent)} \end{cases}$$

Heat Flux:

$$q = A\rho_s ST(V_n - V_s)$$

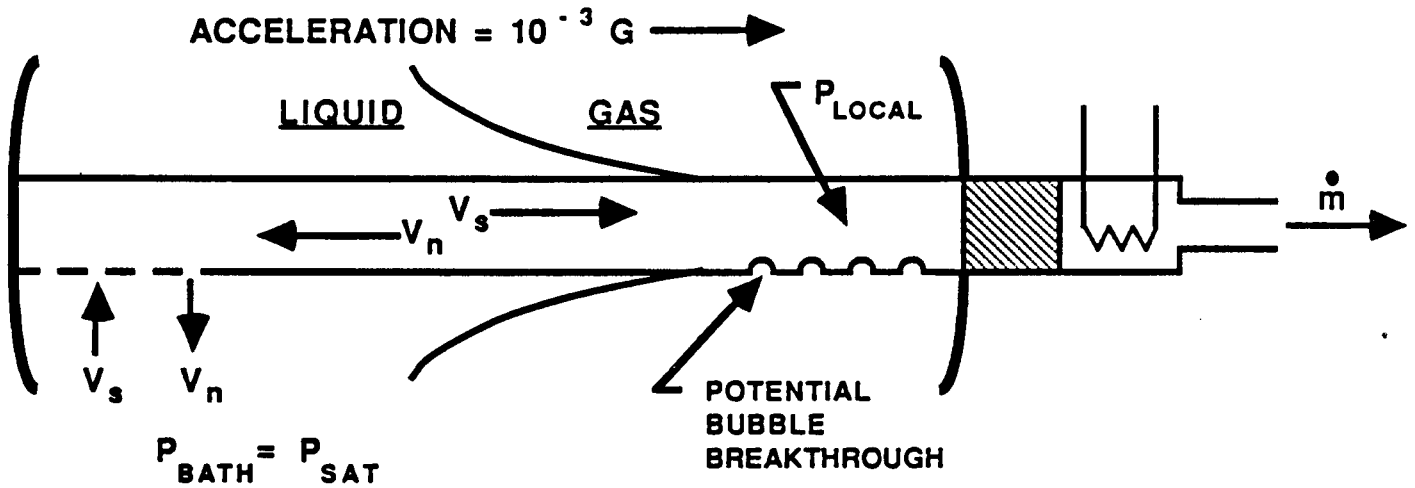


$$P_{LOCAL} = P_{BATH} - \text{VISCOUS PRESSURE DROP OF NORMAL COMPONENT PASSING THROUGH PORES}$$

$$= P_{BATH} - L \left[ \frac{32 \eta V_n}{D^2} \right]$$

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Figure 2-12 Why LAD pumps



**AVOID CAVITATION:**

$$\begin{aligned}
 P_{LOCAL} &= P_{BATH} - P_{SCREEN} - P_{CHANNEL} - P_{ACCELERATION} \\
 &> P_{SAT} - P_{CAV} \\
 &> P_{SAT} \quad (\text{GOAL})
 \end{aligned}$$

**AVOID BUBBLE BREAKTHROUGH:**

$$P_{BATH} - P_{LOCAL} < P_{BUBBLE}$$

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Figure 2-13 LAD design criteria



The other principal design requirement for conventional screen-channel LADs, namely that launch accelerations will not cause bubble breakthrough, does not apply to this system using SfHe. As soon as the main TM pump is started and  $V_n$  starts to flow back from the pump toward the main bath, the pressure rise due to the TM pumping action will cause any bubbles within the LAD to collapse. This makes the LAD self-filling, and allows it to recover automatically if an anomalous acceleration does cause momentary cavitation.

Table 2-5 compares the performance predicted for a SFHT LAD using conventional 325x2300 wire/inch Dutch twill stainless steel screen with one using a porous membrane instead. Four channels were assumed, using a flow area of 80 cm<sup>2</sup> for both the channel and the screen (or porous membrane). The bubble points (the pressure difference required to cause bubble to break through the holes against the surface tension of the liquid) are high enough that bubble ingestion is clearly not a problem with either the screen or the membrane. The principal issue is possible cavitation.

Table 2-5  
EXPECTED LAD PERFORMANCE

<u>PRESSURE CHANGE FROM BATH</u> <u>(EXPRESSED IN CM OF HELIUM HEAD)</u>	<u>SCREEN</u> <u>(3-10 <math>\mu</math>m)</u>	<u>MEMBRANE</u> <u>(0.2 <math>\mu</math>m)</u>
Viscous Drop Across Screen	+8.0x10 <sup>-3</sup>	+2.1
Viscous Drop Across Channel	+6.0x10 <sup>-6</sup>	+6.0x10 <sup>-6</sup>
Acceleration (At 10 <sup>-3</sup> g)	-0.3	-0.3
Bernoulli Pressure Drop	-3.9x10 <sup>-3</sup>	-3.9x10 <sup>-3</sup>
Total	-0.3	+1.8
Bubble Point of Screen/Membrane	30	N/A

With the screen, the pressure rise due to the TM pumping action is tiny compared to the pressure reduction from an adverse acceleration of 10<sup>-3</sup> g. With the finer pores of the membrane, however, it is easy to achieve a pressure rise that will keep the liquid securely above the saturation line under the worst-case design acceleration.

The metallic screen used in this example is a well-developed technology used in conventional LADs. The porous membrane is a filter material used routinely for fairly high (e.g., 55 psi) pressure differentials, and which has been used in SfHe research. The standard screen technology presents essentially no hardware development risk, but makes the performance of the SFHT dependent on the partially-understood capability of SfHe to withstand pressures below saturation without cavitation. The porous membrane (or other porous material with pores smaller than about 1 micron) could be used to make SFHT immune to accelerations during transfer, but would require selection of the material and development of suitable mounting techniques.





#### 2.1.4.4 Recommendations for Development

We recommend that a LAD system like that of Figure 2-5 be baselined for SFHT, with a decision to be made between two possible approaches to the covering for the channel openings:

##### Option 1: Metallic Screen

The well-established manufacturing technology minimizes the hardware development effort, but the tiny TM pressure rise possible means that random accelerations during the transfer will cause the pressure in the channels to drop below the saturation pressure intermittently. Further understanding of the ability of SHe to withstand these pressures may or may not show that cavitation is unlikely. If bubbles do form, they will collapse when the adverse acceleration is removed, and do so at a rate that can be calculated. When analyzing the acceptability of this approach, it is important to recognize that occasional cavitation and interruption of the mass flow may be acceptable because the system recovers gracefully. This is the approach currently baselined for SHOOT.

##### Option 2: Fine-Pore Material

Using either thin membranes or conventional porous plug materials allows the liquid to be kept above saturation under any accelerations likely to occur during transfer, but does require some hardware development effort. Previous experience with the plastic membranes at SHe temperatures and separately in high-pressure filtering applications makes this effort seem quite feasible. The additional pressure rise within the LAD may have additional system benefits as well.

Whichever approach is chosen, the LAD must be analyzed and developed jointly with the TM pump and transfer system. In the present example, the pressure and temperature rise within the LAD are so small that the pump and transfer system can be analyzed neglecting them. In an optimum system, however, it may turn out that there are advantages to sharing the pressure rise more equally between the LAD and the main TM pump. In the limit, the main TM pump plug could be eliminated entirely, relying on the LAD to provide the driving pressure and to contain the full pressure rise and temperature rise without structural failure or excessive heat conduction to the main bath.

#### 2.1.5 Thermal Subsystem

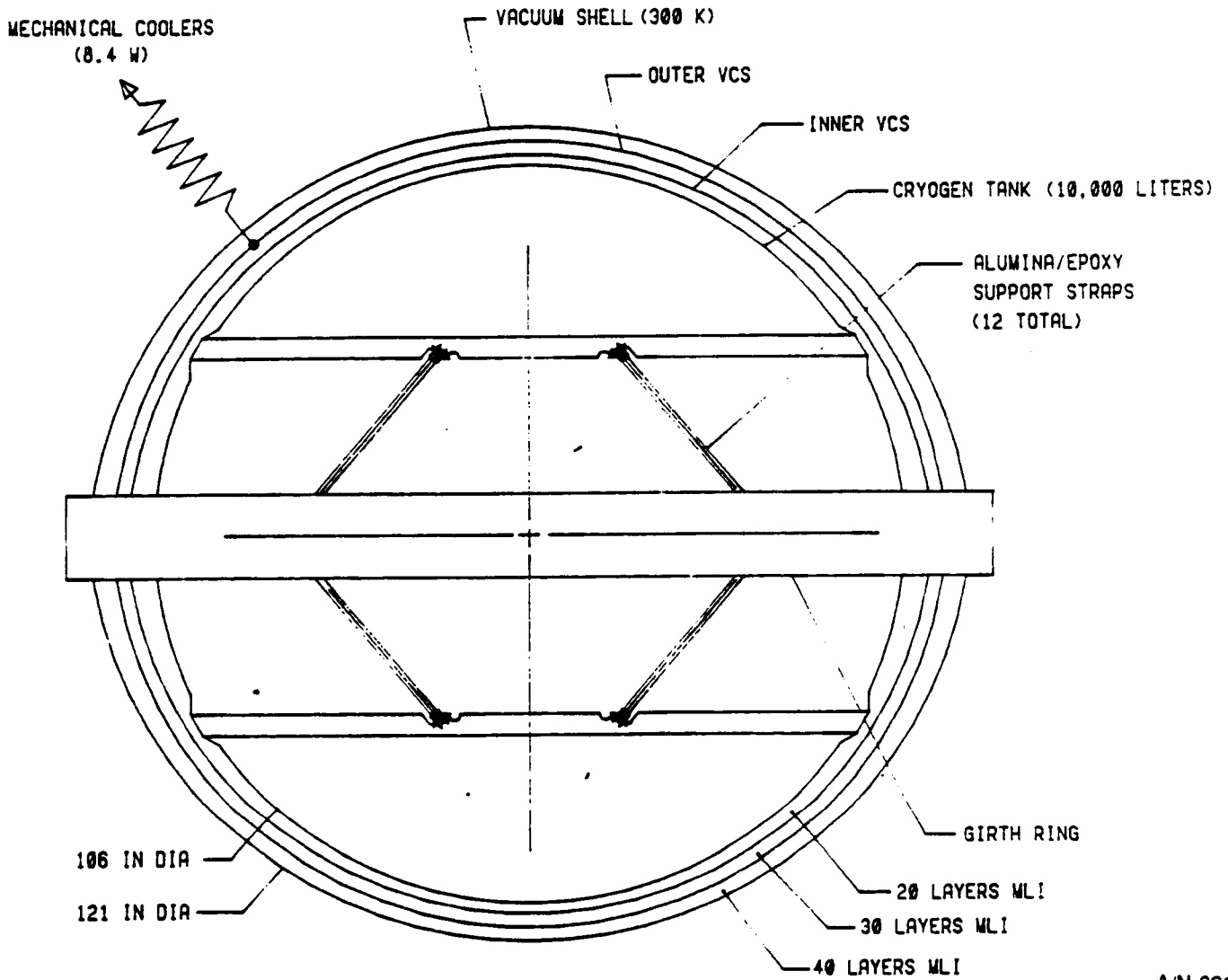
The thermal subsystem consists of two parts: external (outside the vacuum shell) and internal (inside the vacuum shell). The external thermal system controls the vacuum shell temperature and maintains externally mounted equipment within required temperature limits. The internal system limits the heat input to the stored helium.

Internal Thermal Control (Figure 2-14) has five major parts:

1. Because of the low latent heat and high sensible heat of helium, it is essential for long-term liquid helium storage to use a vapor-cooling system that intercepts parasitic heat inputs. For the lifetime, size, and boundary conditions of the SFHT, two



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Figure 2-14 Insulation system design

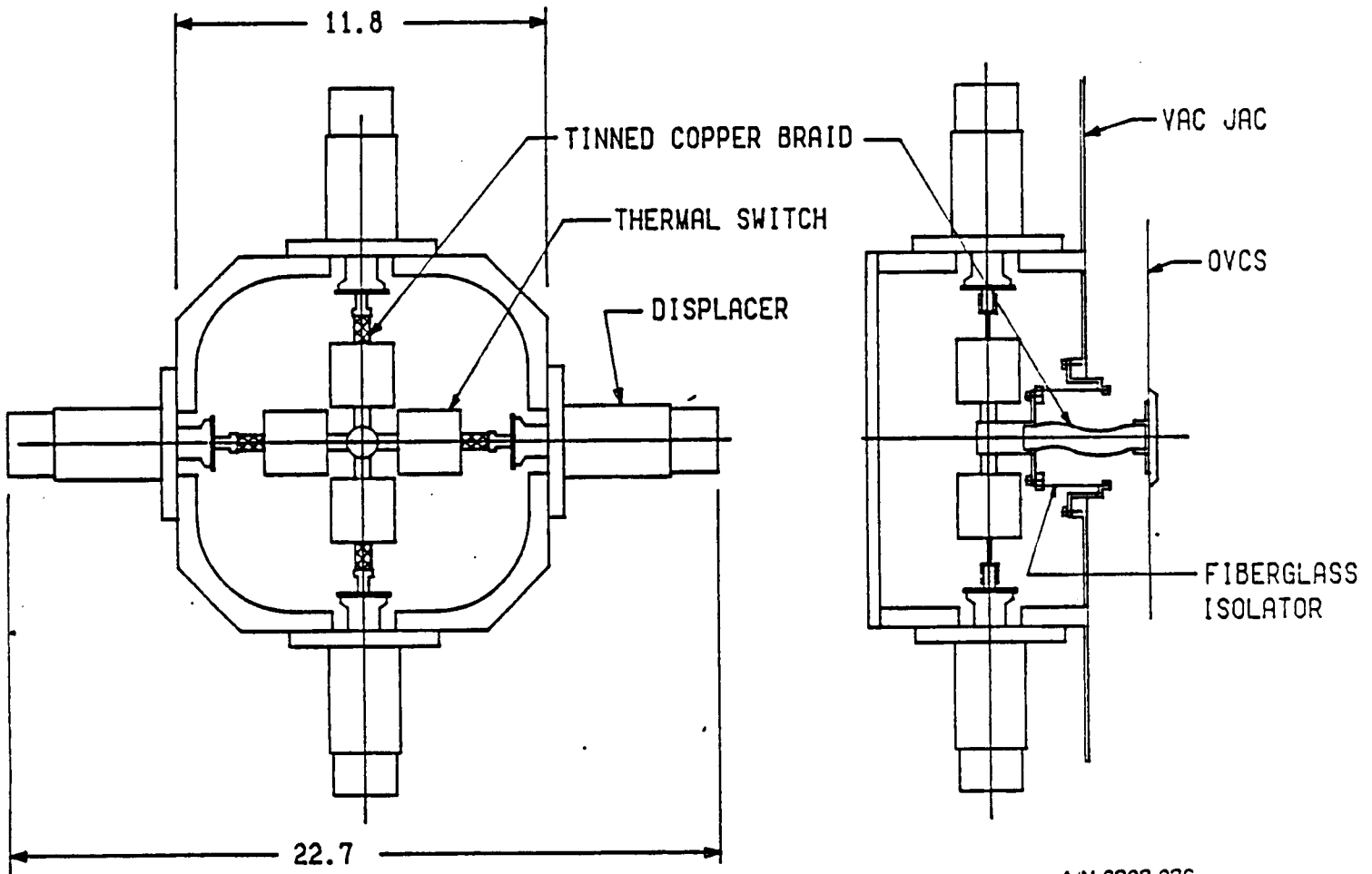


vapor-cooled shields give a mass-optimized system. All radiative and conductive heat inputs are intercepted at each VCS.

2. Radiation input is blocked by high-quality MLI blankets similar to those of the COBE dewar. The three blankets contain 20, 30, and 40 layers (from cold to warm) of double-aluminized mylar with dacron net spacers.
3. Fluid loss during the extended on-orbit standby is reduced by a factor of two by four Stirling cycle mechanical coolers which take heat from the outer VCS. The cost and mass trades related to these coolers are discussed in Section 2.1.1. Four British Aerospace Stirling cycle coolers with 3 W cooling power at 93 K each are baselined; efficiency is about 25 W/W. The cooler consists of a compressor and a displacer, where the cooling is produced. Figure 2-15 shows the interface between the four displacers and the dewar. It provides high thermal conductance by copper conduction, minimal loading on the fragile displacer cold tip by using copper braid, separation between the dewar guard vacuum and the displacers vacuum, and semipassive thermal switching to disconnect a given displacer from the cold finger in case a cooler fails. Cooling by the cold finger will produce the thermal contraction needed to make the switch close, but a heater is needed to force it open since multiple coolers are thermally manifolded.
4. The cryogen tank is supported from the vacuum shell by a thermally-optimized, tension strap support system using alumina/epoxy straps. The thermal efficiency and low risk of this approach make it the obvious choice for the SFHT.<sup>10,11</sup>
5. Gaseous heat conduction into the helium tank is essentially eliminated by a high-quality guard vacuum. The vacuum shell maintains air leakage at no more than  $10^{-8}$  sccs, and helium leakage is held below  $10^{-8}$  sccs by careful assembly of the tank and plumbing and in-process testing.

The external thermal control system maintains heat dissipating components within required temperature ranges and shields sensitive items, such as the avionics, from solar illumination. In many long-life dewar applications, carefully designed combinations of high-emittance coatings on space-viewing surfaces and MLI blankets on sun-viewing surfaces are used to minimize the vacuum shell temperature and standby boil-off rate. For example, the COBE dewar vacuum shell is predicted to be at 150 K. In the case of the SFHT, periods of extended standby will be in a protected area, probably in the SS customer servicing facility. This enclosure will be maintained at a nominal temperature of 300 K.<sup>12</sup> Consequently, our baseline design and performance estimates assume a vacuum shell temperature of 300 K.

Heat producing components on the vacuum shell (i.e., electronics and mechanical coolers) will be cooled by attachment to the vacuum shell, by self radiation, and/or by attachment to the host heat rejection system. Both the shuttle orbiter and the SS have adequate heat rejection capacity<sup>13,14</sup> for the SFHT maximum total power level of about 400 W. The vacuum shell will have a high-emittance/low absorptance finish to provide radiative cooling, even when exposed to solar radiation.



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Figure 2-15 Concept for dewar/mechanical cooler interface



### 2.1.6 Dewar Instrumentation and Cabling

This section discusses instrumentation and cabling that are part of the dewar. The instrumentation is used to monitor the condition or health of the dewar and to aid control of the fluid operations. Instrumentation, primarily thermometers, used to monitor avionics components and other equipment external of the dewar is also required.

Table 2-6 is an instrumentation list, showing wire counts, wire routing, and when the sensors are used (i.e., ground or flight). Figure 2-16 shows approximate locations of the various sensors, which are described further below. Related technology development requirements are discussed in Section 6.

#### Thermometry

Germanium resistance thermometers are used for the range of 1.5 - 10 K, and silicon diodes are used for the range of 10 - 350 K. The high sensitivity of the GRT is needed for the measurements around and in the helium tank. The large range of the SD makes it the choice for all of the warmer measurements.

The thermometers are located in redundant pairs. GRTs are located in the helium bath, at two locations within the liquid acquisition device, on the inner and outer surfaces of the TM pump, on the vent line just downstream of the low-flow porous plug, and on the outer surfaces of the two porous plug phase separators. SDs are located on the inner VCS, on the outer VCS, on each of the four thermal switches connecting the mechanical coolers to the dewar, at three places on the vacuum shell, and on both of the EVA couplings.

#### Pressure Transducers

Two types of pressure transducers are used: high range (0 - 50 psi) and low range (0 - 2 psi). The high-range transducer primarily monitors tank pressure to check for anomalous over-pressure conditions; the Teledyne Taber unit being used by SHOOT is adequate. The low-range transducer is located just downstream of the TM pump and operates at the pump temperature ( $\sim 2$  K). It is part of the transfer flowrate measuring technique described below. The Validyne model AP10 being used in the SHOOT venturi flowmeter is the choice here.

#### Flowmeters

Two mass flowrate measurements are made: the standby boil-off rate (10 mg/s maximum) and the superfluid transfer rate ( $1.5 \times 10^5$  g/s maximum). The standby flowrate is determined by simply measuring the thermal capacitance ( $\dot{m}c_p$ ) of the flow, as shown in Figure 2-17, and knowing the specific heat of the gas. This approach works particularly well at the low temperatures and flowrates involved because a GRT can be used to make very sensitive measurement of temperature, there are no radiation effects, material thermal capacities are so low that their effect is negligible, and very little heat input ( $\sim 50$  mW) is needed to produce an accurately measurable temperature rise ( $\sim 1$  K). This flowrate is measured because it is one of the indicators of dewar "thermal health" and to help determine if helium is leaking from the system via an unknown path. The latter is done by comparing the integrated flow measurements with the mass loss indicated by the mass gage described below.



Table 2-6  
DEWAR SENSORS AND CABLING

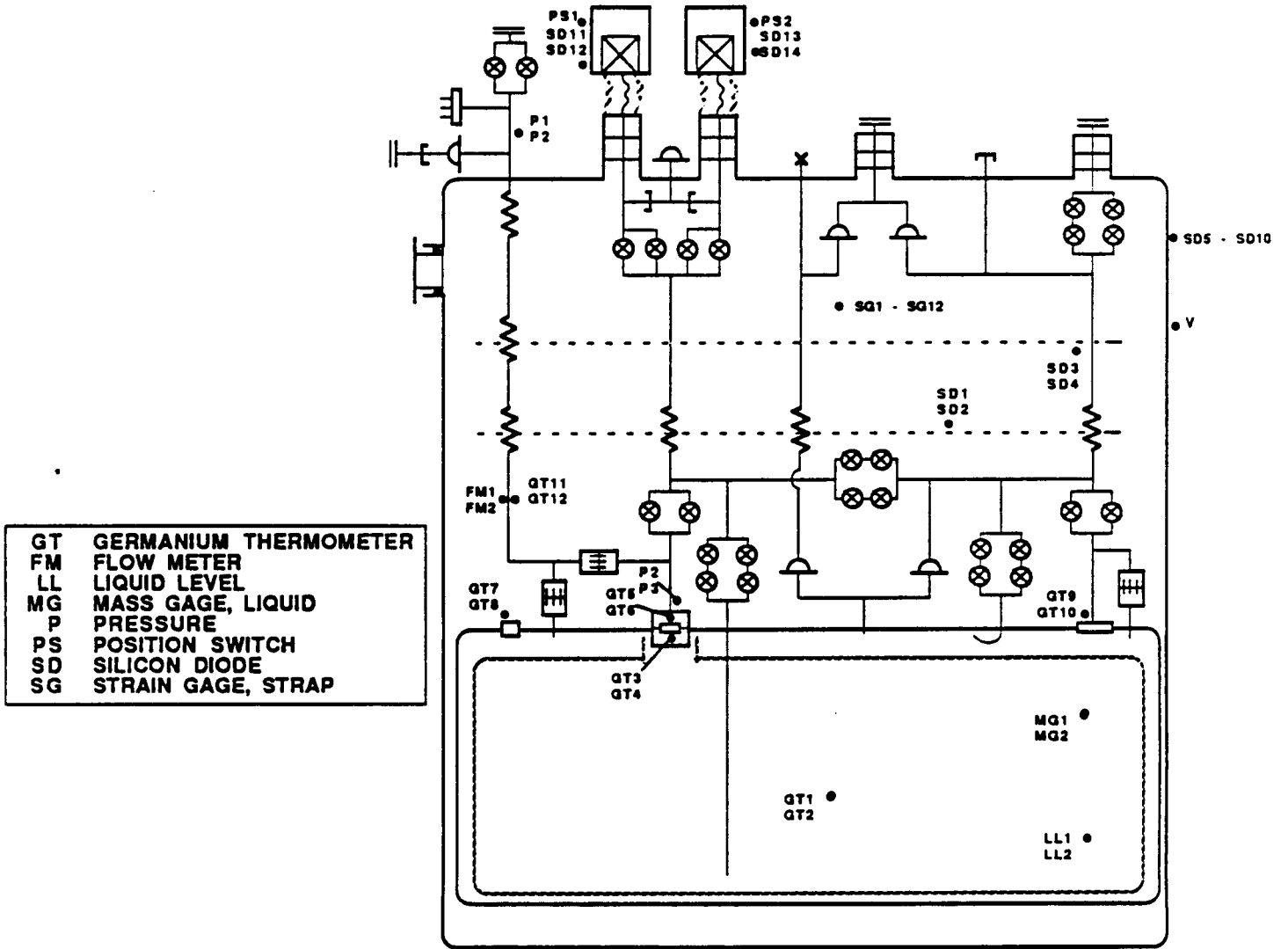
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ITEM	QUANTITY	NO. OF WIRES	WIRE ROUTING*	USE
LIQUID LEVEL, NORMAL (LL)	2	8 (#40)***	VENT	GSE
SUPERFLUID MASS GAGE HEATER (LM)	2	4 (#40)	VACUUM	BOTH
GERMANIUM RESISTANCE THERMOMETER (GT)	12**	10 #(28) 48 (#40)	VACUUM AND VENT	BOTH
SILICON DIODE THERMOMETER (SD)	20	40 (#40)	VACUUM AND EXTERNAL	BOTH
PRESSURE (P), 0-50 psi	2	10	EXTERNAL	BOTH
0-2 psi	2	6 (#40)	VACUUM	BOTH
STRAIN GAGE (SG)	12	48	VACUUM	GSE
ACCELEROMETER (A)	2	12 (#40)	VACUUM	GSE
VACUUM (V)	1	4 (HIGH VOLTAGE)	EXTERNAL	GSE
VALVE POSITION	28	130 (#40)	VACUUM	BOTH
VALVE POWER	28	156 (#28)	VACUUM	BOTH
TM PUMP HEATER	2	6 (#28)	VENT	BOTH
STANDBY FLOWMETER HEATER (FM)	2	4 (#28)	VACUUM	BOTH
SFHE TRANSFER FLOWMETER		NA - FLOWRATE BASED ON GT3, GT5 AND P3		
POSITION SENSOR, EVA COUPLING (PS)	2	4	EXTERNAL	FLIGHT

\* EXTERNAL - External of vacuum shell, VACUUM - In dewar vacuum, VENT - In low-flow vent line  
 \*\* Some of these are used on part of mass gage and flowmeters  
 \*\*\* Heat leak critical wires - manganin



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GT	GERMANIUM THERMOMETER
FM	FLOW METER
LL	LIQUID LEVEL
MG	MASS GAGE, LIQUID
P	PRESSURE
PS	POSITION SWITCH
SD	SILICON DIODE
SG	STRAIN GAGE, STRAP

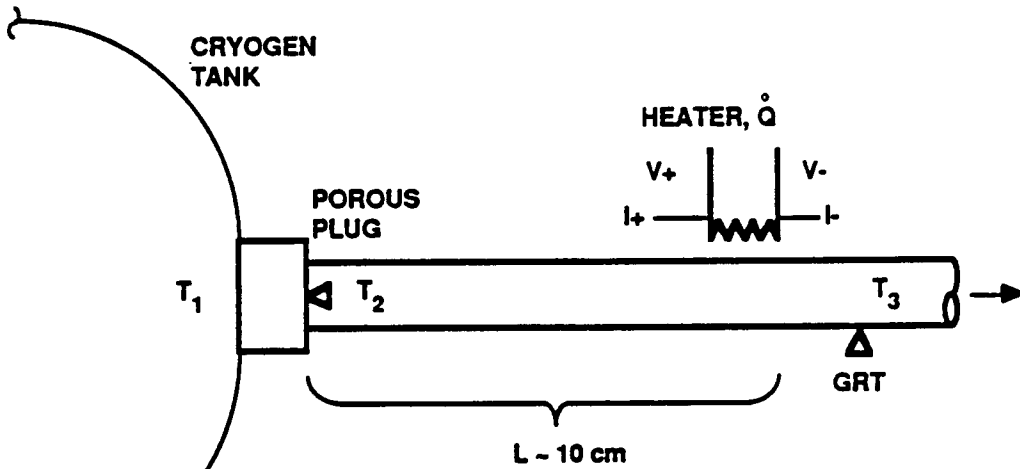
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Figure 2-16 Locations of dewar instrumentation

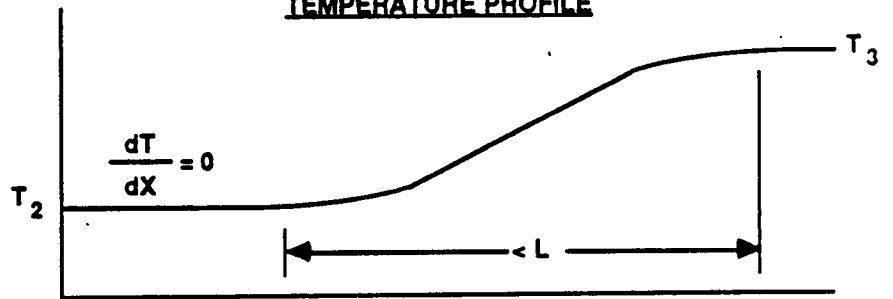


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CONFIGURATION



TEMPERATURE PROFILE



EQUATION

$$\dot{M} = \frac{\dot{Q}}{h(T_3) - h(T_2)}$$

WHERE:  $\dot{m}$  = FLOWRATE  
 $\dot{Q}$  = HEATER POWER  
 $h$  = ENTHALPY OF GAS

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Figure 2-17 Flowmeter concept





The on-orbit transfer rate can be determined to about 1 percent accuracy by measuring the temperatures upstream and downstream of the pump and pressure downstream of the pump. These values will be entered into the performance model of the pump, which will have been validated by ground characterization of the pump by test, and the flowrate calculated.

### Strain Gages

Strain gages are used to measure tension in each of the 12 support straps, as was done in the IRAS and COBE dewars. These are used to pretension the straps during assembly, monitor stress levels during system testing, and ensure that proper pretension is maintained throughout the life of the system. It would also be desirable to measure the stress levels during one launch to verify the fatigue loading history assumed for sizing the straps. However, this capability is not included in our avionics design since it is a one-time gathering of engineering information.

### Accelerometers

Redundant triaxial accelerometers are located on the cryogen tank for system testing. The vacuum shell will be instrumented with laboratory accelerometers during testing.

### Position Sensors

Each motor-operated valve has redundant position sensors to indicate "open" or "close". The EVA couplings also have position sensors for electrical verification of complete mating.

### Guard Vacuum

A Vac-ion gage is used to monitor the guard vacuum level while on the ground, as done with the IRAS and COBE dewars. This is needed to verify the proper age when the dewar contains liquid helium. The gage is not used during flight.

### Mass Gaging

Liquid level is measured on the ground with superconducting wire sensors, as was done in the IRAS and COBE dewars. The sensors are oriented orthogonally so that the liquid level can be measured with the dewar in two orientations. If this is not required, they will be parallel and redundant.

Liquid mass will be measured on-orbit by applying a heat pulse and measuring the resultant temperature rise, as will be done in the SHOOT dewar. This approach can also be used on the ground when the bath is superfluid. Redundant gages are used. Each gage consists of a simple wire-wound heater attached to the tank wall, a GRT, and the external electronics. The GRTs are interchangeable and therefore redundant. The design developed for SHOOT will be directly extended to the SFHT. The main difference is that the greater fluid mass requires a larger heat pulse. Based on the 0.02 K temperature rise recommended by the SHOOT program and a 10 minute pulse duration, the power needed is 100 W. Higher power and smaller pulse time could be used at



the expense of dewar thermal performance. Detailed operational parameters will be based on the results of the SHOOT flight experiment.

## 2.2 FLIGHT AVIONIC SUBSYSTEM

This section presents the conceptual design for the SFHT avionics. Since detail design was not in the scope of this study, specifics are minimized. Several areas are addressed which define the scope of avionic needs and requirements for the SFHT.

The purpose of the SFHT avionics is to provide all control, monitor, and display functions necessary to transport cryogen and perform resupply operations in a flexible and efficient manner. As directed by JSC, our concept starts with the design from the Martin Marietta OSCRS study with modifications for improved operator interface, reduced power and parts count, increased reliability, and SFHT-specific requirements. We also expect the SFHT avionics to utilize both hardware and knowledge from the upcoming SHOOT experiment.

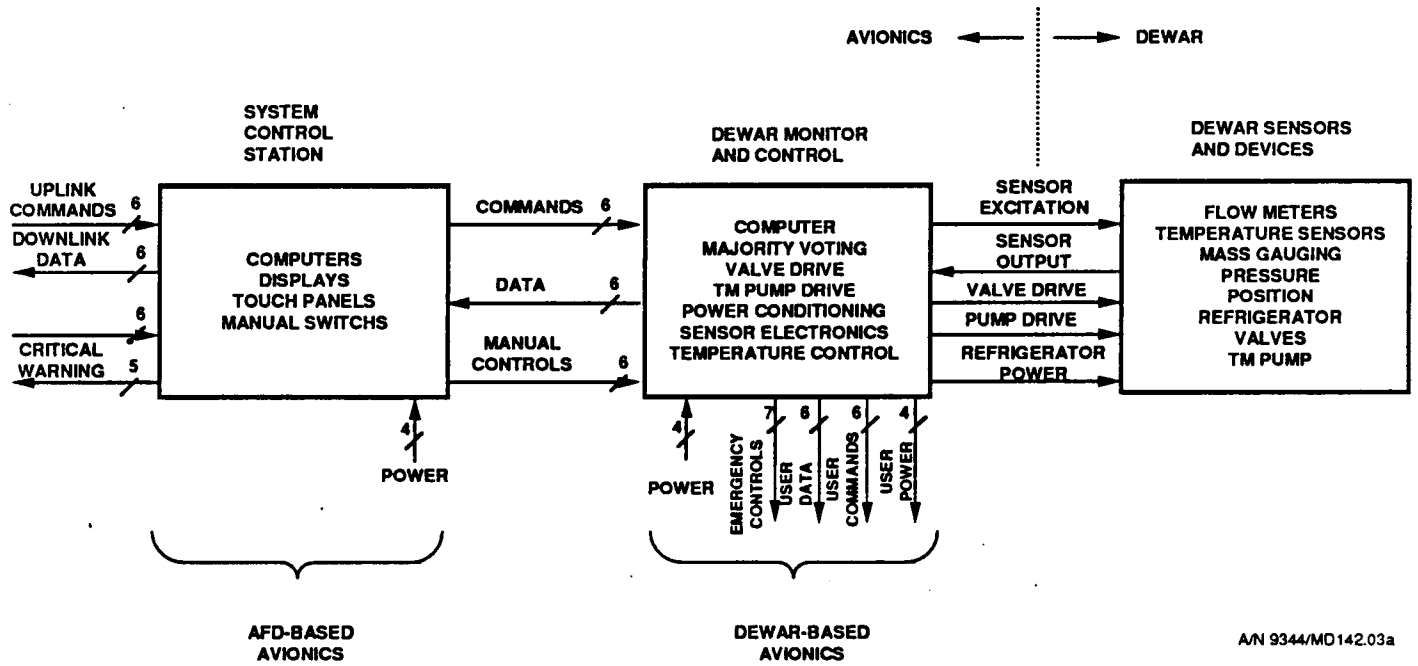
Our baseline concept is primarily intended for resupply at the shuttle with additional considerations for SS and OMV operation addressed. The SFHT will be used to resupply a variety of users, such as Astromag, SIRTF, AXAF, and XRS. We present the basic interface requirements between SFHT and the user to assist the start of planning for compatibility between them.

Our avionics concept is a stand-alone system that uses the orbiter GPC for safety-related functions only, as discussed in 3.3. Growth provisions have been included to allow for future upgraded SFHT systems extending into the 2010 time frame, as well as operation with other cryogenic systems. The SFHT avionics concept is designed to function with minimum, but critical, human oversight and control leading to growth into autonomous operation in the future. Closed-loop control is employed with an intelligent expert system combined with both sensor and actuator feedback to close the loop.

### 2.2.1 System Architecture

The SFHT avionics is broken into two functional blocks: the system control station (SCS) and the dewar monitor and control, in two distinct locations. Figure 2-18 illustrates the two functional blocks with their respective internal functions and I/O needs.

The SCS avionics consists of those components required to make a man-machine interface (MMI) with the SFHT and to provide a communication link between the SFHT and its host. The SCS is located in an operator accessible area in the host, e.g., the AFD of the shuttle. The MMI elements consist of three electroluminescent color touch screen displays providing operator command input and data display feedback, plus a switch panel for hardwired manual inputs to the system. The SCS functions of receiving commands, processing and displaying data, and communication are orchestrated by three computers operating in a three string majority vote configuration. Electrical I/O to the SCS consists of power from the host, two-way communication with the host, a real-time clock (GMT) from the host, two-way communication with the dewar-mounted avionics, and hardware controls for dewar operation and reliability.



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Figure 2-18 SFHT avionics has two segments



Dewar monitor and control electronics provide the first line of control over the cryogen systems sensors and actuators. The design philosophy has been to put most of the SFHT controls near the cryogen system because this approach will best allow evolution to automatic operation, which is required of SFHT. Following this line of thinking, our concept places the dewar monitor and control avionics on the dewar structure near the cryogenic controls and sensors. This major functional block contains the following subfunctions:

- Power conditioning of itself and those elements receiving power from it
- Three computers plus a majority voting unit to complete the three string, majority vote, computing system
- Valve drive circuitry for the cryogenic control valves
- A proportional drive control for the TM pump
- All sensor excitation and readout circuits for monitor of cryogenic and system status
- An active temperature control system to protect its own environment

The dewar monitor and control I/O consists of the following:

- Two way communication between its computers and the SCS computers
- Power from the host
- Hardwire (manual) controls from the SCS switch panel
- Dewar sensors excitation and readout
- Valve actuation for control of cryogen flow
- TM pump drive power
- Switched host power to dewar mechanical coolers
- Power to the user
- Two way communications with the user
- Hardwired emergency controls for pyrotechnic firings, etc.

Instrumentation, discussed in 2.1.6, consists of sensors associated with measurement of the status of the system and of the actuators that can alter the status and/or condition of the system. The sensors include temperature, pressure, flow, and position while actuators include valves, latches, heaters, relays, and refrigerators. All electrical inputs and outputs for the instrumentation come from the dewar monitor and control electronics. Most of the instrumentation is located either inside the dewar or on the dewar plumbing.



## 2.2.2 Demands on Host Vehicle Resources

The SFHT will be used with several different hosts, and even though we are primarily baselining for shuttle, a definition of demands on the host must be made to assure broad host compatibility. Three areas should be addressed to define the electrical demands. These are power requirements, data rates and interconnects.

### 2.2.2.1 Power

The SFHT power requirements are summarized in Table 2-7. Three levels of power requirements are shown. The first is a warning only, low power monitor mode in which a single computer string operates with no touchscreen input or display capabilities. Only anomalous condition alerts are displayed to the operator at the SCS. This lowest power mode requires 35 W. The second is a full monitor mode in which a single computer string operates with one touchscreen display I/O. This monitor power of 83 W will most likely be the level used during resupply missions at the shuttle or during short standby periods. The third occurs during transfer and results in a power consumption of 315 W. This estimate includes an assumed user power of 46 W for operation of one valve, the user's computer, and six thermometers; this user estimate is of course subject to change. Also shown in Table 2-7 is 375 W for operation of the mechanical coolers during the extended standby (storage) at the SS. The warning only monitor mode would also be used at this time for a total power requirement of 410 W.

### 2.2.2.2 Interconnects

Two interconnect areas are required. First, an SCS to host interface is required to provide an interaction path between the SFHT and its host. Second, the host must provide an interface path between the SCS and the dewar mounted avionics to complete SFHT's control and data loop.

The SCS-to-host interface, as shown in Figure 2-19, consists of three pairs of serial communications lines for downlink data, three pairs of serial communications lines for uplink commands, five wires for critical warning signals to the CWEA, and four power wires rated for at least 3.5 A each.

Figure 2-20 shows the interconnect requirements between the SCS and the dewar mounted avionics. Command and data requires six pairs of serial communications lines per computer for a total of 18 pairs. Discrete wire control requires a total of 18 single wires: 4 for power on/off, 7 for pyro control, and 7 for manual valve safing. Additionally the dewar mounted avionics must receive power directly from the host over at least 4 wires capable of 9.6 A each. User power passes through the dewar mounted avionics and requires 4 wires rated at 0.8 A each.

### 2.2.2.3 Data Rates

All SFHT data rates are relatively modest. We are assuming a maximum available STS data rate of 8 KBPS and SFHT's uplink/downlink requirements readily fall within this constraint. Command and data rates between the SCS and



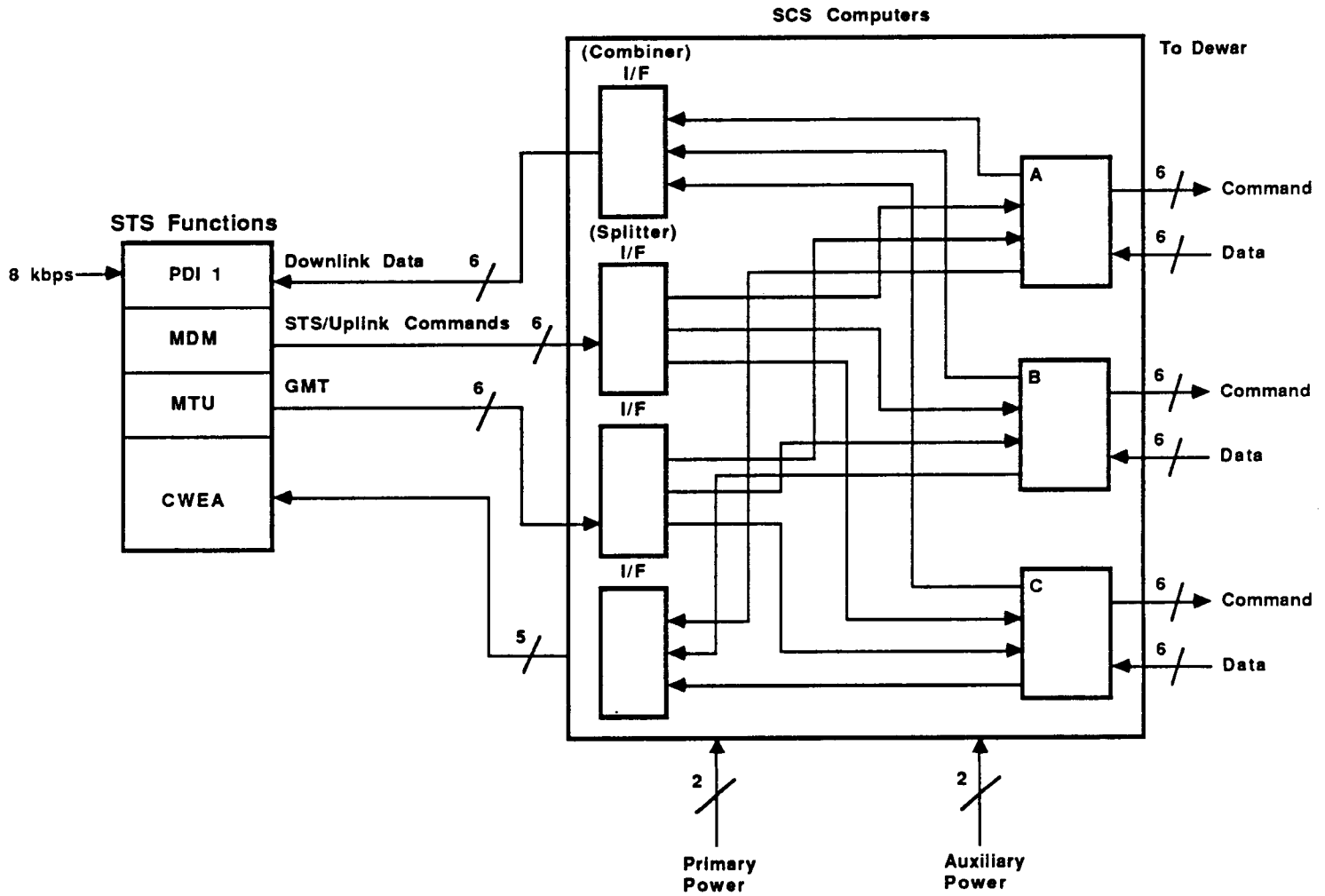
Table 2-7  
POWER BUDGET

	<u>WARNING ONLY MONITOR MODE</u>	<u>MONITOR MODE</u>	<u>TRANSFER MODE</u>
SCS			
COMPUTER	9 W	9 W	27 W
TOUCHSCREEN DISPLAY	-	48	67
SWITCH PANEL	4	4	4
SCS TOTAL	<u>13</u>	<u>61</u>	<u>98</u>
DEWAR MOUNTED AVIONICS			
COMPUTER	16	16	48
MAJORITY VOTE	-	-	12
VALVE DRIVE AND PUMP	-	-	105
TEMPERATURE CONTROL	6	6	6
DEWAR TOTAL	<u>22</u>	<u>22</u>	<u>171</u>
USER	-	-	46
TOTAL	<u>35 W</u>	<u>83 W</u>	<u>315 W</u>

REFRIGERATOR (SPACE STATION ONLY) 375 W

ASSUMPTIONS:

- MAXIMUM 2 VALVES + PUMP OPERATE SIMULTANEOUSLY
- MONITOR MODES HAVE SINGLE STRING COMPUTER
- 80% POWER CONVERSION EFFICIENCY
- SFHT PROVIDES USER POWER FOR VALVE OPERATION, COMPUTER, AND MONITOR



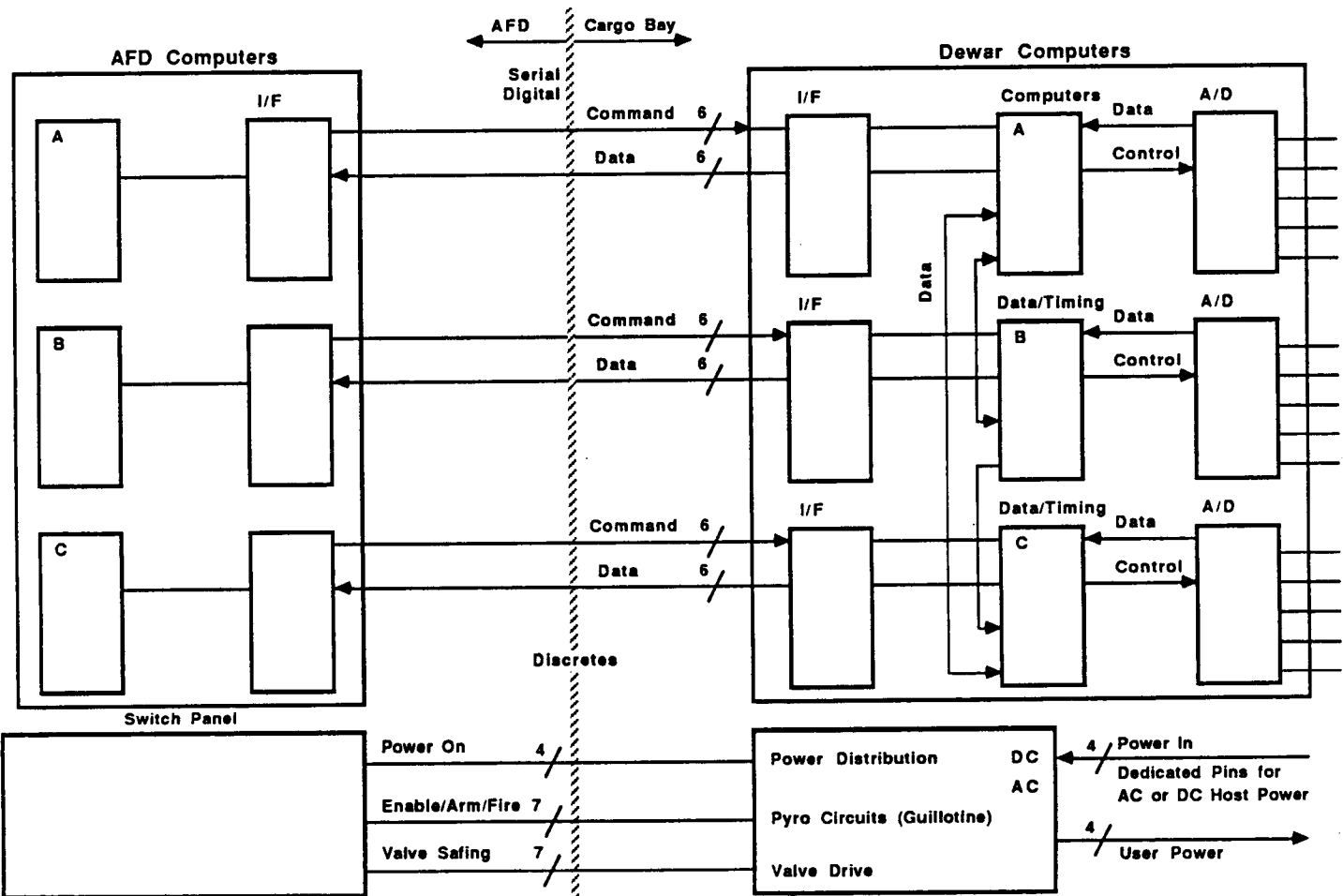
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Figure 2-19 SCS to STS interface



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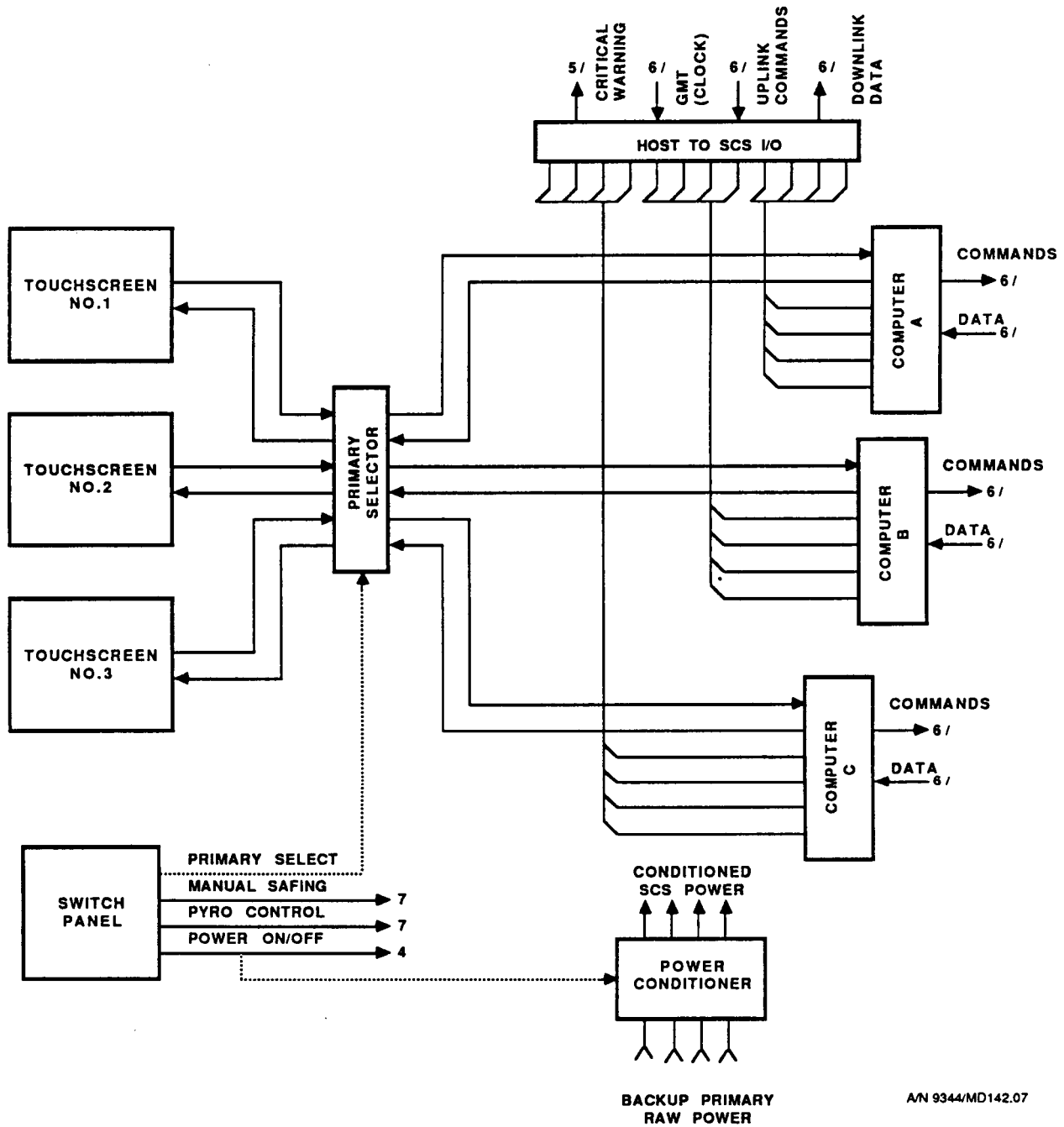
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Figure 2-20 Dewar/SCS electrical interface





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Figure 2-21 System control station

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operator, transfer data to and from the host, and provide only backup limit detection to the dewar computers. This limited role of the SCS computers is in keeping with a design philosophy which will lead to fully automated operation.

Three microprocessor based computer systems can be housed in one assembly and operate as part of the three string computational approach used throughout the SFHT avionics system. Use of CMOS microprocessors from the 8086 family for these computers will allow the sharing of common software development tools with the dewar computers. Computer memory requirements are modest compared to 8086 family capabilities.

Host-to-SCS interface consists of uplink and downlink data, real-time clock, and warning lines to the GPC. The downlink data passes information from any or all computers. An interleaver in the output interface will allow selection of the desired output format. Uplink and real-time clock inputs will be split for application to all three computers simultaneously. The GPC interface will be hardwired for each of five lines.

#### 2.2.4.2 Touchscreen Display/Input

Three identical touch panel and display devices are located at the crew control station for the purpose of providing the MMI. The touchscreens enable the operator to quickly and readily communicate with the SFHT without the need for a keyboard interface.

Only one of the touchscreens will accept inputs at any given time, with that one being the "primary" display. Selection of the primary touchscreen is made by switch selection on the SCS switch panel. All computers will receive command inputs from the primary touchscreen.

Each computer communicates with its companion display independently of which touchscreen is primary. The primary display provides the operator with a continuous operating menu, analysis of the operation in process, and present state of the SFHT. The other displays can provide backup or supporting information for the operator upon command.

#### 2.2.4.3 Switch Panel

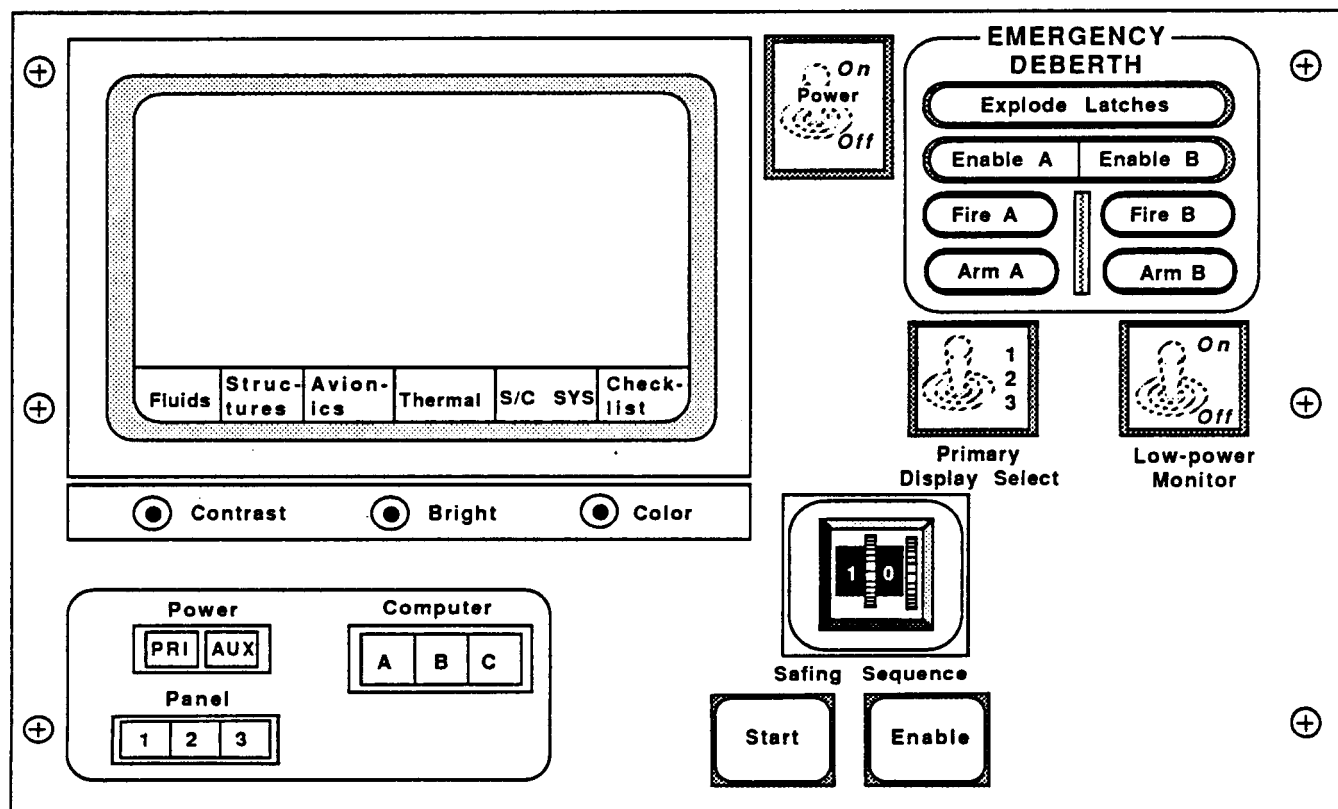
The SFHT switch panel provides a means for the operator to manually control several aspects of the SFHT avionics without relying upon the computational strings. Functions provided include:

- Avionics system power on/off control
- Primary touchscreen selection
- Emergency deberth pyrotechnic device control
- Manual safing sequence control
- Low power "warning only" monitor enable

Figure 2-22 provides a conceptual layout of this uncluttered switch panel. One of the three touchscreen displays is colocated with the switch panel but has no functional relationship with it.



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Figure 2-22 SFHT control panel



The switch panel has three sets of LED indicators to provide a display of first line health and status. These indicators display the source of power (primary or auxiliary) and which touchscreen and computer strings have power applied.

The power control switch actuates power relays in the SCS and dewar based avionics. This one switch controls power to all SFHT avionics. Primary touchscreen selection is provided by a three position switch near the center of the control area. A third switch will put the SFHT into its low power "warning only" mode. A manual switch is used for this function because all touchscreen inputs are disabled during this mode necessitating a manual recovery capability. All toggle switches must have safety flip covers to prevent inadvertent activation.

Emergency deberting involves firing of pyrotechnic devices to sever attachment to the user. A set of pushbutton switches on the switch panel must be depressed in a unique three step sequence to initiate emergency deberting.

A manual safing capability, which closes all SFHT dewar external valves, is provided through the use of a rotary selection switch and two push button activation switches. This is used as a backup capability to place the dewar in a benign mode should two of the three computer chains fail.

## 2.2.5 Dewar Monitor and Control Avionics

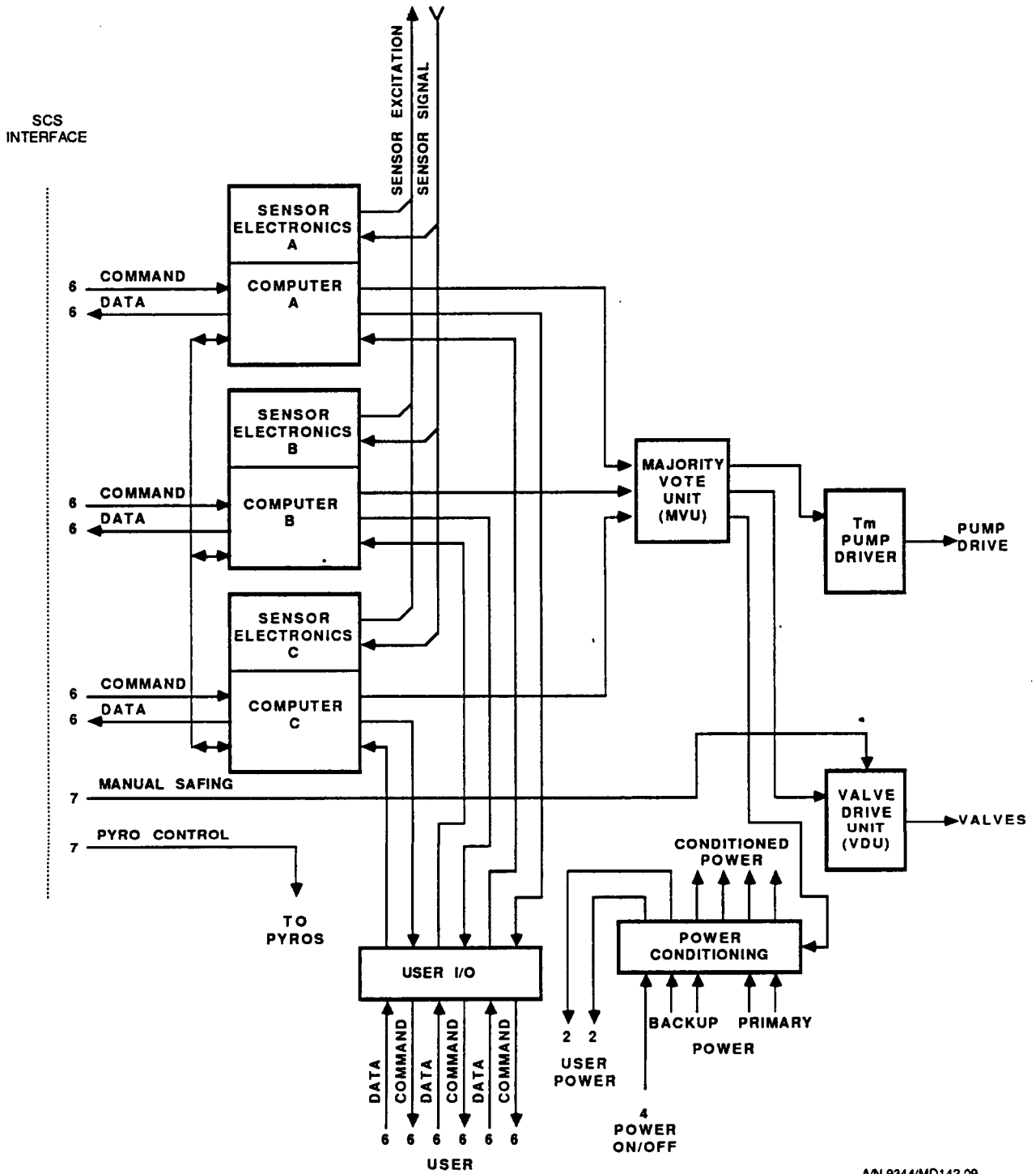
The dewar-based avionics includes the following components: dewar computer unit (DCU) (three computers in one housing), majority voting unit (MVU), valve drive unit (VDU), power distribution unit (PDU), thermal control system (TCS), associated interconnect cabling, and emergency deberting circuits and devices. Interconnections and functions of these components are shown in Figure 2-23.

Dewar avionics provides the first line of control over the cryogen system sensors and actuators. The sensor processing circuits are located in the DCU, and actuator drives are located in the VDU. The design philosophy has been to put most of the SFHT controls near the cryogen system because this approach will best lead to the autonomous operation that is required of SFHT's growth.

### 2.2.5.1 Dewar Computer Unit

The DCU is the heart of the SFHT avionics. Functions within the DCU include the basic expert system control and processing computer, sensor excitation and readout circuits, and I/O interfaces for communication both with the SCS and the user.

Computer - The dewar computer consists of three identical parallel computers continuing the three string majority vote computing chain. Each of these computers will be based on a microprocessor, preferably from the 8086 family. A prime candidate is the 80386 because of its compatibility with the 8086 and its growth capabilities for an expanded expert system knowledge base.



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Figure 2-23 Dewar monitor and control



The expert system hardware is configured to support the evolution of the system. Memory requirements are modest by today's standards. The kernel of the expert system can be contained in UV erasable EPROM. Updatable inference rules and knowledge base can be stored in an easily programmable, non-volatile memory, such as electrically erasable programmable read only memory (EEPROM). Working memory for temporary data, calculations, scratch pad, stack, etc. can be handled by a combination of dynamic and static RAM.

Sensor Avionics - Dewar monitoring requires the following sensor types (see Table 2-6):

- Germanium resistance thermometers (GRT)
- Silicon diode thermometers (SD)
- Pressure gage
- Flowmeter
- Liquid mass gaging
- Valve position

Each of these sensors requires excitation source and readout processing circuits. The result of the basic readout processing is a voltage proportional to the measured parameter that can be converted into a digital form for processing by the dewar computer. Analog to digital (A/D) conversion is performed by two A/D converters per computer. A high resolution 16 bit converter is used for sensors requiring high precision, and an 8 bit converter is used for less critical sensors. An analog multiplexer, under control of the computer, directs the sensor circuits output to the appropriate converter at the appropriate time. The redundant and interrelated sensors are distributed amongst the three computer units to maintain a high degree of failure tolerance. A summary of the operation, circuit requirements, and status of each sensor type follows.

A GRT is a variable resistor whose resistance depends on temperature. Its resistance is measured by passing a known current through it and measuring the voltage developed across it. The SHOOT experiment has developed an AC excitation and readout circuit that meets SFHT's needs and requirements; the SFHT will use the SHOOT GRT circuit.

The SD relies on the forward voltage drop of a silicon diode which is related to both temperature and excitation current. Unlike a resistance thermometer the voltage drop across the SD is not linear with current, and accuracy and tracking are only guaranteed at fixed currents. SDs suitable for SFHT will require a dc current source of 10 mA  $\pm$ 0.05 percent for excitation. Current sources meeting this value and tolerance are relatively straightforward, and applicable circuits exist from other programs. Readout circuits are straightforward differential operational amplifier designs suitable for four wire resistance measurements and also exist.

The pressure transducers are to be determined, but the most likely candidates are the widely used Teledyne Taber Model 2215 and Validyne Model AP10. The Teledyne Taber is flight qualified, and the Validyne will be flown on the SHOOT experiment. Since both of these transducers are familiar, the electronics for their operation should not pose a problem.



The SFHT's standby flowmeter uses a heat input/temperature rise technique. The heat input is generated by applying a known electrical power to a resistive heater. The temperature measurements will be made by GRTs. Actual flow-rate will be calculated by the computers from the power level, temperature data, and catalogued fluid enthalpy.

Liquid mass gaging will also employ a heat pulse/temperature rise technique. The SHOOT program is developing this technique, and we expect the SFHT to be able to use the mass gaging technology developed on SHOOT. The SFHT will require scaling of the SHOOT mass gaging system to accommodate the increased size of the SFHT. Recent SHOOT data indicates that their system may suffer from excessive uncertainty in the energy applied due to transient response characteristics of the power source. An understanding and solution to this problem is expected to exist before the SFHT design is completed.

The SFHT can use the same valves as SHOOT; therefore we expect the valve position sensing circuits to be applicable as well.

I/O - The dewar mounted computers are the heart of the SFHT avionics system and must communicate with the operator and host via the SCS and with the user. Both of these communication channels carry relatively low data rates (1 KBPS) and are best handled by serial interfaces. Numerous serial data standards are available, but we feel the best choice for the SFHT is RS422. This choice is based on the following factors:

- More than sufficient data rate capability
- Tolerance to EMI
- Not dependent on close microprocessor support
- Simple in terms of handshaking and protocol
- Architecture is widely used and understood

The dewar computer-to-SCS computer interface is made up of three full duplex serial communication lines. Each of these lines forms a dedicated interconnect between computers at each end and is part of the total three string majority vote computer system. Information that is carried over this I/O path consists of mode initiation commands and limit changes from the SCS to dewar computers in one direction and both raw and processed data from the dewar to the SCS computers in the other direction.

Dewar computers each communicate with the berthed user over a serial I/O port to send valve commands and to receive instrumentation and status data from the user. It is assumed that three serial command channels continue the philosophy of three-string majority vote to the user and the user is active in this decision process. This is not strictly required, and it may be decided later that it is more appropriate not to extend the three-string majority vote process into the user system. The tradeoffs needed to determine the optimum approach are beyond the scope of the current study. Return information from the user can be provided on two serial data lines, which are examined by the three dewar computers.



### 2.2.5.2 Majority Vote Unit

The MVU is the final link in the three vote computing string where the votes are actually tallied for agreement or disagreement. Input to the MVU consists of the command output words from the three computers and a system clock for synchronization. When at least two of the three simultaneous inputs are equal, an output is generated representing the agreeing command. If only two computers are in agreement, a message indicating which computer string disagreed is sent back to the SCS via the agreeing computers.

The MVU is a passive comparator, with no computing intelligence, made up of many identical sum-of-product (and/or) logic circuits. This circuit can readily be implemented in programmable logic arrays (PLA), which can significantly reduce component count. Typically, 15 to 20 discrete ICs can be replaced by a single IC package containing a PLA.

### 2.2.5.3 Actuator Power and Control

The valve drive unit (VDU) is the element of the dewar mounted avionics that provides appropriate control power to the cryogenic system actuators. Actuators include motor-operated valves, various heaters, and mechanical coolers. Due to the large number of identical valves, there is duplication of a large number of circuits. This duplication lends itself to the use of PLA for component reduction and increased reliability.

Command inputs to the VDU come as redundant parallel words, representing actuator and action, from the MVU. Continuation of redundancy from the MVU to the actuator, through the VDU, provides failsafe operation beyond the three string computer system.

Valve Drive - The valves are driven open or closed by a four-phase variable reluctance stepper motor. The choice of stepper motors was made rather than dc motors because of their much higher efficiency, at the penalty of more wires and increased circuit complexity. Stepping sequence and control can readily be designed using PLAs followed by power switching devices such as DMOS FETs. Drive power and timing constraints will be included in the drive circuits to preclude electrical problems from a stuck valve or drive. Position feedback will be used to terminate actuation upon completion via the dewar based computer.

TM Pump - The TM pump requires the most complex actuator control found in the SFHT. The pumping action is created by an electrical heater and pump operation is determined from several GRTs. Electrical power to redundant pump heaters is supplied by a linear closed control loop. Loop control is performed by a selectable primary dewar based computer using data received from flow rate sensing GRTs and a control algorithm that is part of its expert system firmware. The digital result of the computer signal processing is applied to an 8 bit digital-to-analog converter (DAC), in the VDU, whose output is an analog voltage representing the pump power required. The power amplifier supplying the pump heater power (up to 40 W) can best be accomplished with a programmable switchmode dc to dc converter with the DAC output being used as the programming control. This type of power amplifier can have relatively high efficiency along with a quiet dc output.





Mechanical Coolers - The SFHT uses four Stirling cycle refrigerators. These refrigerators provide their own electronic control circuits, but the VDU provides power on/off control for them. The high current switching requirements for the refrigerators can best be handled by redundant contact relays controlled by simple relay drivers.

The mechanical cooler subassembly includes five electronics boxes: a control unit for each of the four coolers and a power distribution unit. This is the same approach that will be used for the AXAF XRS cryogenic subsystem. Details of the control, data, and power interfacing with the refrigerator electronics are not discussed here, but are assumed to be very similar to that to be developed for the AXAF instrument. The AXAF XRS program has obtained preliminary interface and operations information from the refrigerator manufacturer, British Aerospace.

#### 2.2.5.4 Power Distribution Unit

The PDU provides all power conditioning required by the dewar based avionics as well as power on/off control for the user. Our concept has the SHT as Fa 28 V dc system, and use with a host providing different power will require a power adapter. The PDU receives both primary and auxiliary dc power from the host with automatic switching to auxiliary power in the case of failure of the primary power. Dewar avionics power is connected directly at the PDU and is on/off controlled by redundant contact relays powered from the power switch located on the SCS switch panel.

#### 2.2.5.5 Thermal Control Unit

The SFHT thermal control is the same as that used with OSCRS. This semi-autonomous unit controls the avionics base plate temperature by controlling the opening of a metal foil shade covering the dewar mounted avionics and avionics baseplate. This temperature control is closed-loop in that the baseplate temperature is sensed by silicon diodes whose output, after processing, drives a stepping motor to position the shade. This simple control loop is independent of the dewar computers, except that the computers can command the shade to close in preparation for shutdown and transportation.

#### 2.2.6 Operations

The SFHT flight avionics is designed to provide closed-loop control over as many aspects of operation as is applicable. In particular, tending and transfer of the cryogen is carefully controlled to provide reliability and efficiency. Each valve actuation is closely followed by observing the open/close position sensors associated with that valve. Other sensors such as temperature, pressure, and flow are observed for their expected changes in response to the valve movement in accordance with the overall control scheme. The reading from a single sensor is considered not only on its own, but more importantly by what it indicates about the overall state of the system when considered with evidence from other sensors. The construction of a knowledge base and model such as this serves to provide operational reliability and efficiency as well as providing a means of contingency control should sensors fail.



Major operational modes can be broken into four categories: normal operation, initialize/finalize, power save monitor, and emergency. Each major mode can be broken down into functional submodes that perform the specific tasks required.

#### 2.2.6.1 Normal Operation Mode

The normal operating, full power mode provides capability to conduct normal cryogen resupply operations. Functional submodes conducted from the normal operation mode include:

- Orbital SFHT pumpdown
- Standby (short term or long term)
- User berthing
- User cooldown and transfer
- Preparation for descent

During normal operating mode, all computers and sensors will be operating. The primary SCS display/touchpanel will show the top level operating selections that the operator can make, plus the status of key parameters including key predictions and trends. The secondary displays can provide supporting information. Any anomolous condition alerts will be displayed in real-time at the appropriate location.

#### 2.2.6.2 Initialize/Finalize

Initialization occurs upon application of power to the SFHT avionics. When power is applied, a self-test and configuration determination routine is performed. During this period, all sensors will be examined to determine cryogen and avionics conditions. Interfaces will be exercised and verified, and any changes in system status will be conveyed to the operator and/or ground control along with operating status and applicable operational recommendations. In the event that no operator interchange occurs within a certain period of time and normal dewar conditions exist, the system will revert to a power saving posture.

Finalization is an operator initiated functional mode in which the system prepares for removal of power. During this operation, the system assures that all cryogen valves and actuators are properly positioned. Given the plans for shutdown duration and other environmental aspects, the expert system can formulate predictions of cryogen loss during the unmonitored state. If conditions are detected during finalization that could create difficulties during the unpowered state, the operator will be notified of the situation and options.

#### 2.2.6.3 Power Save

Two power saving modes are available. The first is a low power operational monitoring mode. In this mode the dewar avionics continue to operate but at a much reduced level. Power reduction methods include: only a single channel computer is operational, only critical sensors are excited and monitored, sensor reading rates are reduced, display memory updating is slowed, and



communications are limited. Interfaces with the operator and emergency channels are still operative, but the avionics activities are restricted to only critical functions.

The second, even lower power, critical warning monitor mode uses a single computer string, monitors only critical parameters, and provides no touch-screen interface. This mode is initiated and terminated by a switch on the SCS switch panel. If an anomolous condition is detected, the operator is notified by an alert dispalyed on the CWEA. This is a request for the operator to switch back to the normal operation mode so that the nature of the anomolous condition and recommended corrective action can be displayed. Corrective action would usually be implemented automatically, but the avionics must be switched back to the normal operation mode so that it can command corrective action. An example of this would be a plumbing failure resulting in helium leakage into the guard vacuum and large heat input to the cryogen tank. This occurrence would be detected as a fast and steady rise in flow-rate and bath temperature and pressure. The corrective action would be to open the high-flow vent in hopes that the tank pressure could be controlled without blowing the burst discs. This would simplify the eventual repair process.

#### 2.2.6.4 Emergency

This mode is an automated quick safing method for the SFHT and its attached user. It does not remove the manual safing controls from the operator but only automates the procedure. The emergency mode is available from all other modes except the warning only monitor mode. The following functional sub-modes are accessible in the emergency mode.

Shutdown - This functional submode shuts down the SFHT and/or user dewars and controls venting or cryogen flow into benign plumbing conduits.

Jettison of the User from the SFHT - This action will require firing of pyrotechnic devices for activation of the decoupling guillotine that severs the fluid line and electrical cables. This capability may not be needed for the follow-on concept where couplings are mated and demated automatically. Actual firing of these devices must be done by the operator; and the expert system only makes preparation for the firing and displays instructions for the operator. Simultaneous with instructing the operator, the SFHT will put the user into as favorable a state as possible before jettison.

Jettison of the SFHT from the Cargo Bay - This functional submode sets both the SFHT and the user into states which are the most safe to the orbiter, and secondly to states that will prevent or minimize damage to either the user or the SFHT.

Emergency Checkout - This functional submode provides a means by which the operator can rapidly determine the status of all critical functions within the SFHT and its external interfaces. It presents both critical limits and actual measurements along with questionable or anomolous trends. Operational status of both the cryogenic and avionic subsystems will also be displayed. Ongoing activity will not be altered by this checkout mode, and it is directly accessible from other modes.



### 2.2.6.5 Data Storage

There are two considerations to storage of cryogen and avionics sensor data. First, if TDRSS is used in conjunction with the downlink data, a 40 to 90 percent daily coverage must be considered. Based on the moderate data rates expected from the SFHT, a relatively small amount of temporary storage would be required. This could readily be formed with available static RAM.

Secondly, it may be desirable to store a complete mission data set for reconstruction on the ground near or after mission end. Assuming a 12 month mission with two 10 hour resupplies, the data could be stored in 90 K bytes of memory. Incorporating this memory in solid state non-volatile form, such as EEPROM, can save significant volume and power. Storing the data in three stores, one for each computer, will provide significant redundancy.

### 2.2.7 Redundancy

The only safety related function of the avionics is the command firing of the pyrotechnically operated guillotine for emergency jettison of the user, as discussed in 2.2.6.4. In all other respects, the SFHT concept satisfies STS and SS safety requirements with passive design features that require no power or command. During times when the avionics is powered, unusual conditions will be detected by the avionics and displayed at the SCS, downlinked to MCC, and if necessary displayed on the CWEA.

Two fault tolerance for safety and single fault tolerance for mission success are maintained in the avionics by using a three string majority vote computer, redundancy, and the ability to interpolate around failed sensors. This is followed by hardwired manual controls to critical operations.

A three string computational control approach (Figure 2-24) has been baselined. Three computational strings operate independently in the process of making a command decision; then each outputs its vote to be processed by a majority voting unit. If at least two out of three strings agree, the vote passes and becomes a command to operate an actuator. Three string computation with majority voting is employed in all operations where cryogen fluid control is involved.

All dewar sensors are redundant, and each member of a pair is controlled and measured from a different dewar computer. If both sensors of a pair should fail, sufficient data will be supplied from other sensors to allow mission completion.

Cryogen valves are generally series-parallel redundant for opening and closing cryogen and vent lines. This provides sufficient failure tolerance to meet all SFHT safety and reliability objectives.

Failure of any two computational strings can be handled by operator activation of the manual emergency safing sequence from the SCS switch panel. The remaining computational string will function to provide monitoring of the safing process. The SFHT avionics will attempt to control the user and render it usable and intact under all conditions.

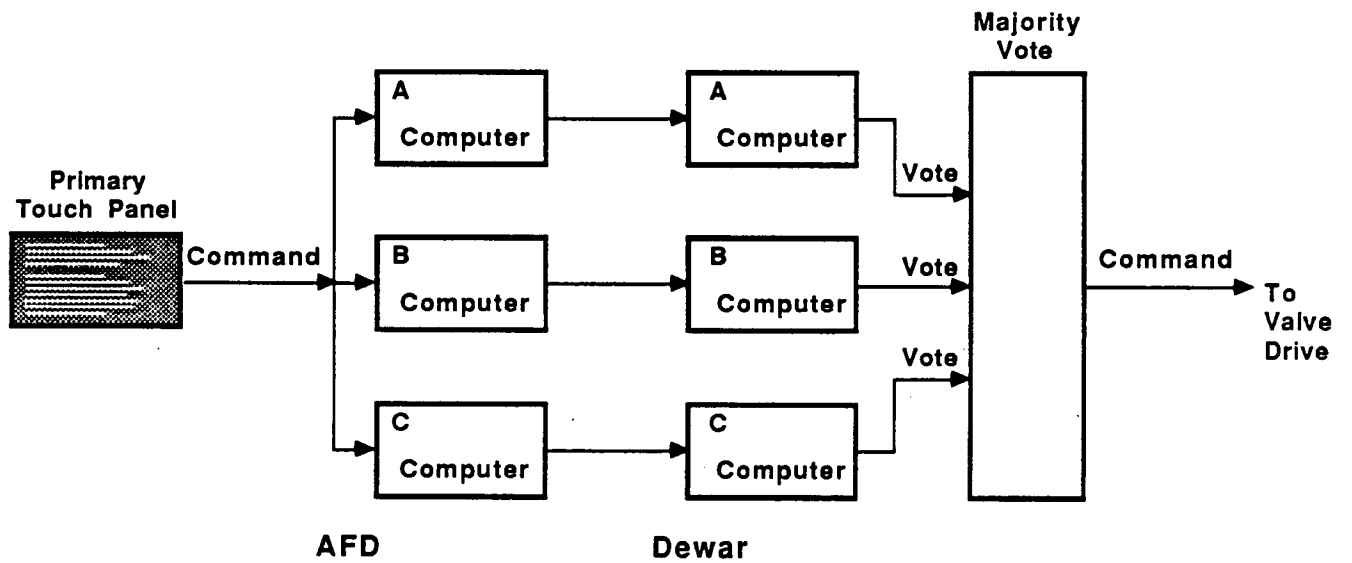


Figure 2-24 Three string - majority voting of commands



### 2.2.8 Adapting to Different Host Vehicles

Our baseline concept has been developed primarily to perform resupply at the shuttle, with resupply at the SS as an alternative. Resupply at the user orbit with the OMV as host has been given low priority in the concept definition effort.

#### 2.2.8.1 Space Station

We envision installing a SCS in the SS that is the same as used in the STS. Major differences between SS and STS are the internal communications and power. Figure 2-25 is a block diagram showing the electrical interface between the SFHT and SS. Communication between the SS LAN and SFHT, and also between the SCS and dewar-based avionics, will require converters to simulate the STS system. Power for the SFHT will require ac-to-dc converters to change the SS 440 Vac at 20 kHz to 28 Vdc.

#### 2.2.8.2 OMV

Figure 2-26 shows the envisioned interface between the OMV and SFHT. Special interface adapters exist between each of OMV's command/telemetry busses and the SFHT. Two interfaces are required to achieve mission success redundancy. A video signal interface to route berthing and boresight camera signals through the OMV downlink to the MCC is required.

### 2.2.9 Deviations from the OSCRS concept

At the direction of JSC, the Martin OSCRS design concept has been used as a starting point for our SFHT avionics design concept. Commonality between the OSCRS and SFHT avionics designs, especially regarding operator interfacing, would have obvious benefits. The following changes to the Martin OSCRS design are recommended for the baseline SFHT concept.

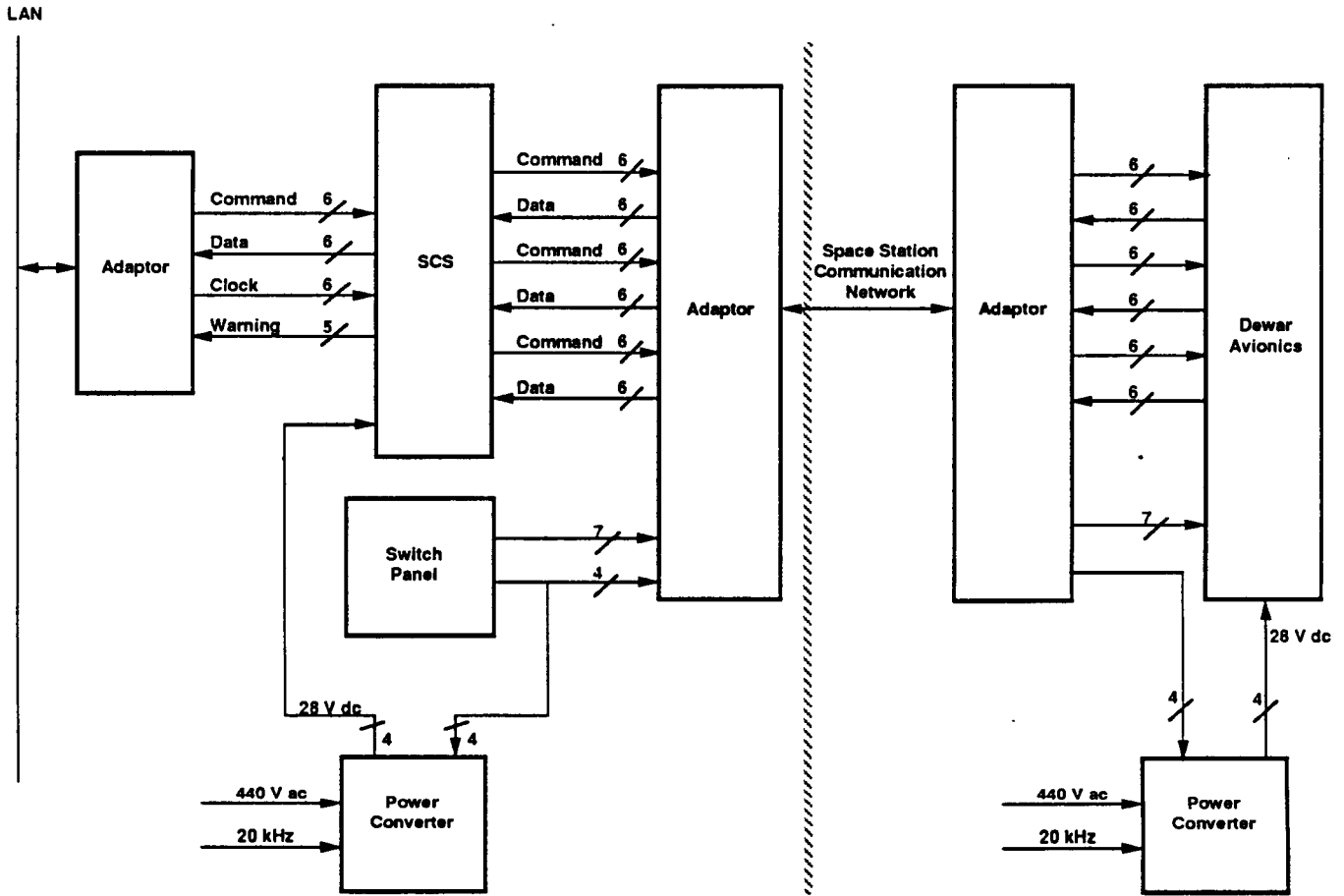
- Three flat panel displays instead of four
- True three independent string majority vote design rather than "vote of confidence" design
- Take advantage of modern technology for improved reliability, reduced power, and lower parts count
- Simplify switch panel
- Use solid state nonvolatile memory (e.g., EPROM) for data storage instead of optical disc

The rationales for these changes are given below.

Displays - The OSCRS design uses four flat panel displays at the system control station. Three displays, including the display collocated with the switch panel, are more than adequate to provide the MMI for the SFHT. The SFHT data rates and quantity of sensors are less than with OSCRS; hence less total display capability is required.



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Figure 2-25 SS-SFHT electrical interface

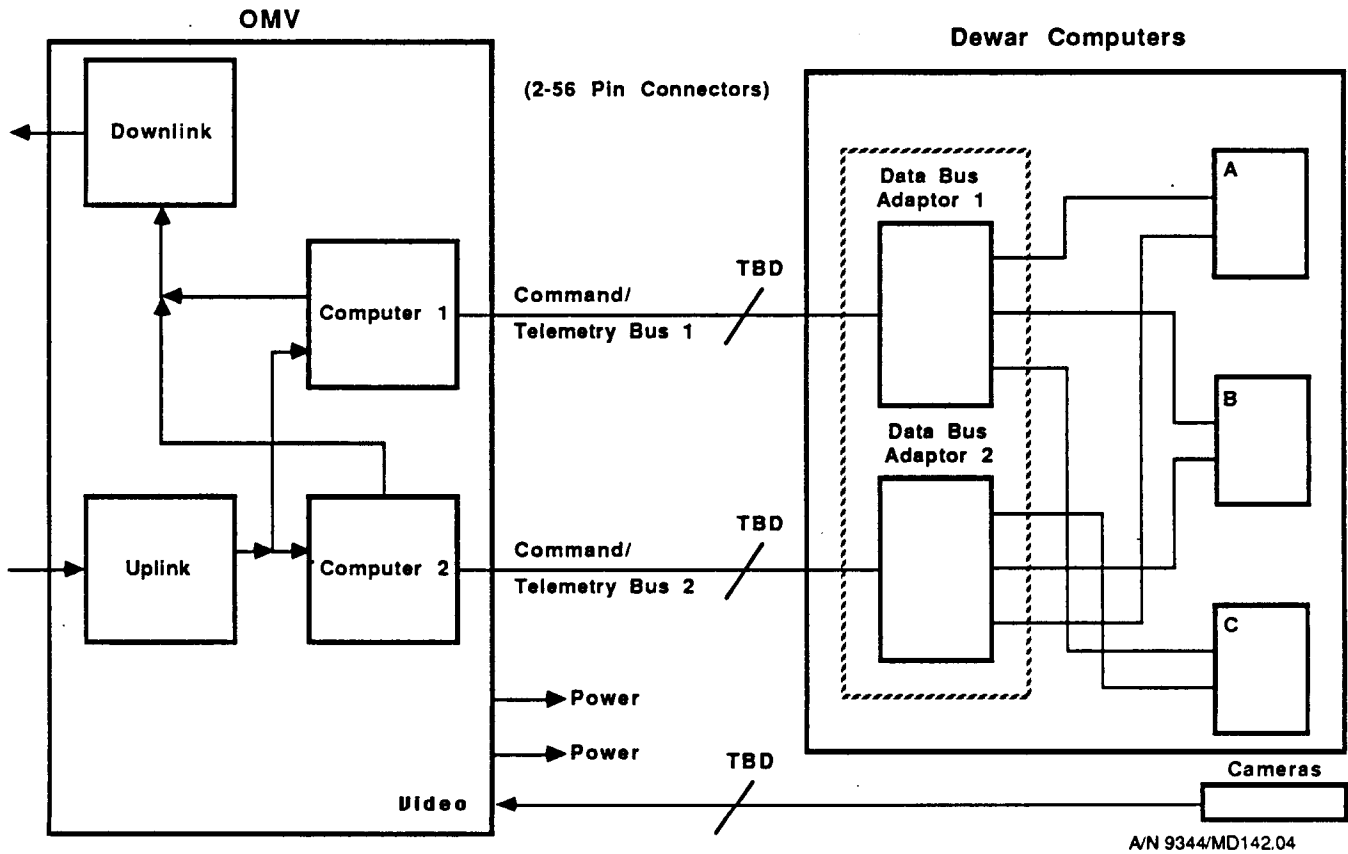


Figure 2-26 OMV-SFHT electronic interface





Switch Panel - The OSCRS switch panel includes a joy stick and calculator-like pushbuttons as inputs. The SFHT will utilize a touchscreen as the primary input, which will provide a simpler and more convenient MMI. Toggle switches will have protective covers to prevent inadvertent actuation. The resulting switch panel will be less cluttered and easier to operate.

Modern Technology - The OSCRS design makes use of many time tested technologies, which unfortunately are not as power or space efficient as current technology will provide. The SFHT avionics concept employs CMOS microprocessors from the 8086 family for all computers. Considering the rapid advancement in microprocessors and the growth path for the SFHT, an 80386 is the microprocessor of choice for the dewar based computers.

The many redundant and repetitive circuits in the SFHT avionics affords an excellent opportunity to reduce component count, reduce volume, reduce cost, increase reliability, and reduce testing through the use of programmable logic devices. A single programmable device can conservatively replace 15 to 20 IC packages.

Data Storage - The OSCRS design includes two write-once-read-many optical disk drives at the control station. Each drive can store 200 M bytes per side. The SFHT does not require anywhere near this much data storage. It is convenient and efficient to provide solid state non-volatile data storage in either the SCS or dewar mounted computers. No development or procurement costs are involved in this approach, and higher reliability is expected than with a rotating device.

Computer Redundancy - The SFHT three string majority vote computer system is configured differently than that used in the OSCRS. The SFHT system is simpler and provides the redundancy required to meet all operational goals. An added advantage of the SFHT approach is that the three strings can be extended into the user with the user making a majority vote decision for commands it receives.

Cargo Bay Payload Retention Latches - The OSCRS design provides monitoring of the payload bay retention latches including opening, closing, and pin insertion. For a two trunion configuration this means twelve position sensors, including redundancy. The SFHT will not provide this monitoring because monitoring of cargo in the cargo bay is best left to the STS. It would not be expeditious or efficient to rely on the SFHT to provide this data since SFHT must be powered to provide such monitoring. SFHT does provide monitoring of the coupling mechanisms for resupply, such as the berthing latches and fluid coupling.

## 2.2.10 Development Issues

Expert System - Many reasons have been presented in various sections for the rationale behind incorporating an expert system design into the SFHT avionics. The SFHT is a very good application for an expert system not only from the standpoint of having an automated advisor available but also when the evolution to remote autonomous resupply operation is considered. The key development effort in a system such as the SFHT involves designing the knowledge base required. No general methodology formula yet applies because of the nature of knowledge base characteristics. Fortunately, both tools and



techniques for doing this are rapidly evolving and fit the SFHT timeline. We envision the knowledge base and inference rule set used in early SFHT missions to be relatively simplistic, but as the system becomes better understood through use, the expert system can become "smarter." Initial development and continued evolution of the expert system must be planned for.

TMP-Flowmeter-Mass Gaging - The SHOOT program will prove the in-flight viability of the TM pump and pulsed heat mass gaging techniques. The SFHT can benefit from, and depends upon, the SHOOT progress to make SFHT design objectives attainable at low risk.

The SFHT uses a closed-loop control of the TM pump. The control input is pressure downstream of the pump and temperatures on each side of the pump, and the output variable is pump flow rate. The TM pump flow rate is a function of power supplied to its heater and is determined by a calibration curve for the porous plug and heater set. Complete ground characterization of the control loop must be made before stable operation can be assured.

The SFHT mass gaging technique is the same as the SHOOT method but must be scaled for larger helium quantity. Continued work must be done on characterization of the temperature response profile vs. input power pulse for the SFHT. Impact on dewar performance of the heater lead wire size must also be considered.

Flow rate through the standby (low-flow) vent will be determined by applying a small, known heating rate to the flow stream and measuring the resultant temperature rise, as described in 2.1.6. The electrical heater power and temperature rise must be accurately measured. Development of the electronic requirements for operation of such a flow meter will be required.

### 2.3 GROUND SUPPORT EQUIPMENT

Ground support equipment needed to prepare the SFHT for launch will be a significant part of the program development effort. As determined in the first phase of the study, it is advisable for several reasons, system mass penalty being the main driver, to launch the SFHT with SfHe in the dewar. This has been done; the IRAS dewar was 93 percent full at a temperature of 1.7 K when launched. However, the fluid capacity of the SFHT is about 20 times greater than IRAS. Filling a dewar of this size with SfHe has not been done, and the process and equipment involved should be carefully planned. Selection of the fill procedure must consider development cost, development and operational risks, operational cost, facility constraints, and operational requirements.

Selection of the GSE design is a five-step process:

1. Understand the operational requirements and design constraints.
2. Identify all possible approaches.
3. Define viable approaches to the extent needed to evaluate their merits.
4. Evaluate and compare the viable alternatives based on the criteria listed above.
5. Select the most desirable solution.



Our choice is the same approach used for IRAS and COBE; i.e., successive topoffs at a pressure just above the lambda point. The rationale for this selection is given in the remainder of the section.

### 2.3.1 GSE Design Concept

GSE consists of three major categories:

1. Mechanical - This is equipment needed to move the SFHT around within a given facility and to ship it long distances. It consists mainly of a handling dolly and a shipping container. The design of this equipment is straightforward and won't be discussed further. It is assumed to be similar to that used in support of the IRAS and COBE dewars.
2. Cryogenic - This includes the supply dewars (custom made), pumps, heat exchangers, transfer lines, refrigerators, etc., needed to accomplish fill of the SFHT dewar and maintenance of the dewar guard vacuum.
3. Monitor/Control - This includes the computers and electronic equipment needed to monitor and control the dewar during all ground operations (up until payload integration). This equipment is not the flight avionics, although it will take advantage of applicable software and hardware designs created for the flight avionics. The monitoring system will likely evolve toward greater automation as SFHT missions are accomplished. The monitoring GSE is discussed further in 2.3.1.2.

The remainder of this section is concerned with the cryogenic GSE.

#### Requirements and Constraints

Operational requirements and design constraints for the cryogenic GSE are relatively simple; this is largely due to the great size and excellent thermal performance of the SFHT dewar. These two features provide an extremely long lock-up capability; i.e., the time it takes for the bath to heat up from its nominal ground temperature of 1.7 K to the lambda point (2.18 K) with no venting. This time is predicted at 4 months with the flight mechanical coolers running and 25 days with the coolers turned off. This superior lock-up capability provides flexibility in planning and performing the prelaunch operations. Our recommended facility usage and schedule of operations is presented in 2.3.2.

The GSE must interface with the SFHT fluid connections and fill the dewar to nearly full with superfluid helium. The fuller and colder the cryogen tank is, the more efficient the system is from the perspective of launch mass. The IRAS dewar was launched 93 percent full at a temperature of 1.7 K. There are methods that will improve this fill efficiency, as will be discussed. There is no hard constraint on the time required for the SFHT fill process; 1 month is realistic. The faster the dewar must be filled, the larger and more expensive the equipment involved, but the manhours required may be fewer. There are GSE approaches that minimize the man attendance required, as will be discussed.



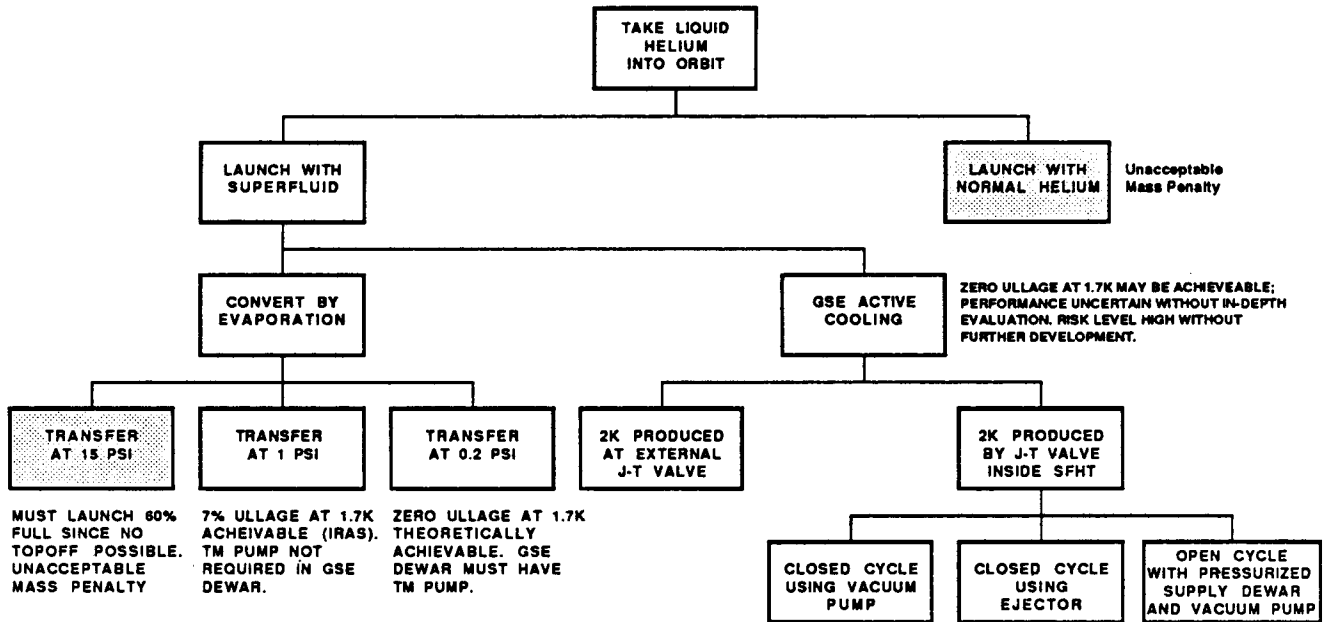
Figure 2-27 is an options tree for filling the dewar. The option of simply filling and launching the dewar with normal helium is shown for completeness, but discarded because of the severe system mass penalty (approximately 50 percent) involved. The next major division is to produce the superfluid helium either by an evaporative process, as done for IRAS, or by an active cooling approach (i.e., Joule-Thomson expansion). Approaches using active cooling are more complex in concept and require more complex SFHT dewar plumbing. They are discussed separately in 2.3.1.1.

The evaporative branch is divided according to the condition of the fluid transferred from the GSE dewars to the SFHT dewar: 15 psi (normal), 1.0 psi (just above the lambda point, as done for IRAS and COBE), and 0.2 psi (temperature approximately 1.7 K). This third possibility requires a GSE dewar with a TM pump and can theoretically provide a 100 percent full tank at 1.7 K. Practical operational considerations, like vacuum pump size, might result in a temperature somewhat higher than 1.7 K.

There are two major distinctions between the first and second evaporative methods. The second method can provide a much smaller ullage at launch, but it requires a supply dewar capable of operating at negative gage pressures to allow pumpdown of the supply bath. Given that the supply dewar must be custom designed and built, this is not a significant cost impact. Caution must of course be exercised though operational procedures when handling a negative-pressure dewar to insure that air ingestion and ice blocking don't occur. During SFHT verification testing, there will be extended periods of operation at negative pressure. The system must therefore be designed for negative-pressure operation regardless of how the prelaunch fill is accomplished. Since the alternative of transferring from a normal supply dewar offers no significant advantage and incurs a large launch mass penalty, it is eliminated from further consideration.

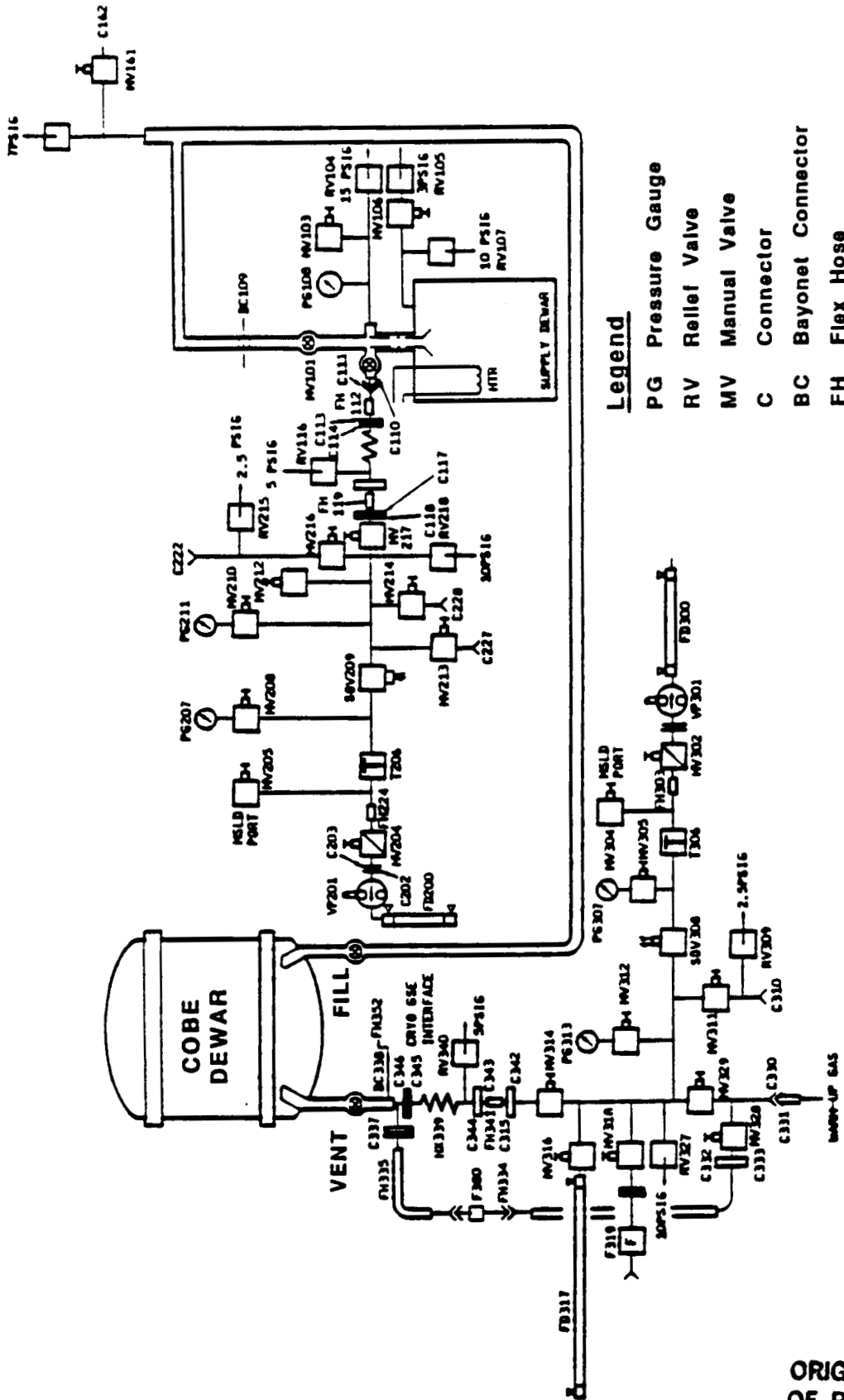
Figure 2-28 is a schematic of the IRAS and COBE cryogenic GSE; the complexity of the equipment and operations is evident. This basic equipment would be required regardless of whether fluid is transferred just above the lambda point or below the lambda point. There is one major distinction between the two approaches. When transferring S<sub>f</sub>He, the supply tank bath must be vacuum pumped to remove the heat produced by the TM pump heater. It would be necessary to transfer at a relatively high rate (approximately 1,000 l/hr) to minimize the degrading effect of parasitic heat input through the transfer system, just as is the case during on-orbit transfer. A rather large (approximately 3,000 CFM) vacuum pump would be required. When transferring above the lambda point, the flow can be driven by pressurization. However, the receiver bath must be vacuum pumped to remove the flashoff produced by the transfer system parasitic heat leaks. This can be done successfully with a relatively small vacuum pump; a 300-CFM pump was used for IRAS and COBE. While it is desirable to minimize the vacuum pump size, there are no facility constraints that prohibit use of a 3,000-CFM pump.

The tradeoff between transferring above or below the lambda point comes down to cost and development risk: the cost of slightly increased launch mass versus the cost and risk of developing a GSE dewar that uses a TM pump. The TM pump method will also save time and money in the prelaunch operation.



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Figure 2-27 Alternative fill process



Legend

- PG Pressure Gauge
- RV Relief Valve
- MV Manual Valve
- C Connector
- BC Bayonet Connector
- FH Flex Hose
- VP Vacuum Pump
- HX Heat Exchanger
- T Trap
- FD Flexible Ducting

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Figure 2-28 COBE GSE

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If the launch cost is mass driven, as with the oblate spheroid dewar configuration, the launch cost savings of the third approach is estimated at \$1.5M. If launch cost is driven by shuttle bay space, as is the case with the spherical configuration, there is no launch cost savings. Based on these considerations and our recommended spherical configuration, our choice is the second approach, the same as used for IRAS and COBE. However, the use of a supply dewar with a TM pump is a very tempting alternative that should be revisited as SfHe transfer technology continues to mature.

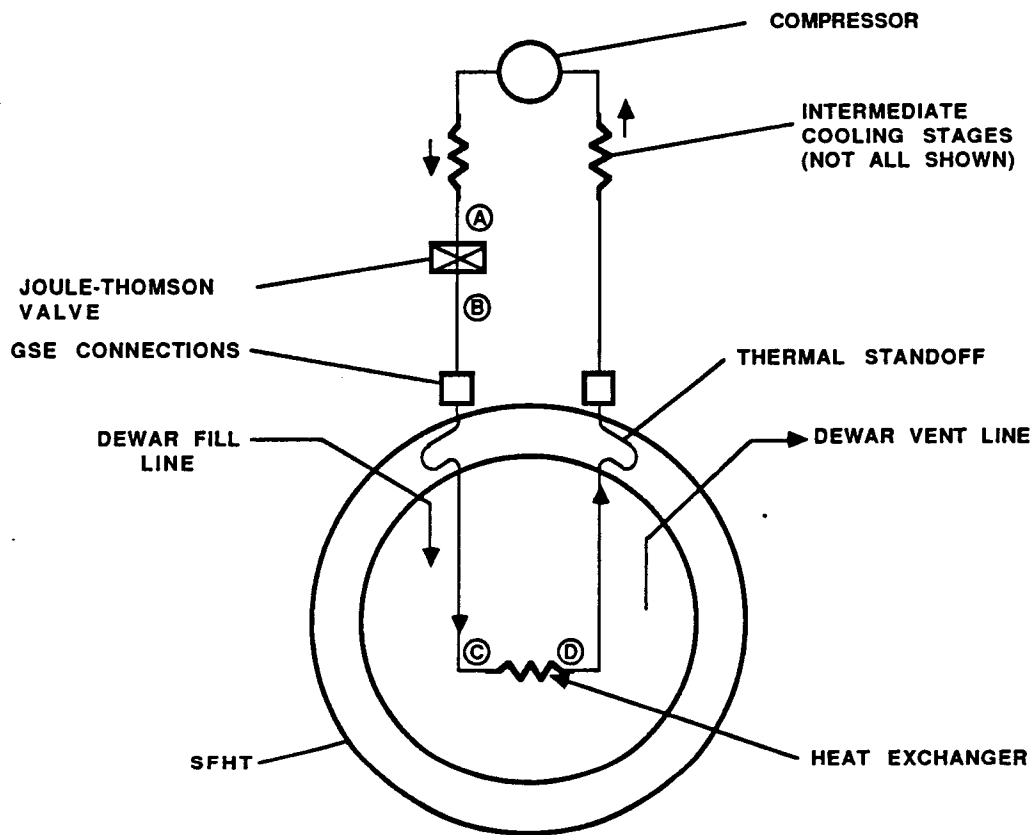
#### 2.3.1.1 Production and Maintenance of Stored Superfluid by Means of Active Refrigeration

There are at least four active cooling schemes that can be used to produce and maintain the superfluid within the SFHT as shown in Figure 2-27. In all of these systems it is assumed that the SFHT has been filled with normal helium from a separate source, and that makeup or topping will be done through that source. These active cooling systems are closed loop in the sense that there is no fluid communication between the cooling system and the stored helium. The true advantages and disadvantages of these arrangements compared with the direct evaporation method will only become clear through much more detailed study. Some potential advantages of active cooling are reduction of GSE cost and lower chance of line ice blockage due to "negative" pressure in the tanker.

Figure 2-29 shows a completely external mechanical cooler that produces superfluid temperature across the J-T valve from A to B. The internal heat exchanger removes heat from the helium bath. The heat exchanger, shown mounted internally, could also be mounted to the outside of the cryogen tank if carefully located. To maintain the proper low temperature in this process, the compressor must have a rather large vacuum pump at its first stage. An advantage of this approach is that almost all of the refrigeration equipment is external in the GSE and accessible. A disadvantage is that superfluid must be transferred through the GSE connection and through warmer regions of the insulation before it can be used to remove heat from the tanker. This is a highly inefficient way to transfer the SfHe and will lead to a large and costly refrigeration system.

Figure 2-30 shows the J-T valve moved to the inside of the tanker. Superfluid will be produced by expansion from B to C so the difficulty with pressurized superfluid transfer of 2-29 will be eliminated. The compressor will still require a vacuum pump for the first stage to produce the required temperature in the heat exchanger, but this pump is expected to be much smaller than for 2-29. The disadvantage is that the J-T valve is buried within the tanker where it cannot be easily accessed and maintained.

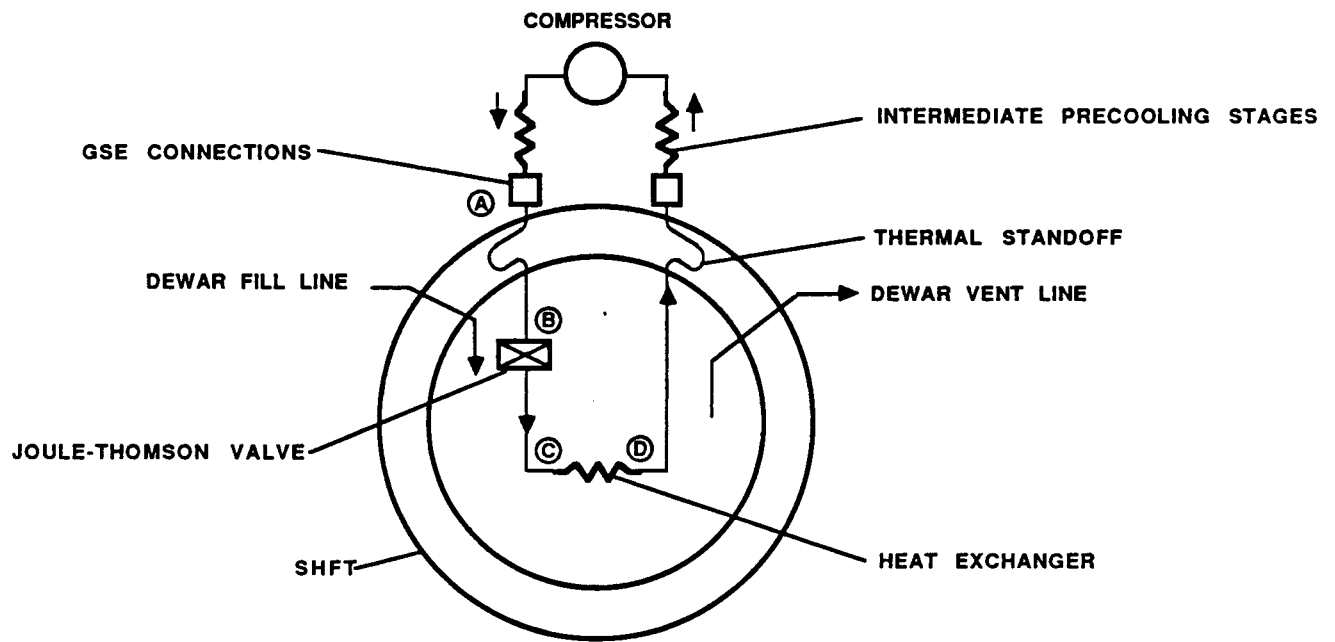
Figure 2-31 shows another version of 2-30, which employs an internal ejector. The function of the ejector is to produce a vacuum inside the tank by using part of the helium flow to produce vacuum on the other portion of the flow by the Bernoulli effect. This scheme has been used in low temperature coolers both to avoid the thermal penalty of the large vent tube passing through the insulation and to eliminate the vacuum pump first stage of the compressor. (The helium will be returned to the compressor at about 1 atmosphere.) The



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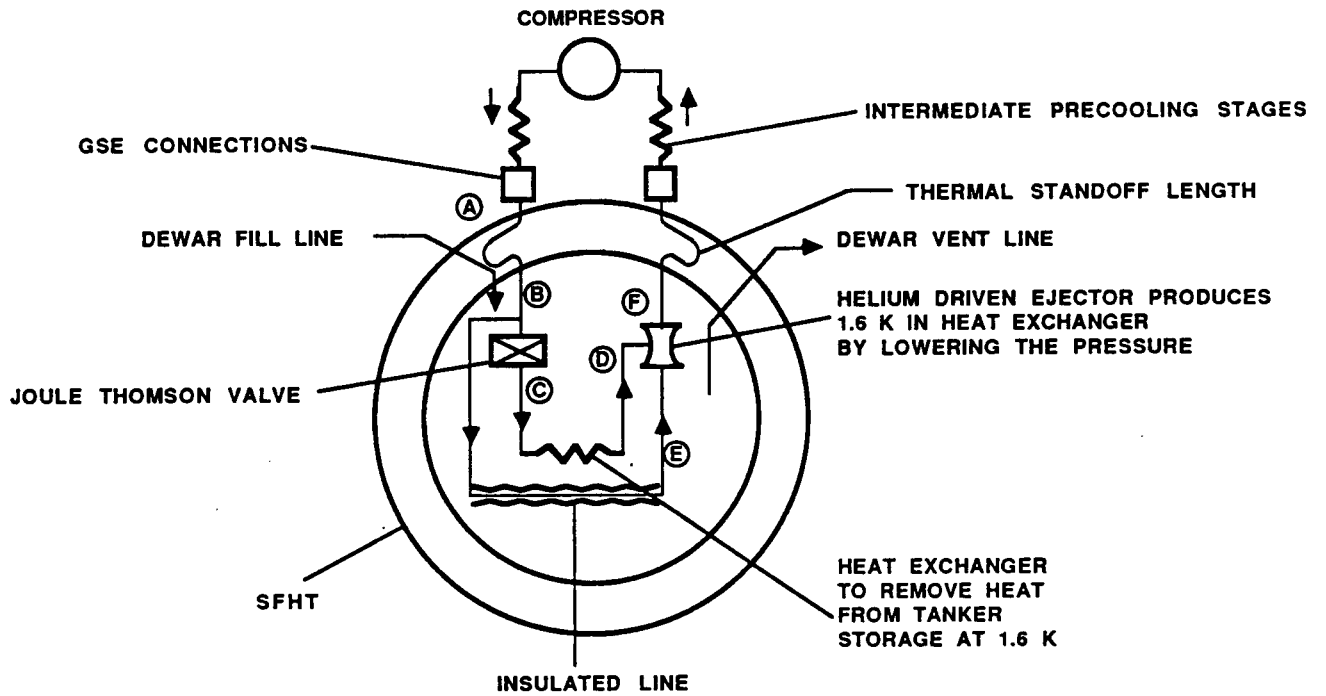
Figure 2-29 Active cooling using external J-T valve and internal heat exchanger





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Figure 2-30 Active cooling using internal J-T valve and heat exchanger



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Figure 2-31 Active cooling using internal J-T valve, heat exchanger, and ejector



disadvantage of this system is that the ejector and J-T valve both are in the cryogen tank where they are difficult to maintain.

### Thermodynamic and Thermal Considerations

We now examine the penalties and sizing of the various active cooling techniques. A first step in doing this can be taken by studying Figure 2-32. In this scheme, a pressurized tanker supplies liquid helium through the connection to point B, which has a condition of elevated pressure and temperature, i.e., 4 atmospheres and 5 K. Four atmospheres is about the highest pressure available from a transport dewar, and 5 K supercritical helium is produced from the 4.2 K liquid by the heat leak of the interconnecting plumbing. The enthalpy of this fluid is 14.32 J/g. An isenthalpic expansion takes place across the J-T valve as shown in Figure 2-33. If the vacuum pump is able to maintain a pressure of 5.6 torr at C, then a temperature of 1.6 K will be produced to remove heat from the tanker. The amount of heat that can be removed is proportional to the increase in enthalpy of the helium in the heat exchanger as the helium boils. If all of the superfluid helium boils, but the temperature at D is not allowed to rise, then the amount of heat that can be absorbed at 1.6 K is  $23.09 - 14.32 = 8.77$  J/g.

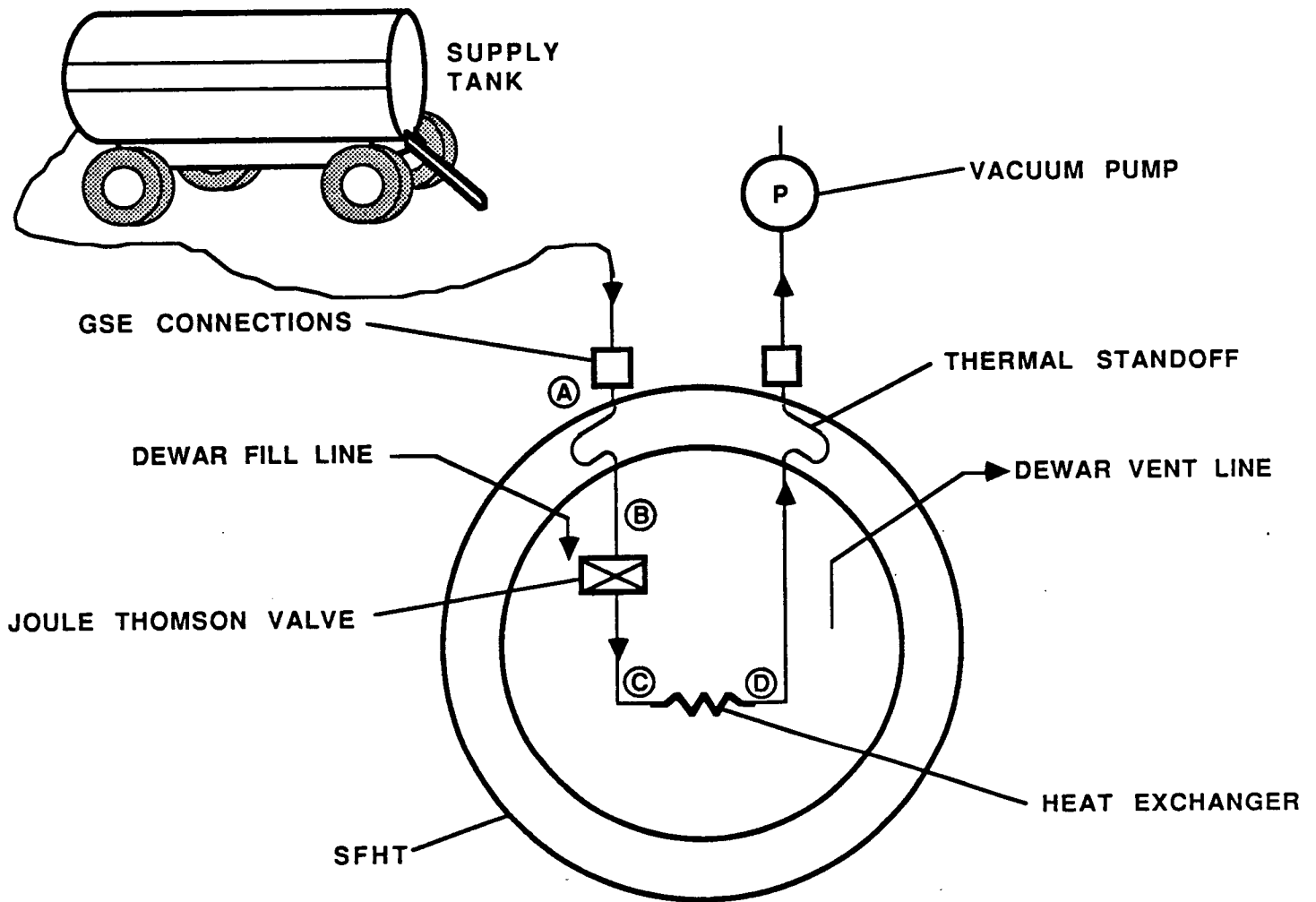
The total amount of heat that must be removed to convert 10,000 l of 4.5 K normal helium to 1.6 K superfluid helium is  $14.2 \times 10^6$  J. Therefore, the total amount of helium that must flow through the cooling loop is  $1.6 \times 10^6$  g or about 13,000 l of normal liquid helium from the supply, assuming there are no other losses. Note that if the temperature at B is allowed to rise to 6.9 K at 4 atmosphere, the cooling available will have decreased to zero. This temperature sensitivity of the cooling effect makes the cooling system approach a very imposing design problem requiring significant study. Simply increasing or decreasing the supply pressure will not be an adequate solution as can be seen by study of the thermodynamic properties of helium in this region.

The closed-loop compression driven systems do not waste helium, but the same inlet line temperature sensitivity problem exists. In all of the active cooling approaches a very important consideration is the size of the return line that must pass through the SFHT insulation space. The density of the return vapor is extremely low, and the pressure losses due to flow must be held to less than about 1 torr to avoid a significant rise in the desired low storage temperature (approximately 1.6 K).

This leads to trade-offs involving vent line heat leak, vent line size, tanker thermal efficiency, and cool down time. The use of the internal ejector could largely desensitize this trade-off. The feasibility and risks of the active cooling methods cannot be well understood without a considerably more detailed evaluation than possible within the scope of this study.

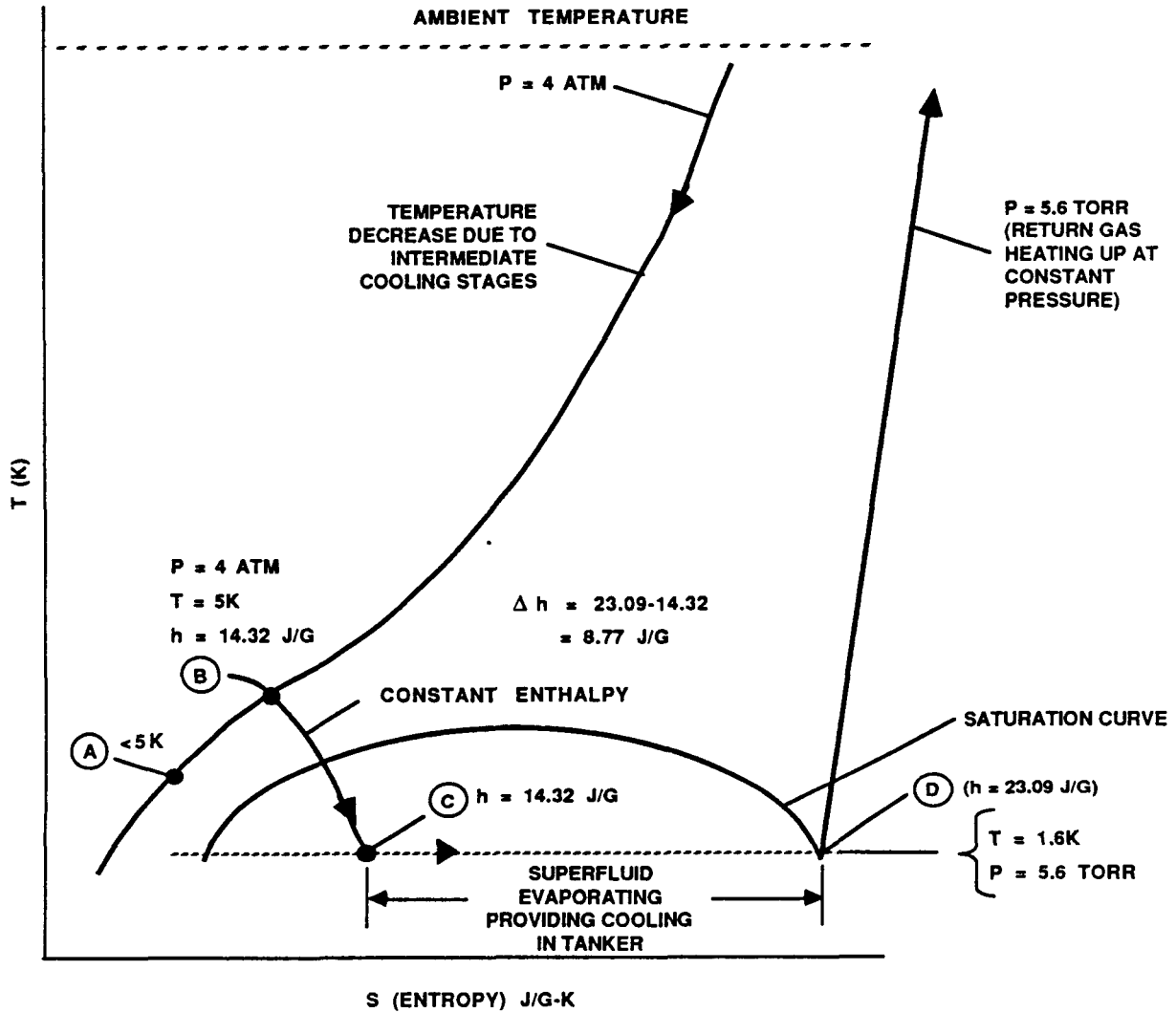
### Conclusion

Without a more detailed evaluation, it is not clear whether an active cooling approach can be made to work well for the SFHT or what the advantages might



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Figure 2-32 Internally produced refrigeration using pressurized external storage tanker



A/N 9344/MD142.26

Figure 2-33 Temperature-entropy diagram of helium showing the cooling process



be compared to an evaporative technique. Active cooling approaches all result in design impacts to the SFHT and associated developmental and operational risks. The use of a GSE dewar with a TM pump will provide lower launch mass than any active cooling method, although it also involves developmental risk compared to the IRAS/COBE approach. Considering all this, we baseline the proven, low-risk procedure used for filling the IRAS and COBE dewars.

#### 2.3.1.2 Monitor/Control Equipment (MCE)

The MCE provides monitor and control of the dewar during the final stages of in-process testing, during system testing, during maintenance and prelaunch fill operations, and for post integration checkout. Its functions include monitoring of all dewar sensors, control of motor-operated valves and heaters, and data reduction and storage.

If the SFHT uses mechanical coolers, as currently baselined for SS-based resupply, the MCE must also provide control commands and monitoring of the coolers and related sensors. This capability will be needed during system testing and possibly during ground lock-up, if it is decided to use the coolers at that time.

##### Monitor Functions

Dewar sensors fall into two basic categories: 1) those, such as temperature sensors, which indicate the general condition or health of the dewar, and 2) those, such as valve position indicators, which give the status of active devices. Table 2-6 is a complete list of sensors and electrical devices in and on the dewar. Only one item on that list, the EVA coupling position sensor, will not be monitored by the MCE.

Monitoring serves several functions. It provides characterization of the dewar performance so that changes in behavioral patterns can be detected. These changes can then be related to quickly or slowly developing malfunctions that might be correctable. Based on the dewar performance observed during system testing, regions of abnormal readings will be established for various critical sensors. Out-of-limit warnings, both visual and audible, will be provided. The audible warning will be used to announce impending burst disc rupture or that a guard vacuum failure is in progress; these would be indicated by the bath pressure. No action would be required other than to stand clear of the emergency vent. During dewar fill and tophoff operations, certain sensors will be used as the signal to proceed to the next step of the operation. The MCE will provide continuous indication of all valve positions and heater power.

##### Control Function

The MCE will provide commands via mechanical switches and 28 V power for actuation of valves. It will also provide constant or variable 28 V and 100 V power to the various heaters within the dewar. If mechanical coolers are used in the design, the MCE will provide command and power to the coolers.



## Data Reduction and Storage

In some cases, raw data from more than one sensor is combined according to an algorithm to provide the desired information. This is true, for example, of the mass quantity gage that determines mass quantity based on heater current and voltage drop, fluid temperature rise, and a curvefit of fluid specific heat versus temperature. In other cases, such as thermometers, the engineering data is produced from the sensor voltage output by a simple curvefit. All data generated during the test program and during prelaunch fill operations will be recorded for future reference and troubleshooting.

## Hardware Description

There are two separate sets of MCE: 1) the full-up MCE that is used for dewar testing before the dewar-based avionics package is installed and 2) the partial MCE used after the dewar-based avionics is installed. The full-up set essentially duplicates the control and monitor functions of the flight avionics, although aspects such as packaging, display, redundancy, and use of high-reliability parts will be different from the flight system. The partial MCE performs the functions of the remote segment of the flight avionics. The partial MCE is a segment of the full-up MCE; the interfacing would have to be somewhat modified to be compatible with the dewar-based flight avionics. The partial MCE will also be able to monitor selected interfaces between SFHT functional blocks, SFHT and host, and SFHT and users to verify correct interface functions.

The MCE consists of the following major components:

- AT-sized personal computer with interface buses, printer, and plotter
- Digital voltmeter
- A variety of power sources for valves and heaters
- Constant current sources for various sensors
- Controller/readout for liquid level sensor and Vac-ion gage
- Calve drive electronics
- Digital-analog converter
- Scanner
- Front control panel
- Connector panel
- Sensor stimulation board
- Strip chart recorder
- Audible warning system

### 2.3.2 Ground Operations/Facilities

K-STSM-14.1<sup>22</sup> prescribes that the filling of cryogenics be accomplished on vertically integrated payloads. Payloads involving hazardous operations are normally serviced in the PHSF<sup>23</sup> or the SAEF 2. The SFHT will be serviced and installed into the orbiter in a shorter time before launch when filled and installed in the sequence dictated by vertical, rather than horizontal, processing. There is almost continuous access to the SFHT during the vertical processing flow until it is transferred to the vertical canister for



transporting to the RSS. Vertical integration is accomplished in the VPF. Post-flight operations are performed in preparation for storage and the next flight.

Horizontal processing is also described so that a comparison can be made to the vertical processing time frame and operations.

### 2.3.2.1 Vertical Processing

Figure 2-34 summarizes the flow of operations to install the SFHT in the orbiter when it is in the vertical position. The time to process the SFHT from receipt at KSC to launch is shown by the schedule in Figure 2-35 to be 1,041 hr (43.4 days).

The SFHT is transported to the PPF in its shipping container upon receipt at KSC. The shipping container provides and maintains a clean environment for the SFHT during the handling at KSC. The shipping container cover is removed at the PPF for damage inspection, functional tests, and checkout.

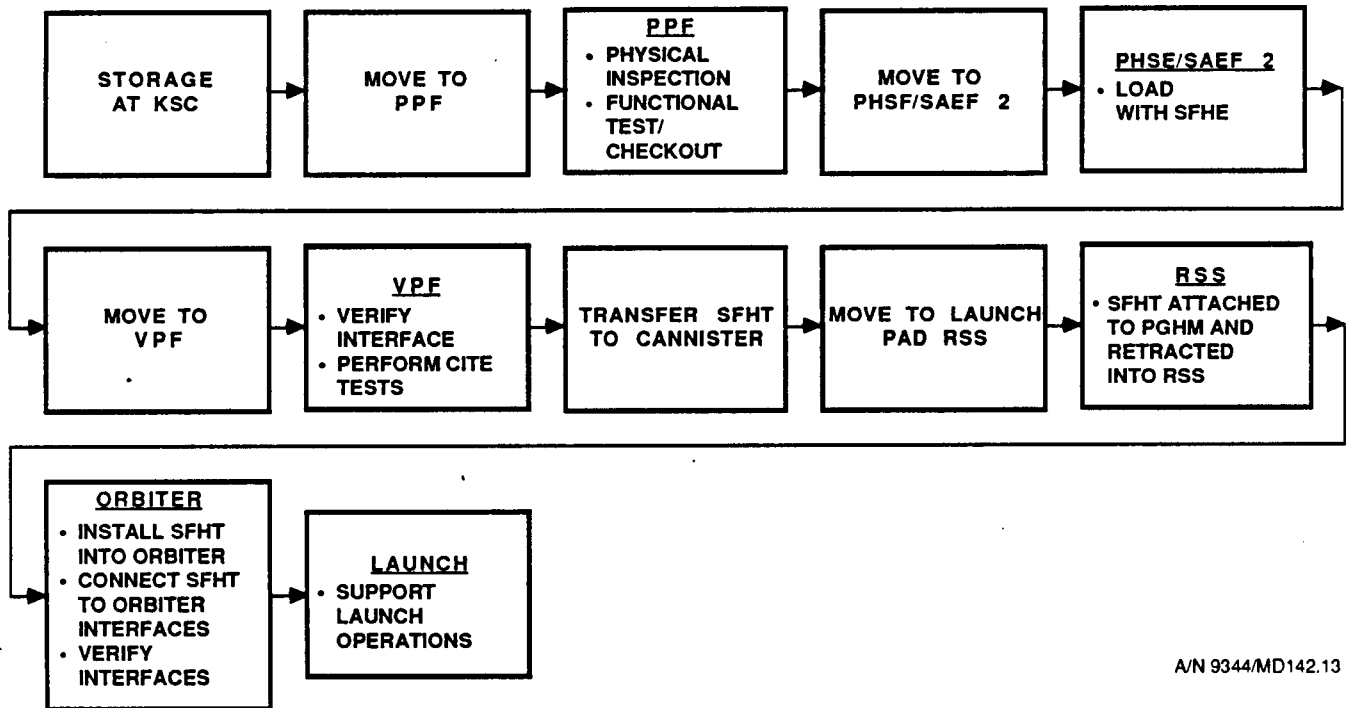
After completion of the functional tests and checkout, the shipping container cover is reinstalled, and the SFHT is moved to a PHSF or SAEF 2 area to load it with SfHe. The fill operation is discussed in 2.3.1. The SFHT will have some final tests and checkout made in preparation for its next move to the VPF. The fill operation will take a maximum of 30 days.

Upon arrival at the VPF, the shipping container will undergo cleaning operations in the airlock. Then the unit will be moved to the bay area where the shipping container cover will be removed, and the SFHT will be hoisted into the VPHD. The SFHT will be connected to the CITE simulated orbiter interfaces to verify all hardware interfaces including redundant paths. These tests will include power turn-on, health and status checks, power control tests, and SFHT command, monitor, and control checks. All data and command paths, all formats, and the data stream will be verified in mission simulation tests.

GSE will be disconnected after all tests are completed in preparation for installation into the canister and transporting to the RSS. Any GSE required to support the RSS and launch pad SFHT operations will be installed and validated in the RSS prior to arrival of the SFHT. The SFHT must be installed into the RSS prior to the shuttle transfer to the launch pad.

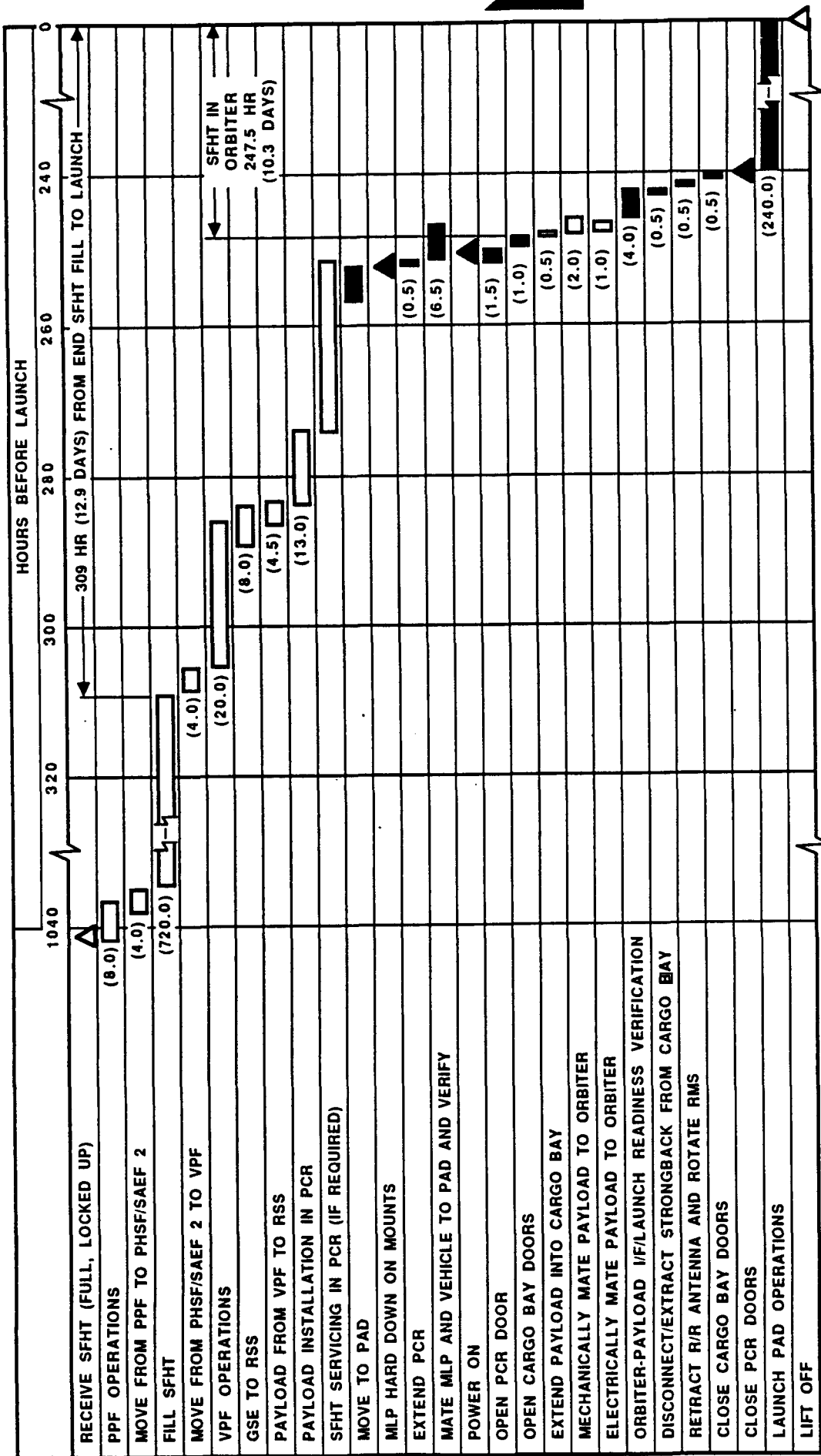
After the canister is installed in the RSS, the SFHT will be removed by the PGHM, which will retract into the RSS. The canister is then removed after the RSS doors have been closed. When the RSS is moved into position to enclose the orbiter, the PGHM will install the SFHT into the cargo bay. SFHT-to-orbiter interfaces are connected and verified, and then the SFHT is ready for launch. Launch can take place a minimum of 247.5 hr after the SFHT is installed in the orbiter or 309.5 hr (12.9 days) after the SFHT is filled. The predicted dewar lock-up capability of 25 days, without the mechanical coolers running, therefore provides 12 days of margin to accommodate integration and launch delays.





A/N 9344/MD142.13

Figure 2-34 Preparation of SFHT for launch through the vertical processing facility



A/N 9344/MD142.14

□ SFHT OPERATIONS  
 ■ SHUTTLE OPERATIONS

Figure 2-35 Schedule to prepare SFHT for launch with vertical processing



### 2.3.2.2 Horizontal Processing

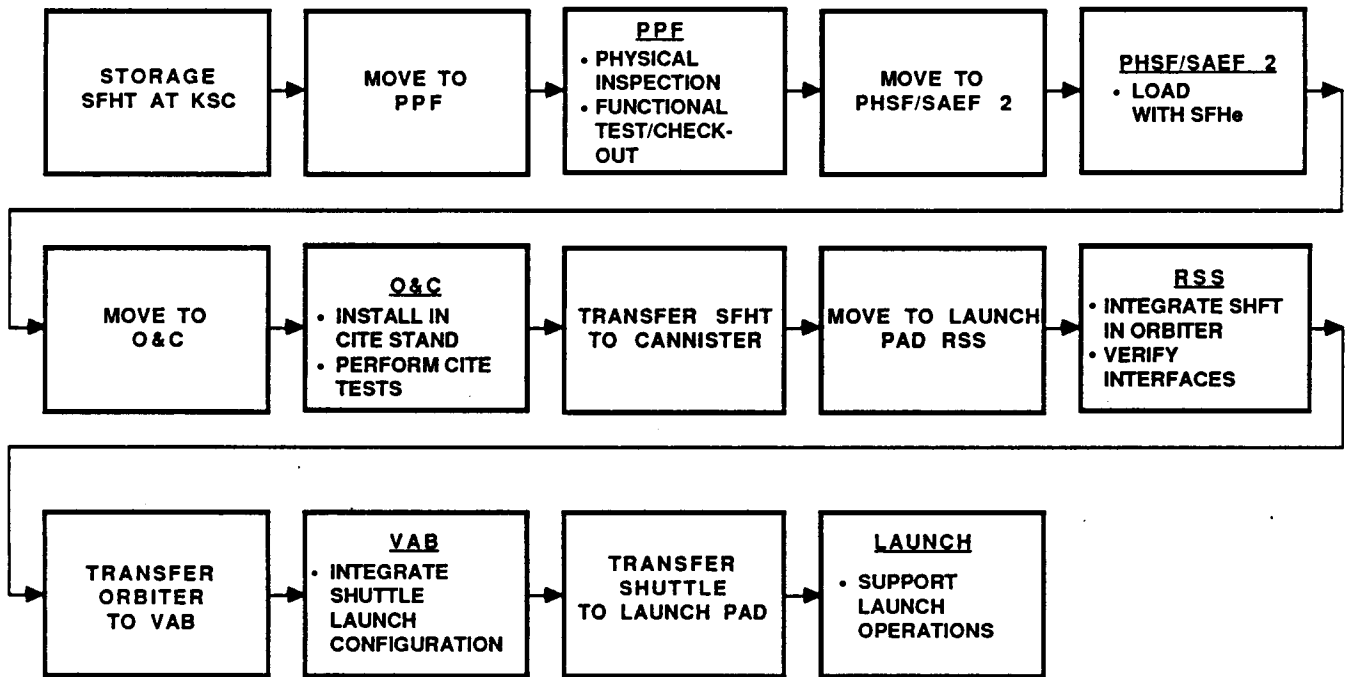
Figure 2-36 summarizes the flow of operations to install the SFHT in the orbiter when it is in the horizontal position. The time to process the SFHT from the receipt at KSC to launch is depicted by the schedule shown in Figure 2-37 to be 1,480 hr (61.7 days).

The SFHT is transported to the PPF in its shipping container upon receipt at KSC. The shipping container cover is removed at the PPF for damage inspection, functional tests, and check out.

After completion of the functional tests and checkout, the shipping container cover is reinstalled, and the SFHT is moved to a PHSF or SAEF 2 area to load it with SfHe. The fill operation will take a maximum of 30 days. The SFHT will have some final tests and checkout made in preparation for its next move to the O&C building.

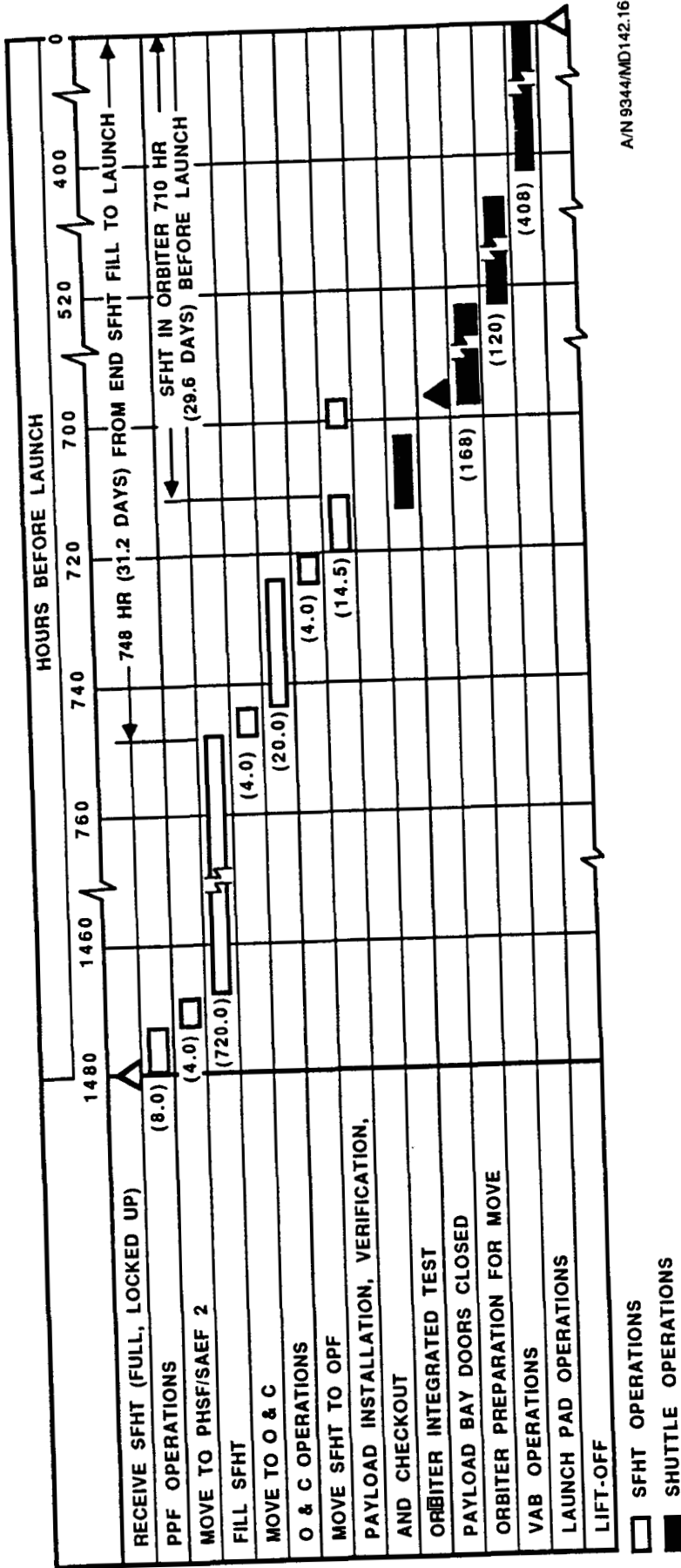
Upon arrival at the O&C, the shipping container will undergo cleaning operations. Then the unit will be moved to the bay area where the SFHT will be removed from the shipping container and installed in the CITE-simulated orbiter interfaces to verify all hardware interfaces including redundant paths. These tests will include power turn-on, health and status checks, power control tests, and SFHT command, monitor, and control checks. All data and command paths, all formats, and the data stream will be verified in mission simulation tests.

GSE will be disconnected after all tests are completed in preparation for installation into the canister and then transporting to the OPF. The SFHT will be hoisted from the canister in a horizontal attitude and positioned over the orbiter and then lowered and secured into the cargo bay. SFHT-to-orbiter interfaces are connected and verified, and then the SFHT is ready for launch. Launch can take place a minimum of 710 hr after the SFHT is installed in the orbiter or 748.0 hr (31.2 days) after the SFHT is filled. Compared to the vertical processing schedule, an additional 18 days of dewar lockup is therefore required.



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Figure 2-36 Preparation of SFHT for launch through the horizontal processing facility



A/N 9344/MD142.16

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Figure 2-37 Schedule to prepare SFHT for launch with horizontal processing



### Section 3 MISSION OPERATIONS

#### 3.1 HOST/USER INTERFACES AND OPTIONS

The SFHT must interface with the following:

- Launch vehicle
- The user with the shuttle as host
- The user with the SS as host
- OMV
- GSE

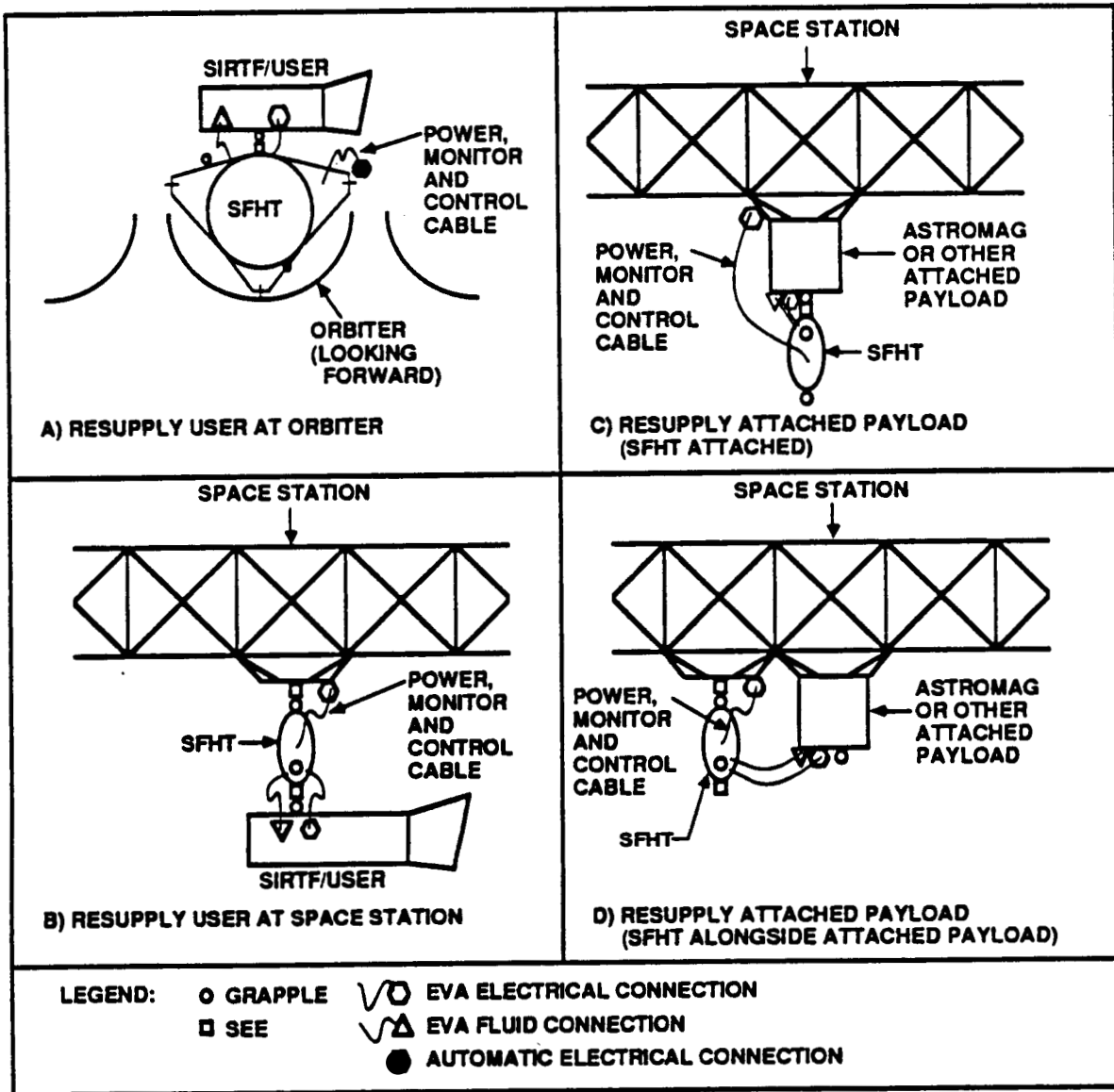
These interfaces require the mating of docking/berthing hardware and electrical and fluid connectors. With the exception of the docking/berthing interfaces, the initial connections of the fluid and electrical connectors will be accomplished by EVA. Eventually all interfaces are to connect automatically.

The shuttle is to be the baseline launch vehicle and host for the initial SfHe resupply customers. The docking/berthing mechanism recommended for initial mission is the grapple and the SEE because of its successful use on the shuttle program to remove and handle payloads. It has been designed to remove 32,000-lb payloads from the cargo bay. Allowable grapple fixture loads are specified in NSTS 07700, Volume XIV, Appendix 8, Section 4.2. A special purpose end effector may be used to provide an electrical connection across the interface for control power and/or signals to payloads<sup>19</sup>. The electrical connector is located on the outside of the SEE at the SEE/payload interface.

It is recommended that the TPDM be used when considering the automatic connection of the electrical and fluid lines. Considerable force is required to make these connections, which can be accommodated by the TPDM. The TPDM has two 56 pin electrical connectors incorporated in the design that provide sufficient pins for the SFHT power, control, and monitor requirements for transfer of SfHe to a user. The fluid coupling will require additional design effort to incorporate into the TPDM configuration. Moog is currently under contract to NASA/JSC to design a SfHe coupling<sup>4</sup>. This coupling will be used on the SHOOT program for the transfer of SfHe in space, and may be extended to robotic.

##### 3.1.1 Initial Capabilities

Figure 3-1 depicts the initial concepts and EVA connections for servicing of users with the shuttle or the SS as host and shows the SFHT in storage at the SS. The electrical and fluid EVA connections that have to be made are shown. An electrical cable connected to the shuttle or to the SS provides power and the capability to monitor and control the activities of the SFHT. The power, monitor, and control hook-up to the shuttle, Figure 3-1(a), is assumed to use the shuttle umbilical retraction system (SURS) so that EVA is not required for disconnect of this cable when the SFHT is removed for transport to the SS. This requires a separate, parallel power, monitor and control cable



A/N 8203/MD136.020

Figure 3-1 Initial capability - EVA required to connect avionics and fluid lines

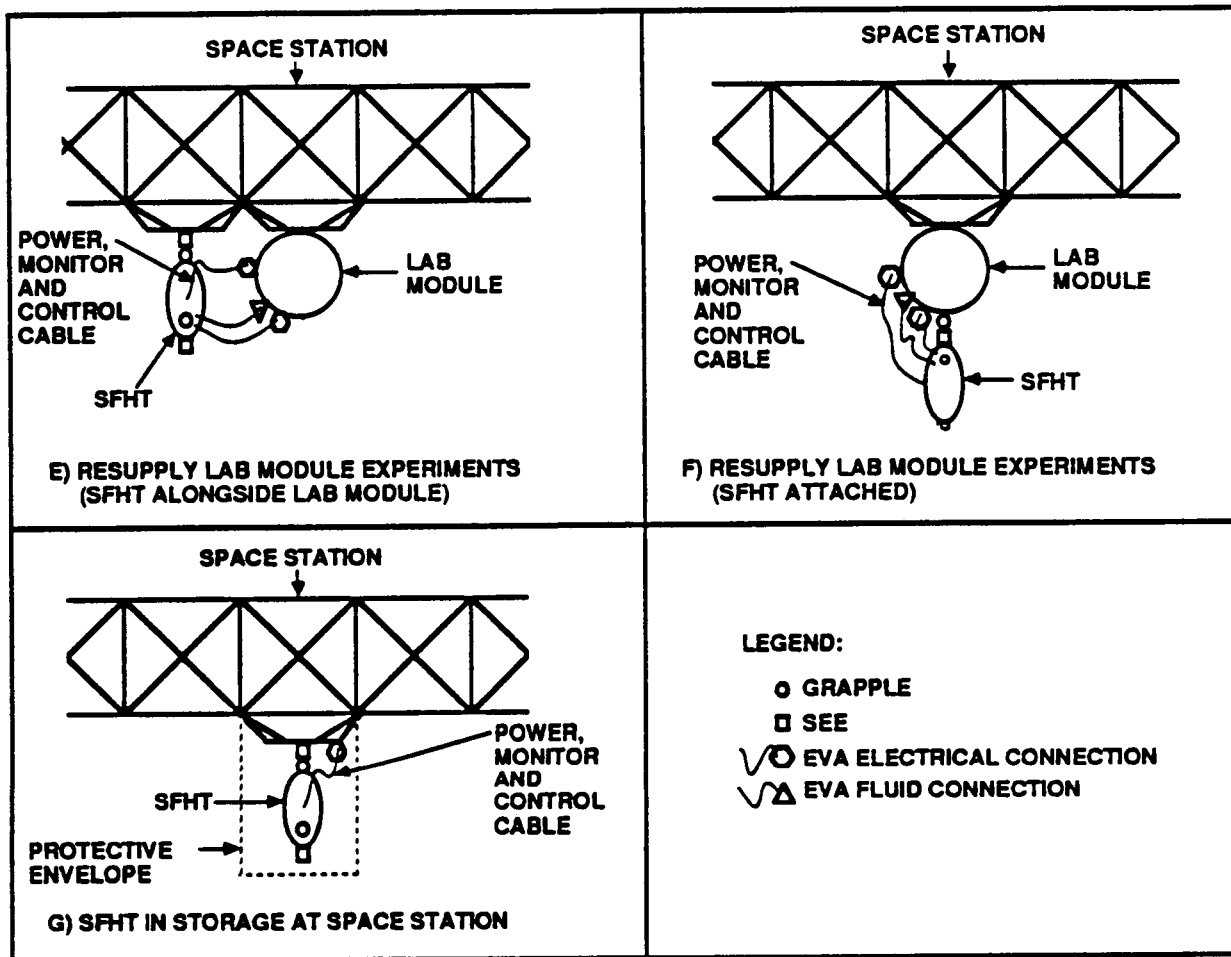


Figure 3-1 Initial capability - EVA required to connect avionics and fluid lines (concluded)





which will then be connected to the SS. The electrical connection made between the SFHT and the user, AP or LM, provides the capability to monitor and control the components of the user, AP or LM, during the fill operation. Two fluid couplers are provided on the SFHT for redundancy to connect to the user, AP or LM, for transfer of the SfHe. A grapple is shown on the port side (see Figure 2-3) so that it will be located on the same side as the shuttle RMS. The grapple is used to remove the SFHT from the shuttle cargo bay and to transport on the truss system of the SS using the mobile RMS of the SS. A grapple is also shown on the lower end of the SFHT, which is used to attach the SFHT to the SS truss system for storage and to locate near users for servicing. The options shown in Figure 3-1 for resupplying are as follows:

- a. SFHT services user while located in the shuttle cargo bay
- b. SFHT docked to SS truss and user docked to SFHT
- c. SFHT docked directly to AP such as ASTROMAG
- d. SFHT docked to SS truss with electrical cables and fluid lines going to AP such as ASTROMAG
- e. SFHT docked to SS truss with electrical cables and fluid lines going to LM
- f. SFHT docked directly to LM
- g. SFHT in storage at SS

#### 3.1.1.1 Resupply at Space Station

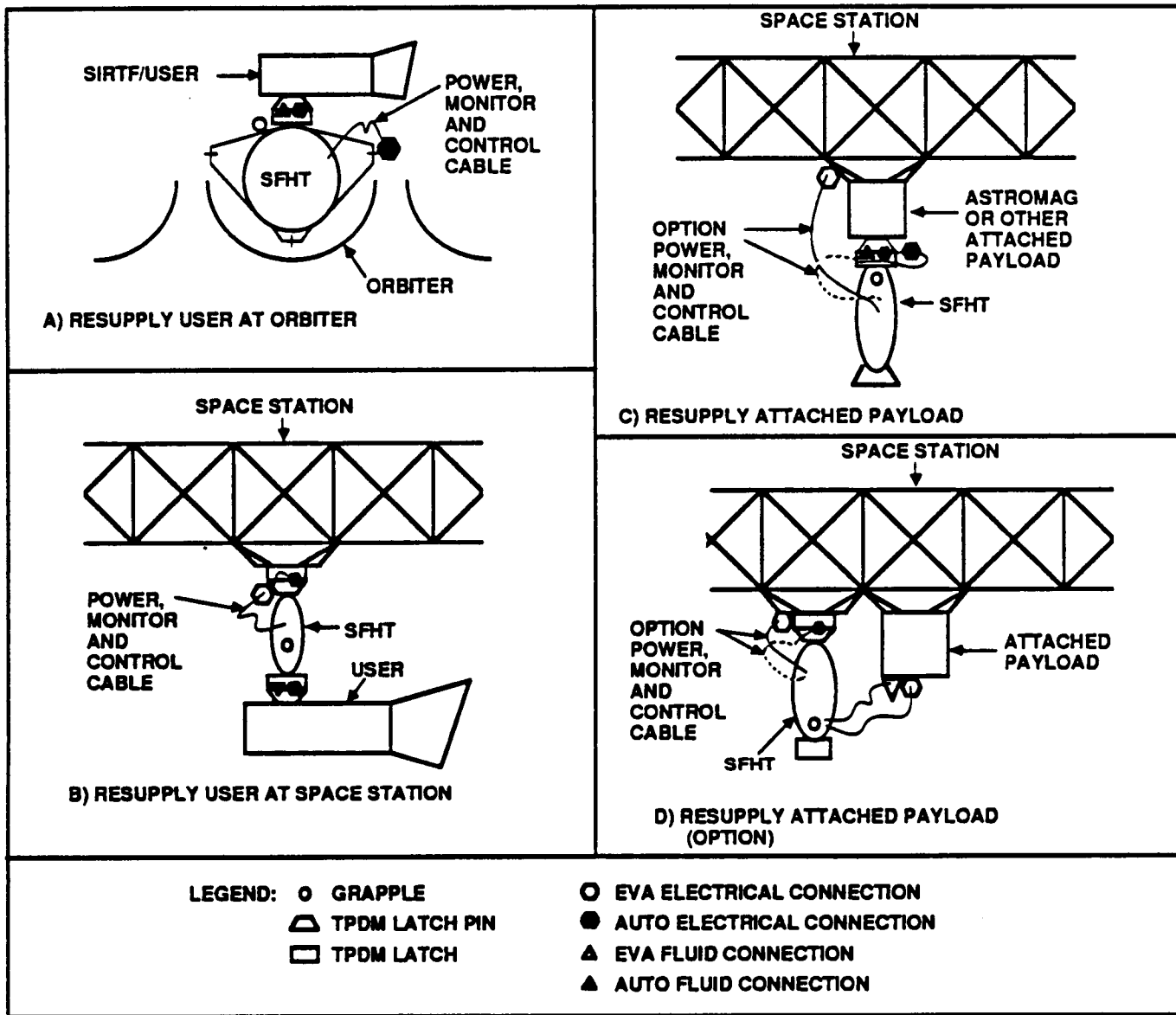
The grapple at the top of the SFHT will be used to remove the SFHT from the orbiter and to transport it around the SS from storage to the user, AP and LM, with the SS mobile RMS. The electrical and fluid connections must be made by EVA. The required connections are power, monitor, and control cable connection to the SS SCS, two 52 pin electrical connectors to the user, and the fluid connection to the user.

Two different configurations are shown for servicing the AP, Figure 3-1 (c and d) and the LM, Figure 3-1 (e and f). In the configurations shown in Figure 3-1 (c and f) the SFHT is mated directly to the AP or the LM. The configurations shown in Figure 3-1 (d and e) have the SFHT docked to the SS truss system next to the AP or the LM. The actual configuration to be used must be determined at a later date when the SS configuration becomes more solidified and the relative advantages and disadvantages of each approach can be evaluated.

The SFHT is shown stored in Figure 3-1 (g) on the SS truss system in a protective envelope for thermal and meteoroid protection. When the SS servicing facility becomes available, the SFHT may be stored in that facility using the two sill and one keel trunnion fittings as the attachment method.

#### 3.1.2 Automatic Resupply Capability

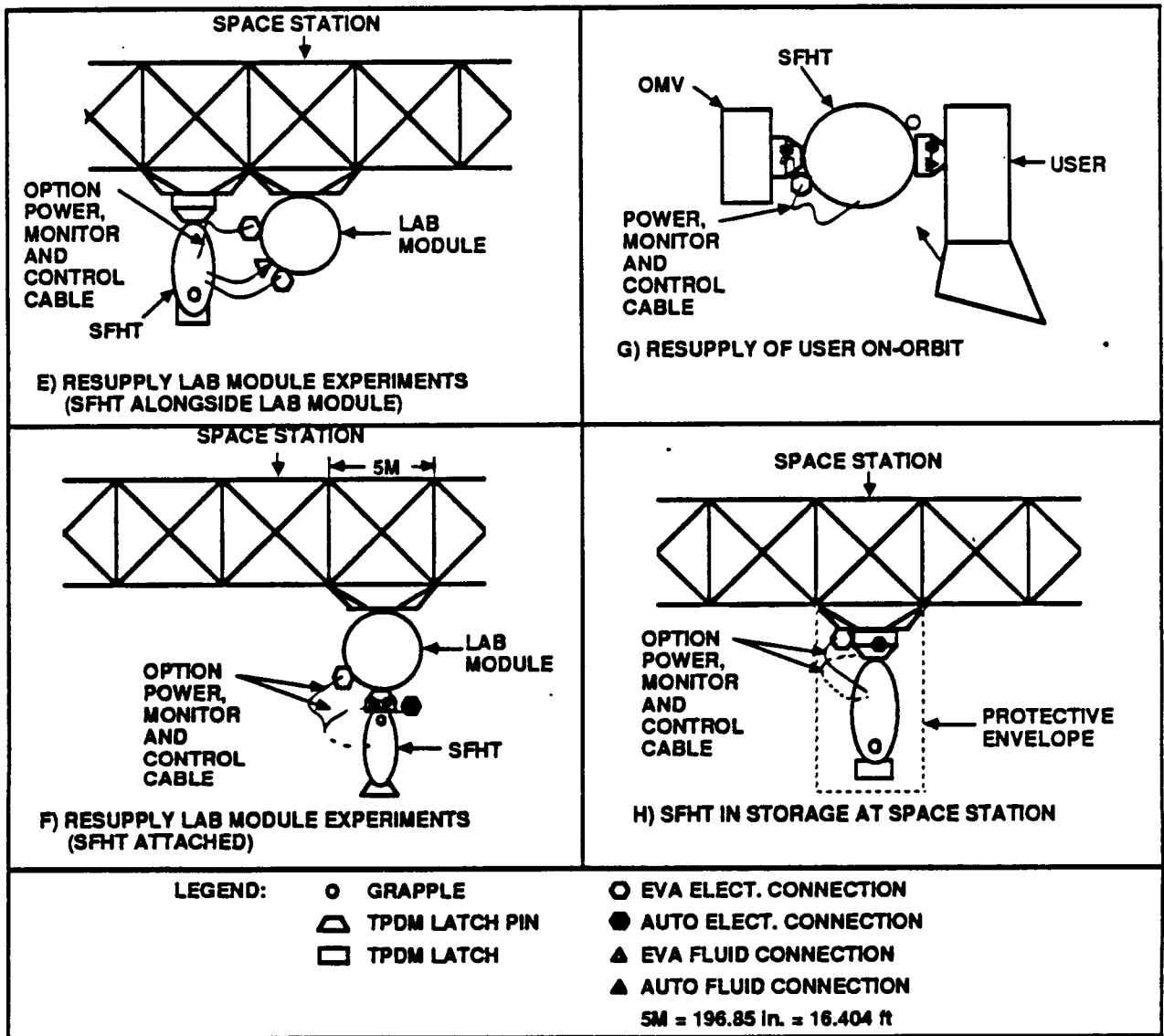
Figure 3-2 depicts the follow-on concept with automatic connections for servicing of users with the shuttle or the SS as host, and shows the SFHT in storage at SS. The electrical and fluid connections required and whether these connections are to be made by EVA or automatically are shown. The shuttle power, monitor, and control cable will use the SURS, as in the



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Figure 3-2 Automatic connection of avionics and fluid lines

C-2



A/N 9203/MD135.021

Figure 3-2 Automatic connection of avionics and fluid lines (concluded)



initial concept. However, for automatic operation, the parallel cable may connect either to the TPDM or directly to the SS, as shown in Figure 3-2. A grapple is shown in the port side of the shuttle so that it will be located on the same side as the RMS. The TPDM latch pin is shown on the lower end of the SFHT which is used to attach the SFHT, to the SS truss system for storage and to locate near users for servicing. The options shown in Figure 3-2 for resupplying are as follows:

- a. SFHT services user while located in the shuttle cargo bay
- b. SFHT docked to SS truss and user docked to SFHT
- c. SFHT docked directly to attached payload such as ASTROMAG
- d. SFHT docked to SS truss with electrical cables and fluid lines connected by EVA to the attached payload such as ASTROMAG. An option is shown for connecting the control and power cable directly to SS or to SFHT
- e. SFHT docked to SS truss with electrical cables and fluid lines connected by EVA to the lab module
- f. SFHT docked directly to LM. An option is shown for connecting the control and power cable directly to SS or to SFHT.
- g. SFHT delivered to user orbit by OMV. All operations are performed in the automatic mode
- h. Storage of SFHT on SS truss system. An option is shown for connecting the control and power cable directly to SS or to SFHT

#### 3.1.2.1 Resupply at the Orbiter

The SFHT is attached to the orbiter in the cargo bay with two sill and one keel trunnion fitting. Power, monitor, and control electrical cable is connected to the orbiter using the SURS. This connection is made on the ground and no EVA will be required for servicing users at the orbiter.

The user will be docked to SFHT using the RMS. As the user is mated to SFHT, the two electrical connectors and the fluid connector will be automatically connected to the user.

#### 3.1.2.2 Resupply at Space Station

The grapple at the top of the SFHT will be used to remove the SFHT from the orbiter and to transport it around the SS from storage to the user, AP and LM, with the SS mobile RMS. EVA will not be required to disconnect the power, monitor and control cable from the orbiter to connect it to the base of the TPDM (latch pin side). The electrical and fluid connections are made automatically to the user, AP or LM.

Two different configurations are shown for servicing the AP, Figure 3-2 (c and d) and the LM, Figure 3-2 (e and f). In the configuration shown in Figure 3-2 (c and f) the SFHT is mated directly to the AP or the LM. The configurations shown in Figure 3-2 (d and e) have the SFHT docked to the SS truss system next to the AP or the LM. The actual configuration to be used must be determined at a later date when the SS configuration becomes more solidified and the relative advantages and disadvantages of each approach can be evaluated.



The SFHT is shown stored on the SS truss system in a protective envelope in Figure 3-2 (h) for thermal and meteoroid protection. When the SS servicing facility becomes available the SFHT may be stored in that facility using the two sill and one keel trunnion fittings as the attachment method. For storage outside the servicing facility, where the SS heat rejection system may not be available, handling the 350 W heat load from the mechanical coolers will be more difficult.

### 3.1.2.3 Resupply at User Orbit

Users may be resupplied on-orbit with the SFHT based either at the orbiter or SS. The OMV will be required to transfer the SFHT to the user orbit. All connections and the berthing/docking maneuvers must be made automatically. Figure 3-2 (g) displays the configuration required for the resupply on-orbit of the user.

## 3.2 RESUPPLY OPERATIONS

The step-by-step process of resupply is shown in Figure 3-3. It accounts for resupply based at either the shuttle or the SS and the user being either warm or cold. The user is not vented after liquid begins collecting in the user cryogen tank. Figure 3-5 shows a plumbing schematic for the AXAF XRS dewar,<sup>21</sup> which is presented here as an example user system. User valve numbers referred to in Figure 3-3 are those shown in Figure 3-5. Notice that the XRS fluid management concept does not incorporate all the redundant valves required of SFHT to meet the requirement of fault tolerance for mission success. User fault tolerance is a topic that should be evaluated further. Figure 3-4 shows the operation timeline for resupply at the shuttle, where resupply must be accomplished within 7 days after launch (or 3-4 weeks with the extended duration orbiter). The total operation duration shown in Figure 3-4 is 4.4 days for a warm SIRTF.

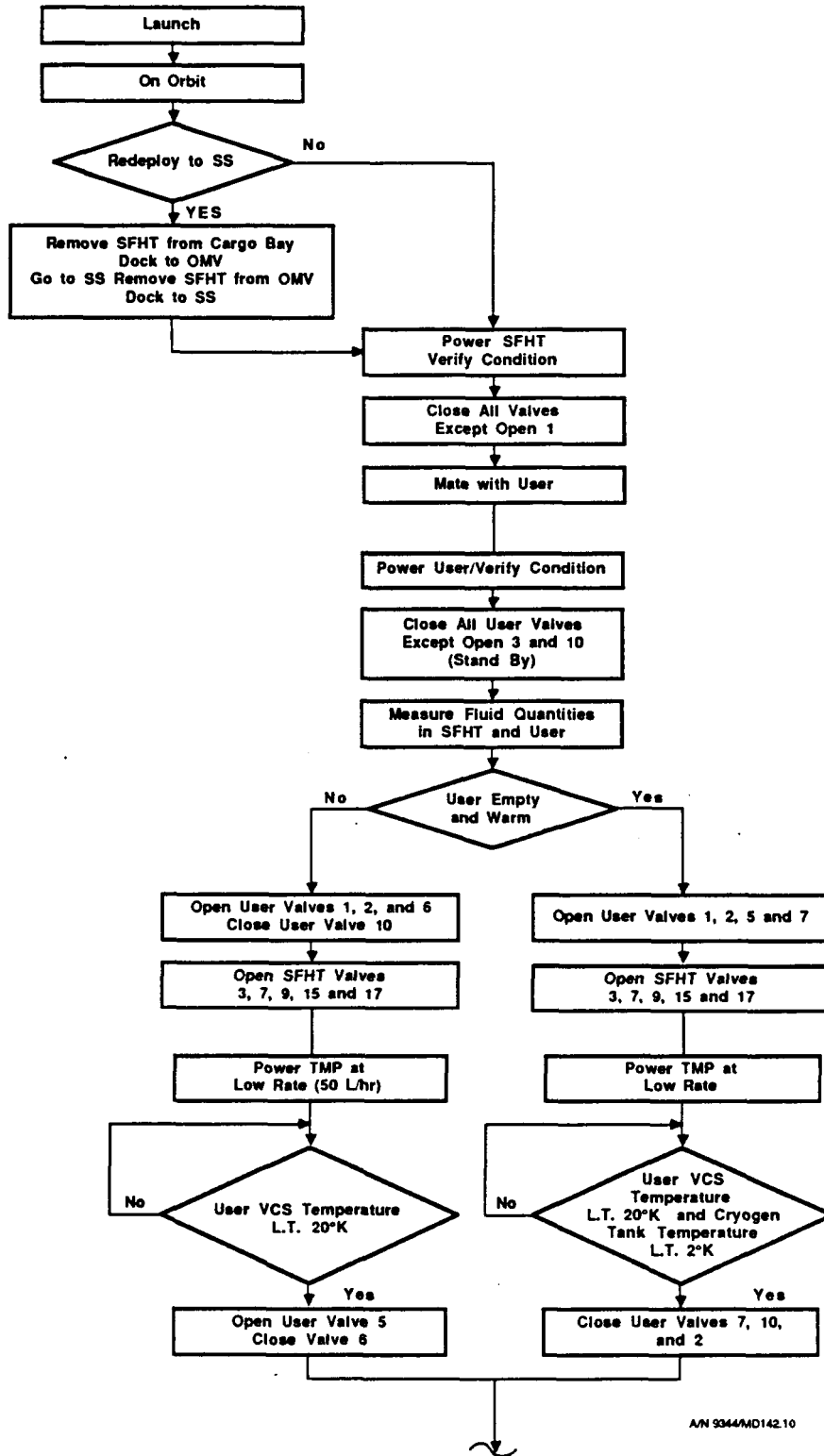
The time required to pump down the SFHT bath in preparation for transfer is not shown in Figure 3-4. As shown in Figure 4-4, this operation will take 12 hours, or less. It can, therefore, be performed during the time that the OMV is retrieving the SIRTF.

## 3.3 USER IMPACTS

Interfacing between the SFHT and user has been discussed in 2.2, 3.1, and 3.2. This section summarizes the user design impacts that specifically result from the on-orbit resupply.

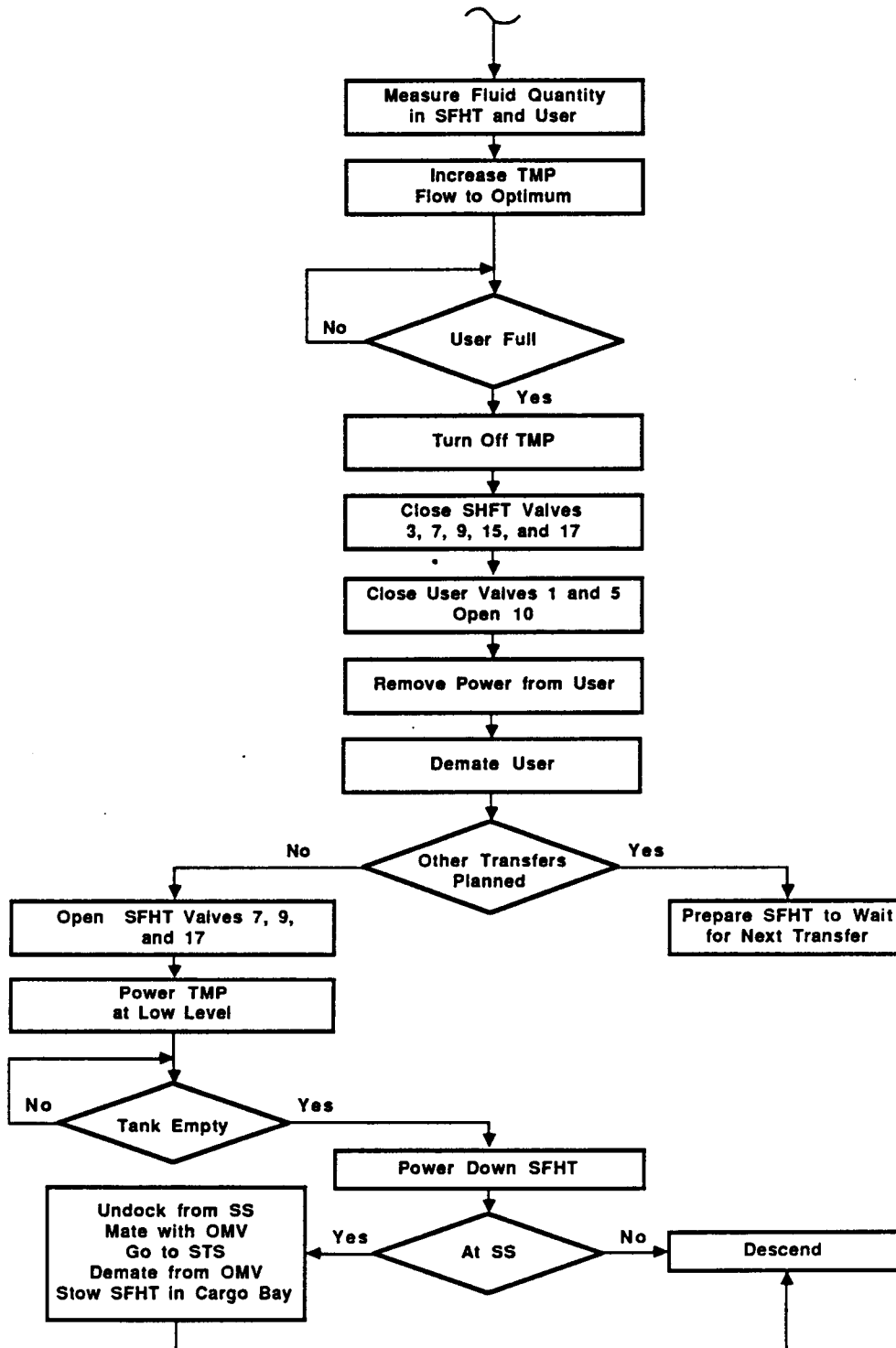
The following SFHT-to-user interface features are required:

- Berthing - The recommended berthing concept is to use the SEE and grapple for the initial EVA configuration and the three point docking mechanism for the automated configuration. The user would therefore need to have either the grapple or the mating half of the TPDM.
- Fluid - The superfluid helium coupling being developed for the SHOOT experiment is baselined for the fluid connection. It would have to be somewhat modified for incorporation into the TPDM in



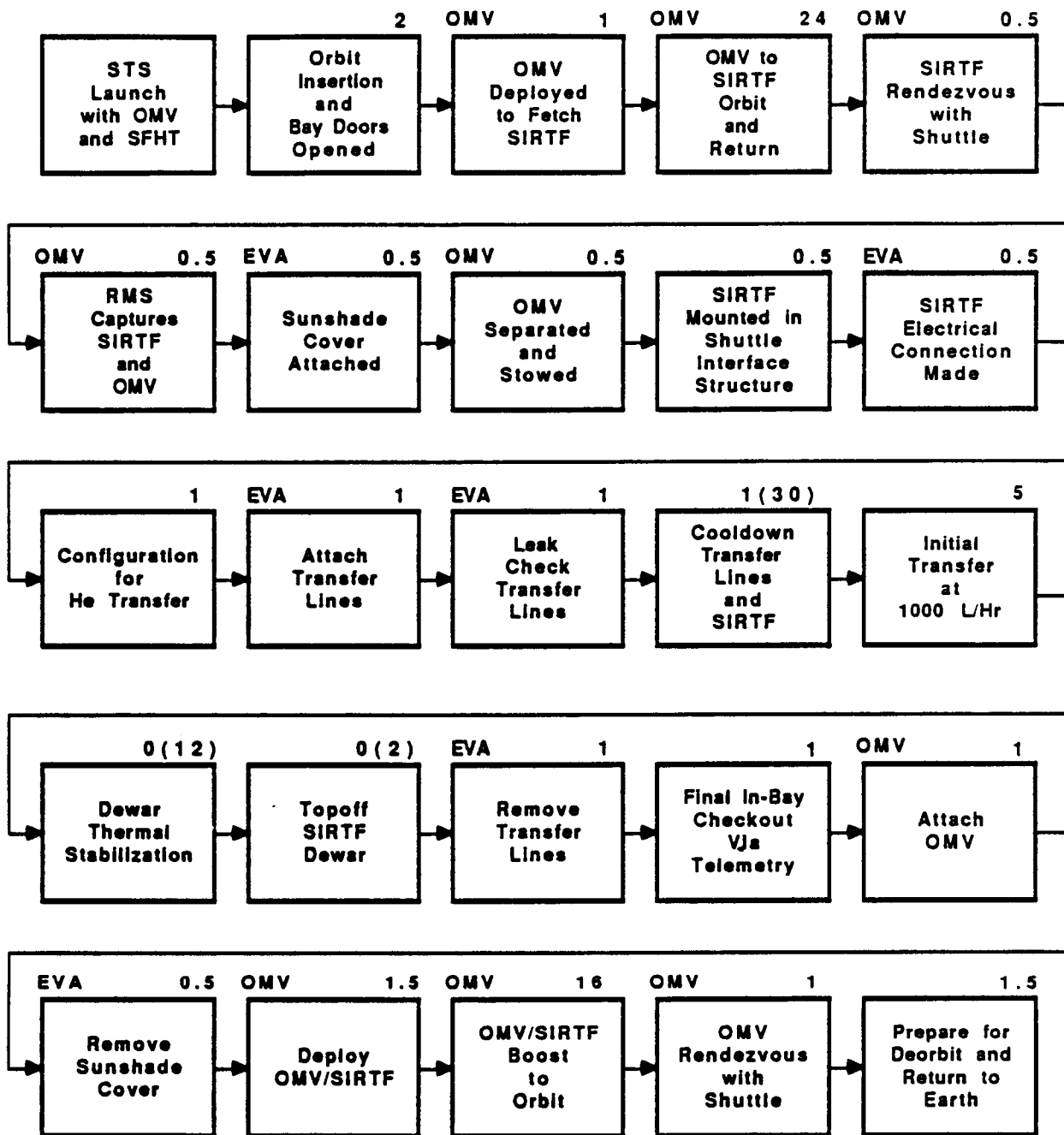
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Figure 3-3 SFHT resupply process flow chart



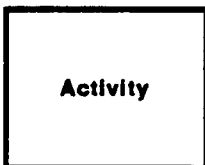
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Figure 3-3 SFHT resupply process flow chart (concluded)



**Legend**

A            B(C)



**A: Resource Required**

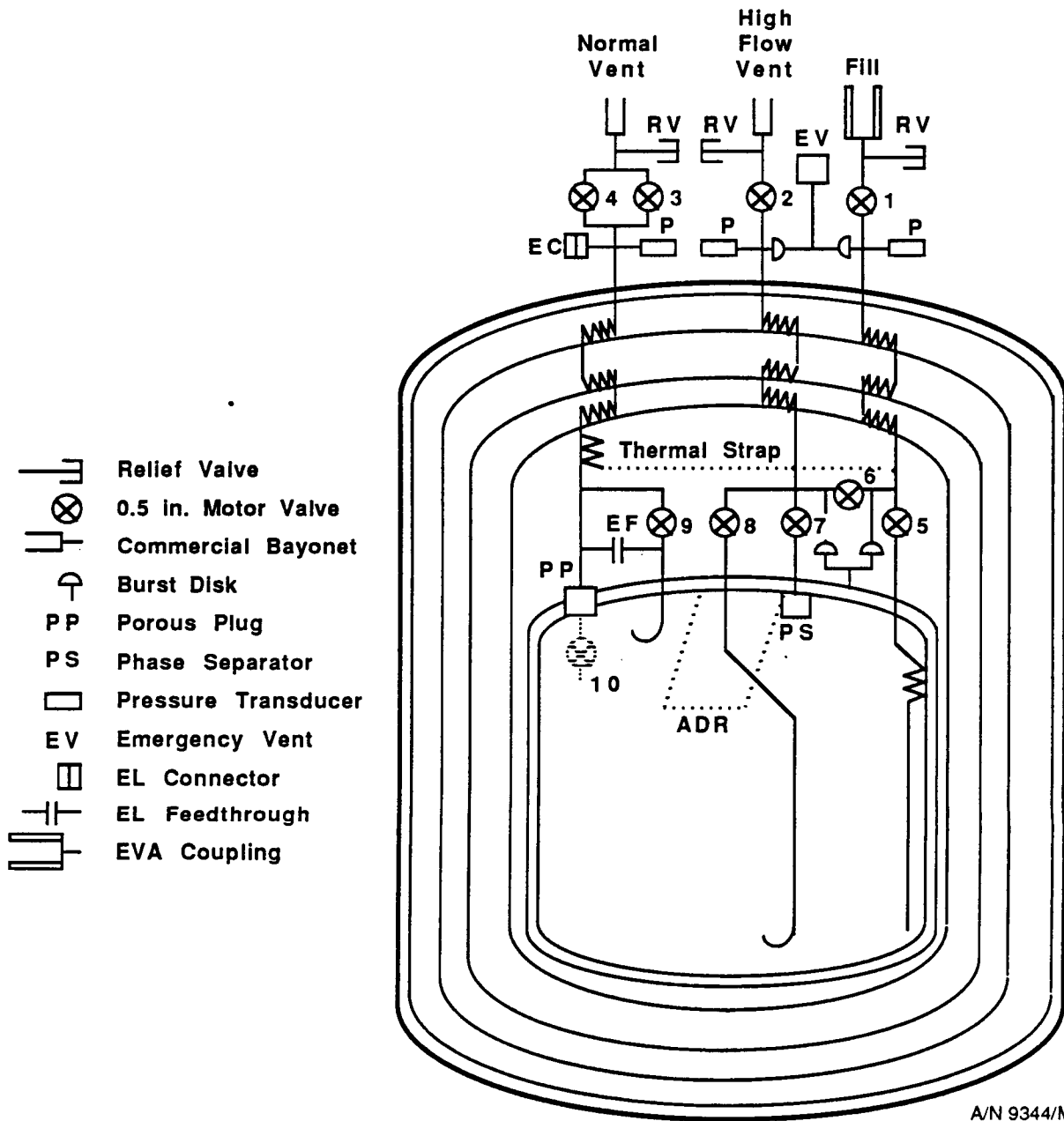
**B: Hours Required with SIRTf Cryogen Tank at 2K**

**C: Hours Required with SIRTf Cryogen Tank at 150K**

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Figure 3-4 Operations for shuttle-based resupply





A/N 9344/MD142.12

Figure 3-5 AXAF XRS fluid management schematic



the automatic configuration. The baseline has two of these coupling for redundancy; this is because a single failure in the coupling could prevent mating and mission completion. This requirement and the coupling failure modes should be examined further to determine if two of these costly couplings, or if two of the user half, are absolutely required.

- Electrical - Command, data, and power hookup to the user requires two 56-pin connectors. These are existing connectors for the initial EVA approach or connectors mounted in the TPDM for the automatic approach. The SFHT avionics provides power to the user for operation of its computer, valves, and sensors.

The SFHT must be able to command all user valves except the phase separator bypass valves. It is probably just as easy to plan on giving the SFHT control of all user valves; a reason for operating the bypass valves may be determined later. The SFHT must be able to monitor user thermometers at approximately four locations: 1) inside the tank, 2) the downstream side of the low-flowrate phase separator, 3) the downstream side of the high-flowrate phase separator, and 4) the inner VCS. It is assumed that the user is responsible for monitoring the sensors needed to verify the health of its system and issue alerts of abnormal conditions to the SFHT.

It is assumed that the three-string majority vote feature of the avionics extends into the user and that the user participates in the voting process for command of its valves. This approach is not absolutely required, but it does provide for more flexible contingency action if abnormal conditions occur in the user.

There are two potential impacts to the user fluid management system. First, a high conductance vent line must exist for removal of flashoff gas without excessive back pressure during cooldown. This is an insignificant impact if the user already has a high conductance line as part of its emergency vent system. If the user is vented through this line during the fill (to minimize the post-transfer bath temperature), then a high-flowrate phase separator is required. Second, a valve is required on the upstream side of the standby phase separator. Our baselined procedure is to close the user tank when it approaches full (or throughout the transfer process). Thus, when the user reaches full, it can easily be detected by a sharp pressure rise in the transfer system. In the absence of the aforementioned valve, SfHe would be forced through the porous plug phase separator. The large amount of heat conducted to the porous plug through the downstream column of SfHe would then prevent establishing the temperature drop through the plug, which is needed for it to act as a phase separator. SfHe would continue to flow unconstrained through the plug with no means of recovery. This is the "Castles' catastrophe." The only failsafe method of preventing this situation is to place a valve upstream of the plug.

### 3.4 SAFETY

The SFHT design and operations must comply with the safety requirements of NHB 1700.7A. The underlying requirement is that no credible SFHT failure shall result in personnel injury or damage to any part of the STS or other payloads. Four hazards are identified that require specific safety control



measures: 1) overpressurization of the cryogen tank, 2) overpressurization of the vacuum shell, 3) overpressurization of plumbing, and 4) emergency jettison.

### 3.4.1 Cryogen Tank Pressure Relief

Cryogen tank overpressurization could occur if the vent system cannot remove fluid from the tank fast enough to keep up with the heat input to the tank. A failure resulting in rapid leakage of helium or air into the guard vacuum is the circumstance during which this becomes an issue. If helium floods the guard vacuum, the heat input to the tank is estimated at 30,000 times greater than during normal operation. This estimate is based on the assumption of continuum gaseous conduction, which will occur if the gas pressure is above about 0.001 torr. Higher pressure does not result in increased heat conduction. This heating rate is equivalent to the condensation of air leaking through a 1 cm diameter hole in the vacuum shell. Occurrence of a hole larger than this is not considered a credible failure, and flooding of the guard vacuum with helium is therefore considered the driving case for design of the cryogen tank emergency vent system.

The SFHT fluid management system provides redundant vent paths for preventing cryogen tank overpressurization in the case of a guard vacuum failure. (See 2.1.3.) This provides two-fault tolerance, the first fault being the guard vacuum failure and the second being loss of one of the vent paths. Safety is thus provided by totally passive design features (burst discs) and does not rely in any way on the avionics. Analysis of the emergency vent system is discussed in 4.3.3.

### 3.4.2 Vacuum Shell Pressure Relief

The vacuum shell is equipped with a 3 psi relief device like that used in the IRAS and COBE dewars. This is a 3-in. diameter piston in a cylinder with two "o" rings for sealing; it also doubles as the vacuum pumpout port. It is available off-the-shelf from Cryolab. The internal pressure capability of the vacuum shell is several atmospheres, providing considerable margin.

### 3.4.3 Plumbing Pressure Relief

Any section of plumbing in which cold fluid could be trapped must be protected by a relief device to prevent overpressurization as the fluid warms up. This is done with off-the-shelf relief valves where possible and with qualified burst discs where the risk of relief valve back leakage or freeze out is unacceptable. (See 2.3.1.)

A pyrotechnically actuated guillotine is provided to sever the fluid and electrical lines to the user so that jettison of the user can be accomplished without EVA. Redundant guillotines and firing circuits are provided. Firing of the umbilical cutter is commanded from the GPC and requires the SFHT avionics to be in the normal operating mode. This feature is probably not required if the SFHT is designed for fully automatic mating/demating with the user.



No EVA is required in the event the SFHT dewar must be emergency jettisoned from the shuttle. Electrical hookup from the dewar-based avionics to the shuttle uses the shuttle umbilical retraction system for automatic disconnection.



## Section 4 ANALYSIS

Several types of analyses have been performed in support of configuration trades and concept development and to characterize the performance of the baseline design. These include structural, thermal/cryogenic, venting, and fluid transfer analyses.

### 4.1 STRUCTURAL ANALYSIS

Calculations have been made to determine thicknesses and masses of the cryogen tank, vacuum shell, and vapor-cooled shields and to size the cryogen tank support straps. The assumed operating conditions and structural design criteria are given in Table 4-1.

#### 4.1.1 Sizing of Shells

The vacuum shell is sized for 1 atm external pressure and launch loads. It consists of two shells welded to a girth ring, which also supports the cryogen tank, insulation system, and plumbing. The required shell thickness is 0.65 cm for the spherical shape and 0.98 cm for the  $\downarrow 2$  oblate spheroid shape.

The cryogen tank also must withstand 1 atm of external pressure for the in-process leak test. It must also be designed for the maximum operating pressure (internal) and for launch loads with essentially no pressure. The external and internal pressure conditions drive the design about equally; buckling strength is usually the primary driver. The required wall thickness is 0.55 cm for the spherical tank and 0.92 cm for the  $\downarrow 2$  oblate spheroid tank. The cryogen tank could be lightened somewhat if a smaller factor of safety is allowed for the leak check condition. This was done for the IRAS and COBE tanks.

The thickness of the vapor-cooled shields is estimated at 0.10 cm. This provides adequate buckling strength for launch loads.

#### 4.1.2 Sizing of Cryogen Tank Support Straps

The support straps are sized by fatigue; 100 cycles of limit load per flight is assumed. Considering the relatively large mass of the SFHT and results of the coupled loads analysis for systems of similar size, such as the COBE, this assumption is realistic. With 50 missions and a fatigue factor of safety of four, the total fatigue life requirement is 20,000 cycles of limit load. Measured fatigue strength of straps the size of those used in the COBE dewar is shown in Figure 4-1. Straps made of fiberglass/epoxy (i.e., the COBE straps) and alumina/epoxy were tested by the National Bureau of Standards in Boulder, Colorado, as part of a BASG internal research and development program. The figure shows that for 20,000 cycles, the fiberglass/epoxy straps have a fatigue strength of 65 ksi, while the alumina/epoxy straps provide 100 ksi. These values were used for the strap sizings.

For a given dewar geometry, strap angles are arranged to provide minimum strap area. The SFHT dewar is assumed to use 12 straps. The strap-supported mass is estimated at 2,070 kg for the 10,000- $\ell$  spherical



Table 4-1  
STRUCTURAL DESIGN CONDITIONS AND CRITERIA

- Operating Conditions
  - Vacuum Shell
    - 1 ATM External Pressure with Launch Loads
  - Cryogen Tank
    - 1 ATM External Pressure (During Leak Check)
    - 54 psi Maximum Operating Pressure (Internal)
    - Launch Loads with No Pressure
  - Vapor-cooled Shields
    - Launch Loads with No Pressure
    - Thermal Contraction Effects
- Design Criteria
  - 10g Limit Load (STS or Titan IV Launch)
  - Yield Factor of Safety:
    - 1.6 (Internal Pressure)
    - 1.4 (Other)
  - Ultimate Factor of Safety:
    - 2.0 (Internal Pressure)
    - 1.4 (Other)

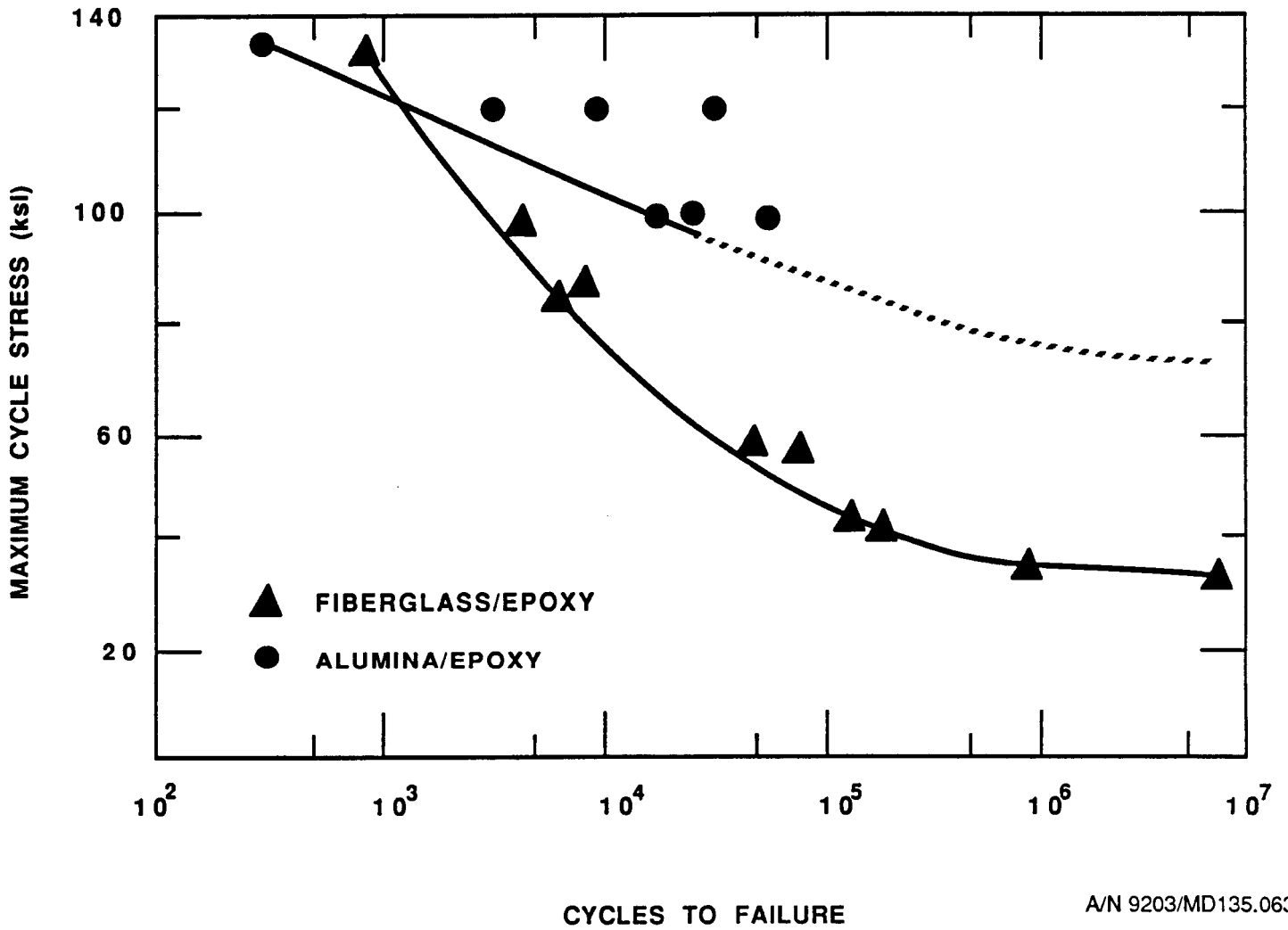


Figure 4-1 Strap fatigue test results at R=0.05 and room temperature



tank and 2,370 kg for the  $\sqrt{2}$  oblate spheroid. The calculated strap size is approximately the same for both the sphere and the oblate spheroid. The greater supported mass of the oblate spheroid is compensated for by a more favorable strap angle. The cross-sectional area of all 12 straps is 16.0 cm<sup>2</sup> for alumina/epoxy and 25.5 cm<sup>2</sup> for fiberglass/epoxy.

The measured tensile modulus of elasticity is  $8.7 \times 10^8$  psi for the fiberglass/epoxy and  $19.7 \times 10^8$  for the alumina/epoxy. Based on an estimated strap length of 100 cm and the strap-supported masses, the natural frequencies for the various combinations of strap material and dewar shape vary from 23 to 30 Hz. These are acceptable levels.

## 4.2 THERMAL ANALYSIS

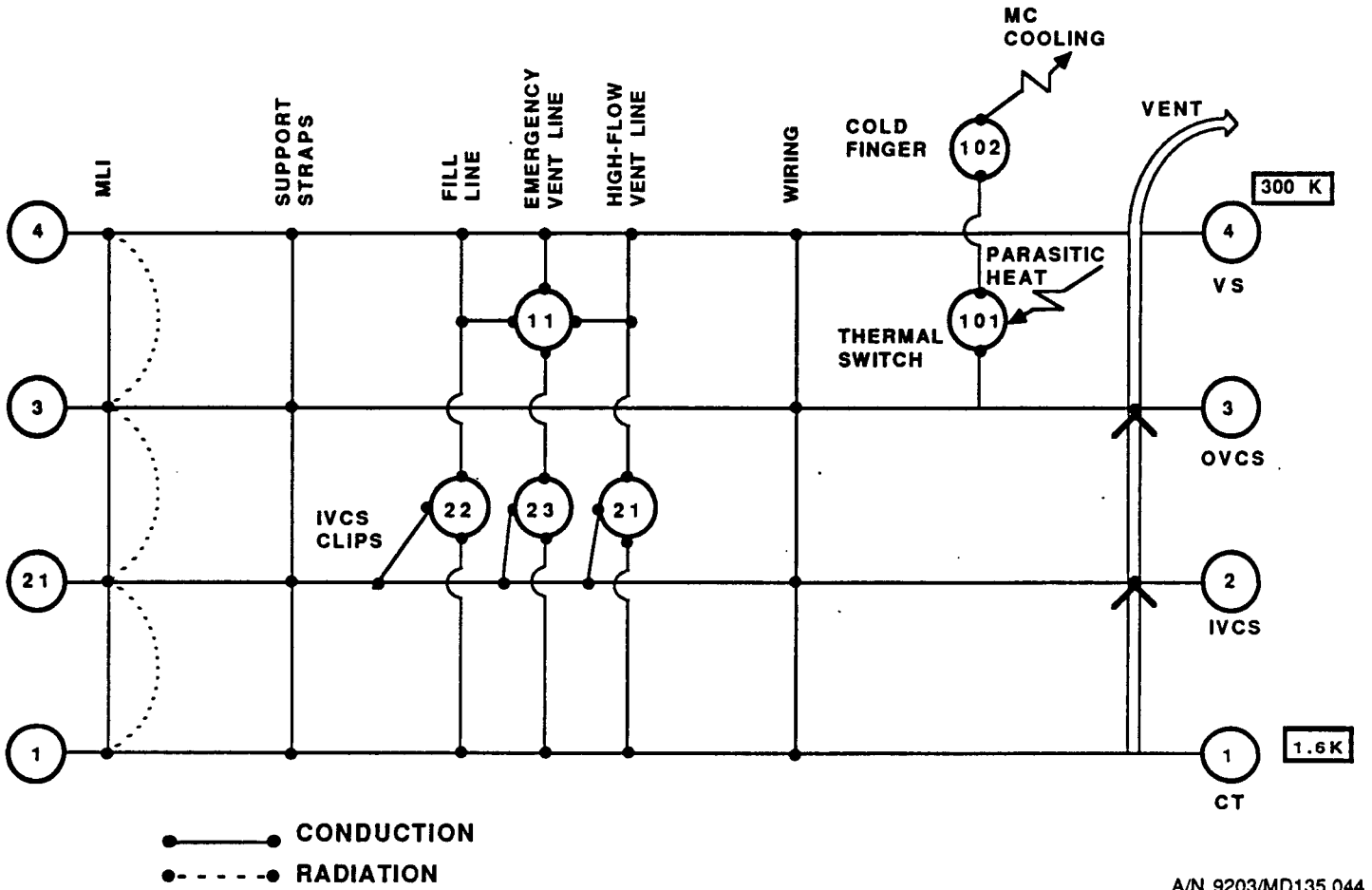
The thermal analysis indicates that a hybrid system with four Oxford Sterling cycle refrigerators offers a significant mass savings and extended dewar lock-up capability while meeting the thermal performance requirement of delivering 8,900  $\ell$  of SfHe at the end of a 270-day on-orbit standby. This amount of SfHe is required to cool and fill a 150 K SIRTF.<sup>18</sup> The 270-day period represents a 180-day servicing interval with a 50 percent margin added. The objective of this analysis was to define a thermally optimum dewar subsystem while meeting cost and payload constraints.

### 4.2.1 Model Description

The SFHT dewar thermal analysis was conducted using a SINDA computer model (Figure 4-2). The model uses single nodes to represent the CT, IVCS, OVCS, and the VS. Heat transfer paths include conduction through the supports and MLI, and radiation through the MLI. Also incorporated in the model are secondary effects including heat transfer through the plumbing and wiring and parasitics at the refrigerator thermal switch. The ground rules for this modeling effort were:

- 8,900  $\ell$  of SfHe at 1.6 K are available for a warm SIRTF resupply at the end of a 270-day on-orbit standby period.
- The baseline design includes four Oxford Stirling cycle refrigerators providing OVCS cooling, each with a capacity of 3 W at 93 K.
- The nominal conductance of both the refrigerator cold-finger and thermal switch is 500 mW/K. The parasitic heat leak at the thermal switch is 500 mW.
- The nominal on-orbit and ground hold vacuum shell temperature is 300 K.
- Dewar exit wiring consists of 130 40-gage and 102 28-gage manganin wires exiting along a support strap. Wiring inside the vent line is inherently vapor cooled.
- 12 support straps are of alumina/epoxy construction.
- Vent and fill lines are 3/4-in. diameter, 0.016-in. wall thickness, stainless steel.





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Figure 4-2 Schematic of thermal math model



- A 5 percent ullage exists when the dewar is locked up for pre-launch hold.

The model was designed to run either a steady-state or transient case. Steady-state runs were used to determine on-orbit standby losses. Transient runs were used to determine the dewar lock-up capability during prelaunch ground hold.

The model incorporates refrigerator cooling capacity values as a function of OVCS temperature. Integrated values of the alumina/epoxy support thermal conductivity and temperature dependent values of helium vent gas enthalpy were also included in the model. Heat transfer through the MLI was calculated using conduction and radiation correlations validated by test data from the IRAS and COBE programs.

#### 4.2.2 Baseline System Performance

System performance was calculated for the dewar with the mechanical coolers (SS-based resupply) and without the mechanical coolers (shuttle-based resupply). The heat load breakdown for the two cases based on a 300 K vacuum shell temperature is as follows:

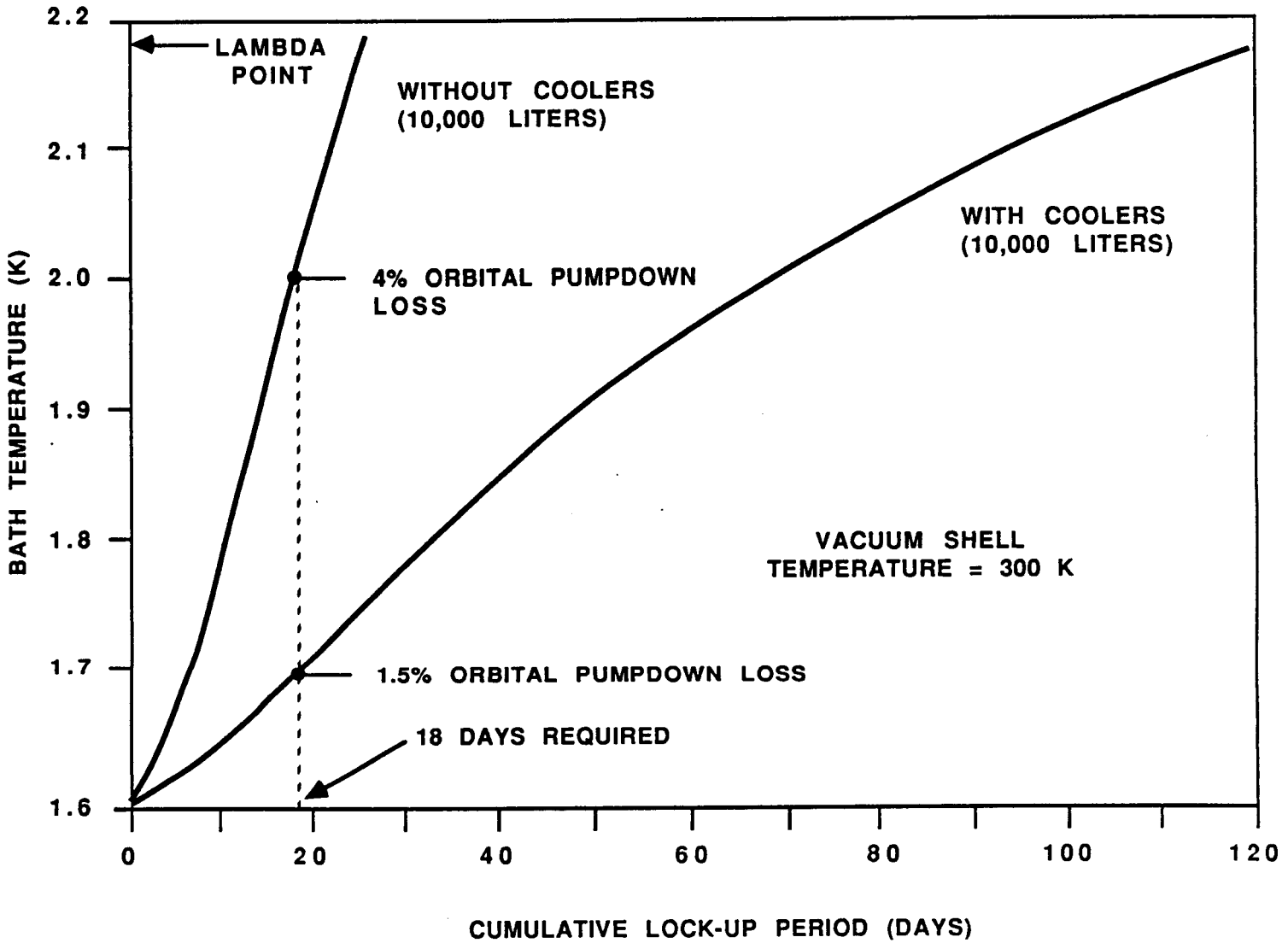
	<u>WITH COOLERS</u>	<u>WITHOUT COOLERS</u>
Total Heat Leak, mW	62	163
• Support Straps, %	52	43
• MLI, %	32	43
• Plumbing, %	14	12
• Dewar Exit Cables, %	2	2
Boil-Off Rate, g/day	238	630

Bath temperature rise during the prelaunch lockup is shown in Figure 4-3. Time to reach the lambda point, temperature after the required 18-day lockup, and mass loss after orbital pumpdown may be seen for the cooler and no-cooler configuration. Figure 4-4 shows orbital pumpdown time based on pumping through the high-flow vent. For the predicted fluid exit temperature of 2.05 K, pumpdown time is 12 hours without use of coolers during ground lockup and 4 hours with coolers used during ground lockup. Pumpdown would be at least 10 times slower if it were done through the low-thrust vent alone. Pumpdown time is critical for only shuttle-based resupply, in which case coolers are not used. For SS-based resupply the major advantage of using the coolers during lockup is not shortened pumpdown time, but rather a system launch mass reduction of about 75 kg.

Table 4-2 gives the breakdown of helium usage throughout the mission for the two cases. It is assumed that the transfer rate is throttled back near the end of the resupply operation so that a 5 percent residual is achievable.

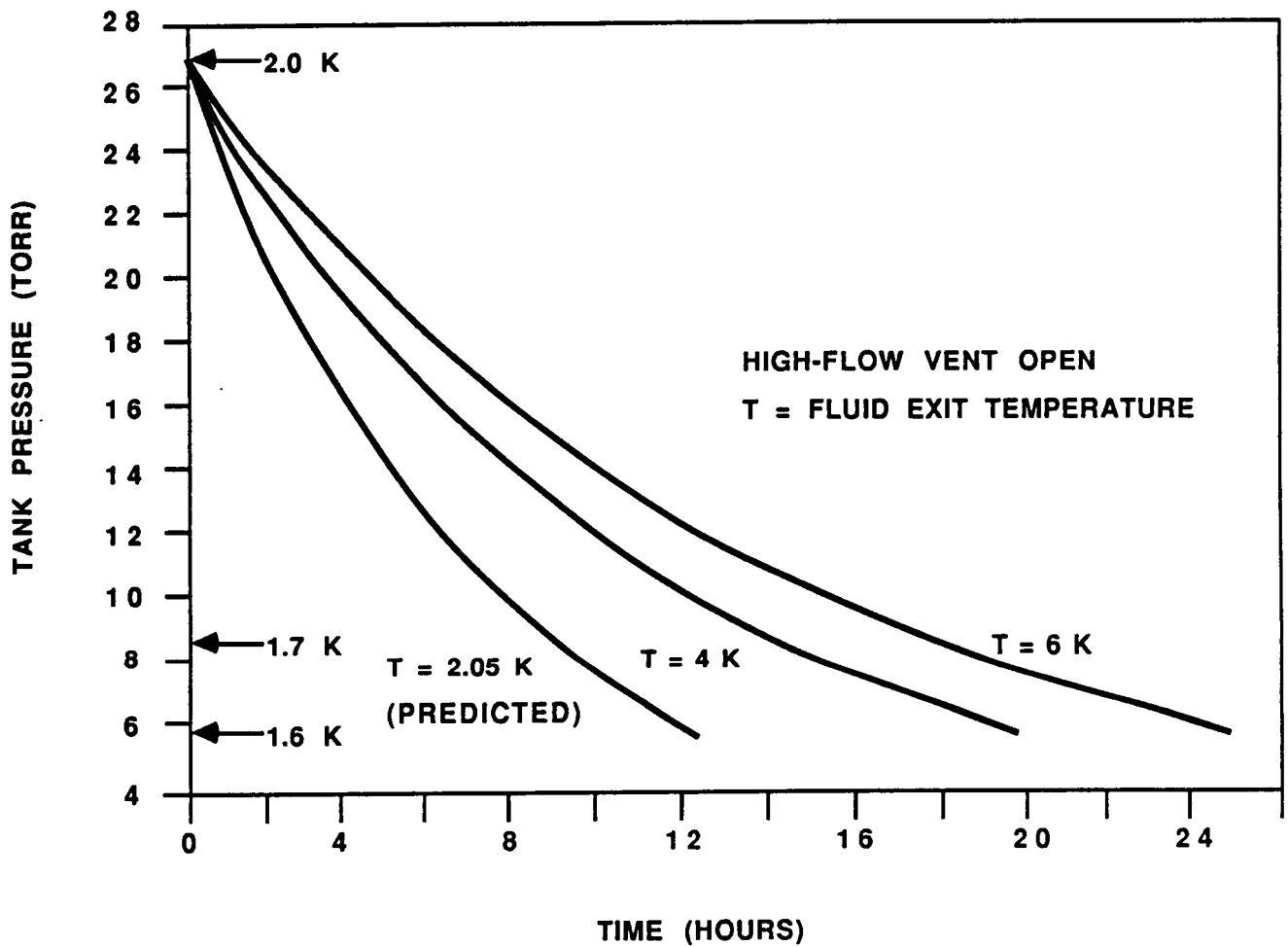
#### 4.2.3 Sensitivity Studies

Several cases have been considered concerning uncertainties in vacuum shell temperature, the effect of larger support straps, and a 360-day standby period. The results are presented in Table 4-3 as a dewar mass penalty. The



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Figure 4-3 Ground lock-up capability



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Figure 4-4 Orbital pumpdown time



Table 4-2  
BREAKDOWN OF HELIUM USAGE

	<u>WITH COOLERS*</u>	<u>WITHOUT COOLERS**</u>
Final Ground Pumpdown	500	500
Orbital Pumpdown to 1.6 K	150	400
Orbital Standby	440 (9 Months)	30 (1 Week)
Transfer (Warm SIRTf)	8,400	8,400
Residual (5%)	500	500
Total	9,990	9,830 Liters

\*Resupply at Space Station

\*\*Resupply at Shuttle

differences are slight since nearly 90 percent of the total mass can be attributed to the 8,900 liter resupply requirement which is not subject to standby losses.

Also, the failure of mechanical coolers on orbit and the resulting reduction in standby lifetime is presented in Table 4-4. The standby lifetime presented represents the maximum period of time SFHT can remain in the standby mode with an adequate helium volume available for a warm SIRTf resupply.

#### 4.2.4 Configuration Tradeoffs

Three dewar design tradeoffs have been assessed including a 1/2 oblate spheroid shaped dewar with four Oxford coolers, a spherical dewar with no coolers, and the substitution of fiberglass support straps for alumina/epoxy straps on the baseline dewar. Table 4-5 shows the mass penalty associated with each alternative for SS-based resupply.

The oblate spheroid dewar with four Oxford coolers has nearly the same thermal performance as the baseline dewar with a 118 day ground lock-up capability and a standby boiloff rate of 243 g or 0.016 percent per day. Therefore, nearly all of the 720 kg mass penalty associated with this dewar configuration can be attributed to the dry weight of the dewar.

The spherical dewar without the mechanical coolers yields a 26 day lock-up period, before the helium bath goes normal, or only 22 percent of the capability of the baseline system. The heat leak to the cryogen tank during orbital standby is nearly 2.4 times greater than the baseline design. The



Table 4-3  
SENSITIVITY ANALYSES

<u>EXAMINED PARAMETER</u>	<u>CRYOGEN TANK VOLUME (L)</u>	<u>DEWAR MASS PENALTY (kg)</u>	<u>% OVER BASELINE</u>
Baseline	10,000	---	---
360 Day Standby (No Margin)	10,150	47	1.5
<u>Orbital Vacuum Shell Temperature (K)</u>			
320	10,080	27	0.9
310	10,030	12	0.4
290	9,950	-11	-0.3
280	9,900	-24	-0.8
<u>Support Strap Size</u>			
1.25 X Baseline	10,070	24	0.8
1.50 X Baseline	10,170	50	1.6

Table 4-4  
EFFECT OF MECHANICAL COOLER FAILURE ON DEWAR PERFORMANCE

- Reduction in Standby Lifetime Calculated
  - 8,900 Liters Required at End of Standby
  - Complete Failure of 1,2,3 or 4 Coolers at Start of Standby Considered

<u>NUMBER OF COOLERS FAILED</u>	<u>STANDBY LIFETIME (DAYS)</u>	<u>LIFETIME REDUCTION (%)</u>
0	270	-
1	250	7
2	180	33
3	125	54
4	100	63



Table 4-5  
MASS PENALTIES ASSOCIATED WITH CONFIGURATION TRADEOFFS

<u>CONFIGURATION</u>	<u>DEWAR VOLUME (l)</u>	<u>DEWAR MASS PENALTY (kg)</u>	<u>% OVER BASELINE</u>
Baseline	10,000	---	---
Oblate Spheroid	10,000	720	23
Sphere/No Coolers	10,800	250	8
Fiberglass Straps	10,200	60	2

8 percent mass penalty is a result of the larger helium and tank volume necessary to meet the 270-day standby requirement, less the weight of the mechanical coolers.

Replacement of the alumina/epoxy support straps with fiberglass straps results in a total mass penalty of 2.4 percent. This entire mass penalty is in the form of excess helium necessary to offset the degradation of the lock-up and standby thermal performance resulting from the necessarily larger fiberglass support straps. The alumina/epoxy material provides 40 percent higher frequency and 10 percent lower thermal conductance than fiberglass/epoxy for the SFHT.

### 4.3 VENTING ANALYSIS

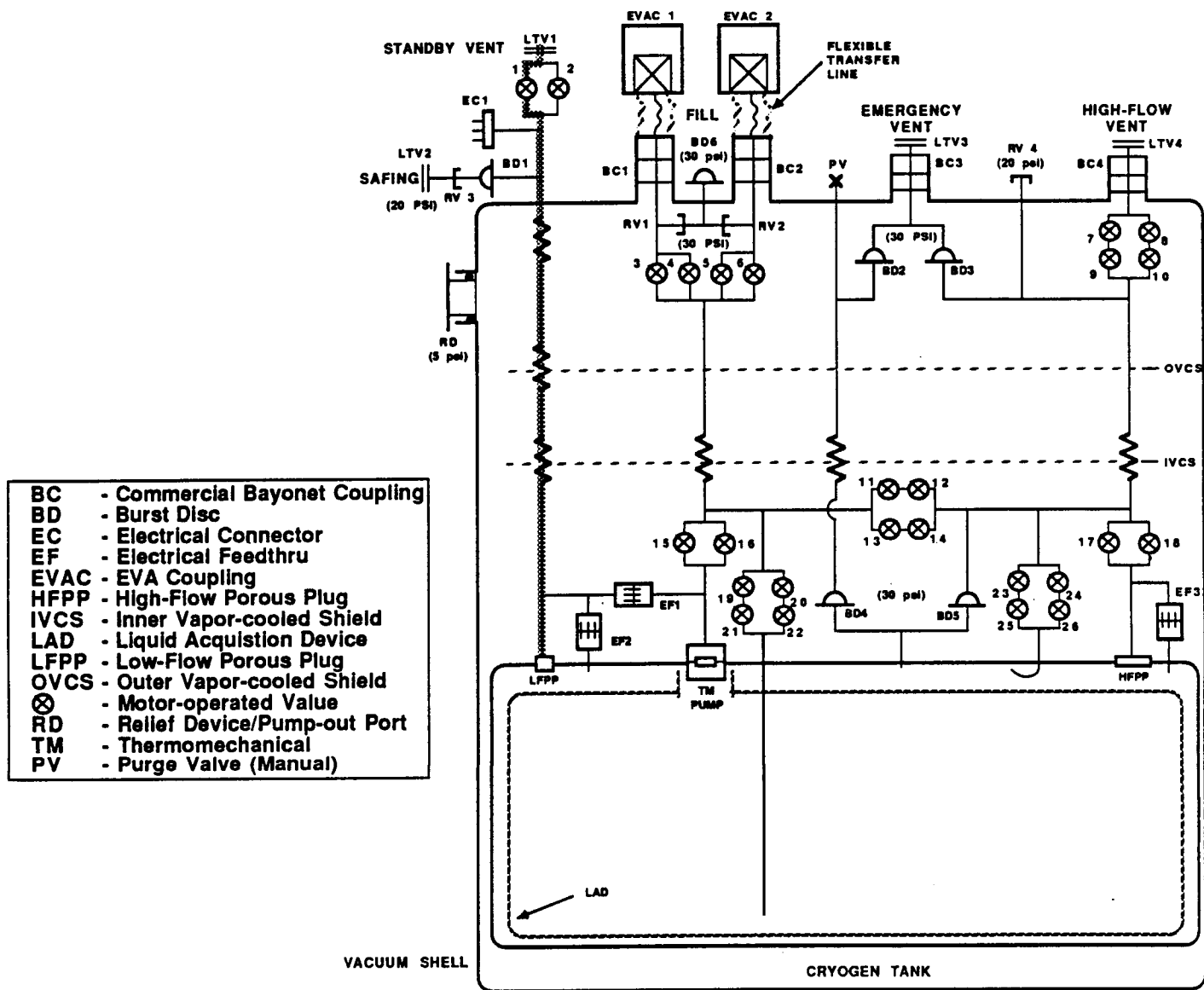
The SFHT venting subsystem is composed of three separate venting paths: the low-flow vent to provide venting in the standby mode, the high-flow vent to provide initial orbital pumpdown and venting throughout the resupply mode, and the emergency vent to relieve uncontrolled tank pressurization due to loss of guard vacuum. Both the low-flow and high-flow vents function by removing heat from the cryogen tank in the form of vapor. The design goal for both of these vent systems is to allow adequate flow conductance to maintain the lowest feasible bath temperature without significantly impacting the thermal performance of the dewar. The emergency vent is a straight exit path specifically designed to maintain tank pressure below yield for a mishap involving guard vacuum loss as a result of helium or air intrusion into the annulus.

#### 4.3.1 Low-Flow (Standby) Vent

The low-flow vent (Figure 4-5) is opened subsequent to launch by a baro switch and remains open until descent. The venting system incorporates a passive phase separator, or porous plug, with roughly four times the surface area of the plug developed for COBE to remove parasitic heat leaks to the cryogen tank during standby. This plug is designed to the higher vapor flow-rates associated with a shuttle-based resupply mission. For the SFHT baselined 3/4-in. low-flow vent system, analysis indicates a bath temperature of 1.6 K is attainable with a cryogen tank heat input of 163 mW for a shuttle-based resupply. A bath temperature of 1.5 K is predicted for the lower standby venting rates associated with space station-based resupply with refrigerators installed.



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Figure 4-5 Standby (low-flow) vent





The low-flow vent plumbing system includes nearly 19 ft of line length internal to the vacuum shell and 25 ft total. A strong thermal attachment at both the IVCS and OVCS provides 100 percent vapor cooling efficiency. External to the vacuum shell are redundant flow paths each with an in-line 3/4-in. valve making the system 1 fault tolerant to mission success. Finally, the vapor exits the system through a low-thrust vent.

The analysis was conducted using the continuum flow equation to predict sectional pressure drops in the line based upon fluid temperatures equivalent to the CT, IVCS, OVCS, and VS temperatures.<sup>17</sup> A 1/4-in. wire bundle entering the line at the vacuum shell and extending into the cryogen tank is accounted for in the analysis.

The predicted bath operating temperature in the standby mode is 1.6 K for the system without coolers and 1.5 K for the system with coolers incorporated. The majority of the flow impedance can be attributed to line length, with valves and bends making an insignificant contribution. This is a result of the laminar flow condition where viscosity effects are dominant. A venting mode with both valves open offers little advantage with respect to flow conductance.

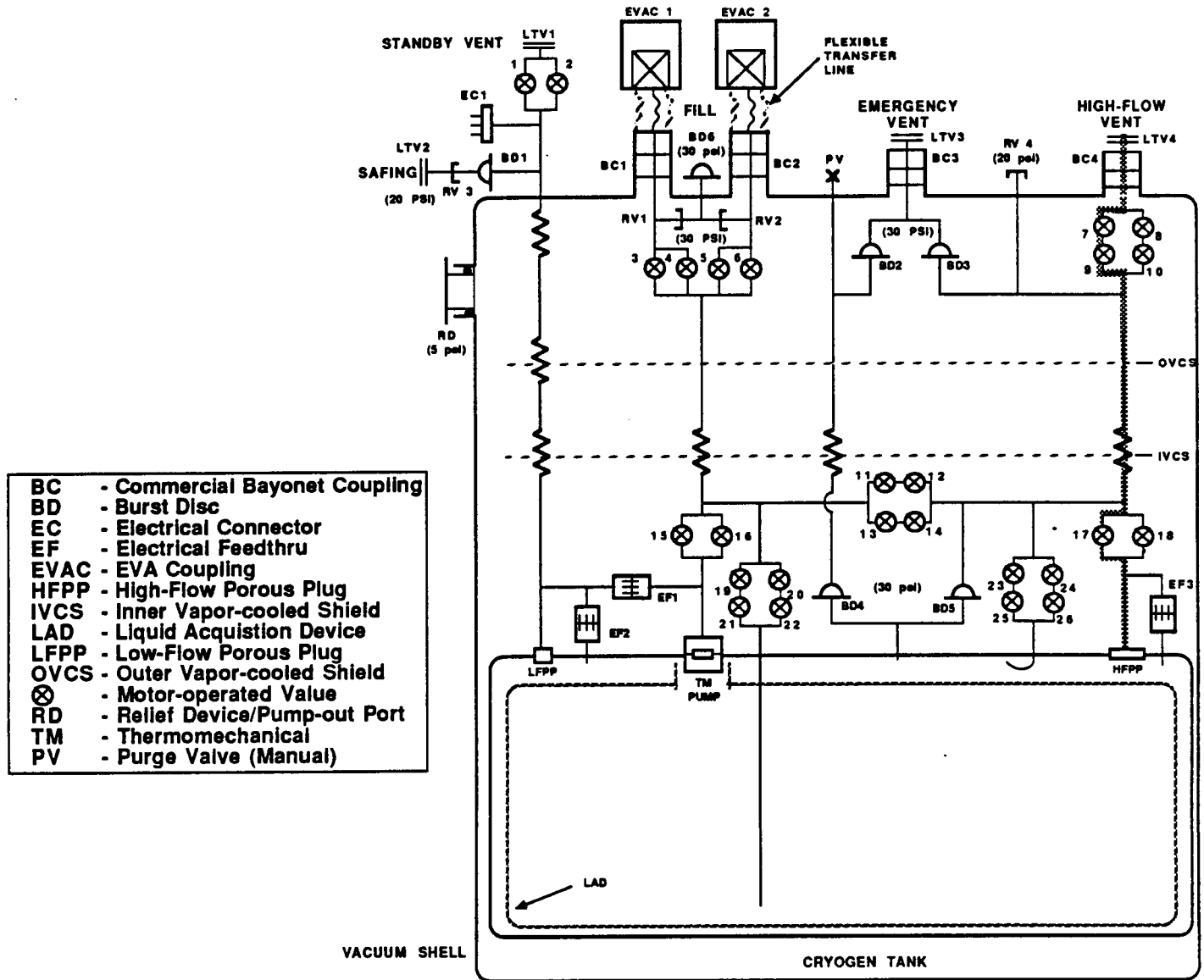
#### 4.3.2 High-Flow Vent

The high-flow vent (Figure 4-6) is opened just prior to resupply and remains open throughout the resupply mode. The venting system includes a large porous plug (200 cm<sup>2</sup>, 10 μm) to remove a greatly escalated heat input to the cryogen tank during transfer while maintaining small pressure drops across the porous medium. This is the same plug as baselined for the SHOOT experiment. The high-flow vent system has been designed to extract large volumes of cold gaseous helium from the cryogen tank while sustaining the bath at the baselined temperature of 1.6 K.

The high-flow vent plumbing is comprised of nearly 6 ft of line internal of the vacuum shell exiting in a nearly straight line. There is a relatively weak thermal attachment at the IVCS. An attachment clip with a small conductance is used to intercept heat conducted toward the cryogen tank during standby while allowing very little temperature rise in the effluent gas during transfer to minimize flow impedance. The remainder of the line is isolated from any heat sources except a 1 W heat input at the external valves. There is a redundant flow path associated with an internal set of valves and a separate redundant flow path associated with two pairs of external valves. A low thrust vent at the outlet completes the system.

The high-flow vent analysis was conducted using the Darcy equation for turbulent flow to predict sectional pressure drops in the line. The design is based upon all valves being open to flow. The vapor exits the tank slightly above the bath temperature, with heating at the IVCS and external valve set only.

In order to maintain a tank temperature of 1.6 K during resupply, the flow conductance through the baselined 3/4-in. high-flow vent must be minimized by



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Figure 4-6 Orbital pumpdown (high-flow vent)



restricting the exit fluid temperature to 2.05 K or less. This is accomplished by design of the vent line thermal attachment at the IVCS. An attachment clip with a nominal conductance of 25 mW/K achieves the desired result without significant impact to the standby thermal performance. For this high-flow situation, the flow impedance associated with valves and fittings dominates the overall system.

#### 4.3.3 Emergency Vent

The emergency vent (Figure 4-7) is used only during a situation of uncontrolled tank pressurization due to loss of guard vacuum and is specifically designed for the scenario of helium gas leakage into the annulus. For such an event, it is necessary to prevent the tank from pressurizing beyond yield (68 psi) and sustaining irreparable structural damage. The SFHT baselined 3/4-in. emergency vent system is capable of such a task. Heat input to the cryogen due to helium leakage is equivalent to air leakage through a hole of about 1-cm diameter; this size of hole is not considered a credible failure.

Two completely redundant flow paths both with two in-line burst discs set at 30 psi on the warm and cold end define the emergency vent system. One of the lines doubles as the high flow vent line; the other is a dedicated emergency vent line. Each line has a total path length of nearly 17 ft. Both lines have a weak thermal connection to the IVCS. The same attachment clip designed for the high-flow vent is used to minimize exit fluid temperature and flow impedance. At the outlet of the line there is a low thrust vent.

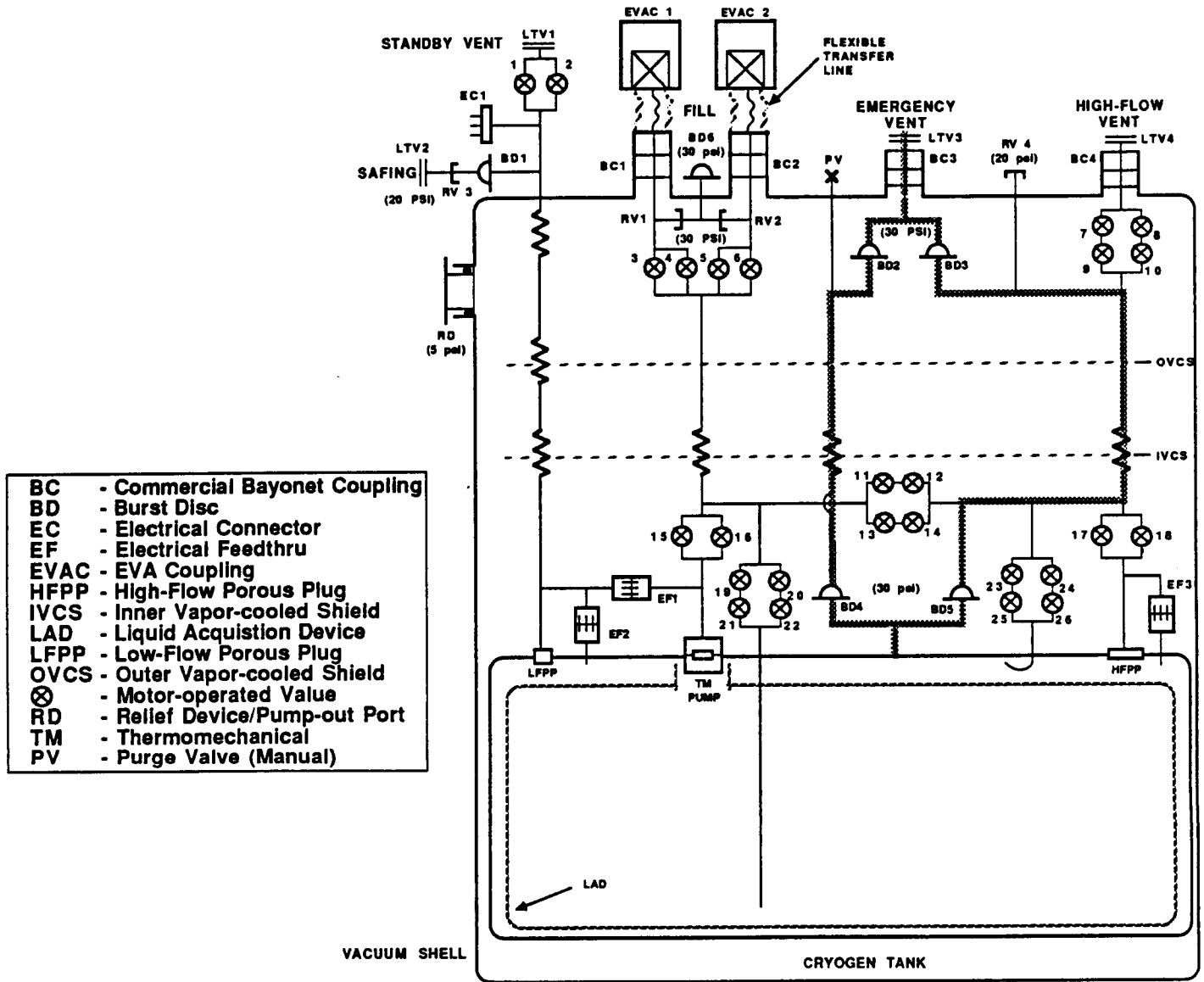
The analysis was conducted using the Darcy equation for turbulent flow. Three cases were considered to study the effect of vapor cooling at the VCSs.<sup>18</sup> The first case considers no effective vapor cooling, resulting in a maximum cryogen tank heat leak. For this situation, the fluid exits at the bath temperature. The second case accounts for a 100 percent heat transfer efficiency at the vapor-cooled shields, with a greatly reduced heat leak to the cryogen tank. The exit fluid temperature is taken sectionally as the CT, IVCS, and OVCS temperatures predicted by a SINDA thermal model. The final case accounts for the heat transfer effects at the IVCS with the designed clip in place. A SINDA thermal model was used to account for the attachment clip conductance at the IVCS. The clip modeled is identical to the clip used in the high-flow venting system.

From these three models, it has been determined that the worst case with respect to pressure drop across the emergency vent line exists when the heat leak to the tank is a maximum and heat transfer to the fluid at the VCSs is negligible. From the third case it can be concluded that this is very near the true situation. However, the important conclusion is that the baselined 3/4-in. emergency vent system will provide adequate flow conductance to maintain a below-yield tank pressure in an emergency venting situation.

#### 4.4 SUPERFLUID HELIUM TRANSFER ANALYSIS

A computer model that incorporates the physics involved in the transfer of superfluid helium<sup>20</sup> has been applied to verify the baselined transfer system design. The governing equations are shown in Table 2-4; it is the Gorter-Mellink equation and the internal heat flux that differentiate this set of

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- BC - Commercial Bayonet Coupling
- BD - Burst Disc
- EC - Electrical Connector
- EF - Electrical Feedthru
- EVAC - EVA Coupling
- HFPP - High-Flow Porous Plug
- IVCS - Inner Vapor-cooled Shield
- LAD - Liquid Acquisition Device
- LFPP - Low-Flow Porous Plug
- OVCS - Outer Vapor-cooled Shield
- ⊗ - Motor-operated Valve
- RD - Relief Device/Pump-out Port
- TM - Thermomechanical
- PV - Purge Valve (Manual)

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Figure 4-7 Emergency vent



equations from that governing the behavior of normal fluids. The Gorter-Mellink equation expresses the relationship among the temperature gradient, the pressure gradient, and the mutual friction. The result of this relationship is a heat flux going upstream in the SfHe flow. At very high flow velocities, mutual friction couples the normal and superfluid components together, and the flow behavior approaches that of a normal fluid. At the low flowrates that will exist during start-up of the SFHT transfer process this is not the case, and it is important to use a model that properly accounts for the unique behavior of SfHe.

The transfer system analyzed includes the TM pump, the SFHT plumbing, a flexible transfer line, and the user plumbing. The model accounts for flow constrictions due to valves and bends and for heat inputs along the line. The thermodynamic properties of SfHe are contained in the program. The line configuration is input as a number of elements. Each element specifies a portion of the line through inputs of length, diameter, and heating. Equivalent lengths are used in the traditional manner to account for constrictions and changes of direction. These configurational and heating data, the saturation temperature of the source tank, the heat flux at the receiver tank, and the porous plug properties define the transfer system. The model uses a finite difference approximation to predict temperature, pressure, velocity, and heat flux along the line length. The model has been validated by correlation with the results of SfHe transfer testing performed by BASG.

#### 4.4.1 Modeling Ground Rules

The ground rules used for modeling the SFHT transfer system are:

- The supply dewar operates at a temperature of 1.6 K.
- Transfer takes place into a non-venting receiver. The only heat transfer taking place at the receiver tank is due to condensation of the gas within the tank as the ullage shrinks.
- The desired maximum transfer rate is 1,000  $\ell$ /hr.
- The user transfer system configuration and heat inputs are identical to those of the SFHT, except for the TM pump.

#### 4.4.2 Baseline System Description

Figure 4-8 is a plumbing schematic of the transfer system; major features are internal and external 3/4 in. valves in both the SFHT and user, a bayonet coupling, an EVA coupling, and a flexible transfer line. The inside diameter of the SFHT plumbing, user plumbing, and transfer line are assumed to be 1.8 cm. The total length of the flow path is just under 11 m; Figure 4-9 shows the diameter profile over the flow path. Flow impedances of the valves, couplings, and corrugated flexible line are represented in the model by equivalent lengths of 1.8 cm pipe.

Based on the measured valve flow coefficient of  $5.3^{24}$ , an equivalent length of 1.8 cm tubing was calculated for input to the model. The flexible transfer line is assumed to be 3 m long with the minor diameter of the inner corrugated line being 1.8 cm. To account for the increased flow impedance due

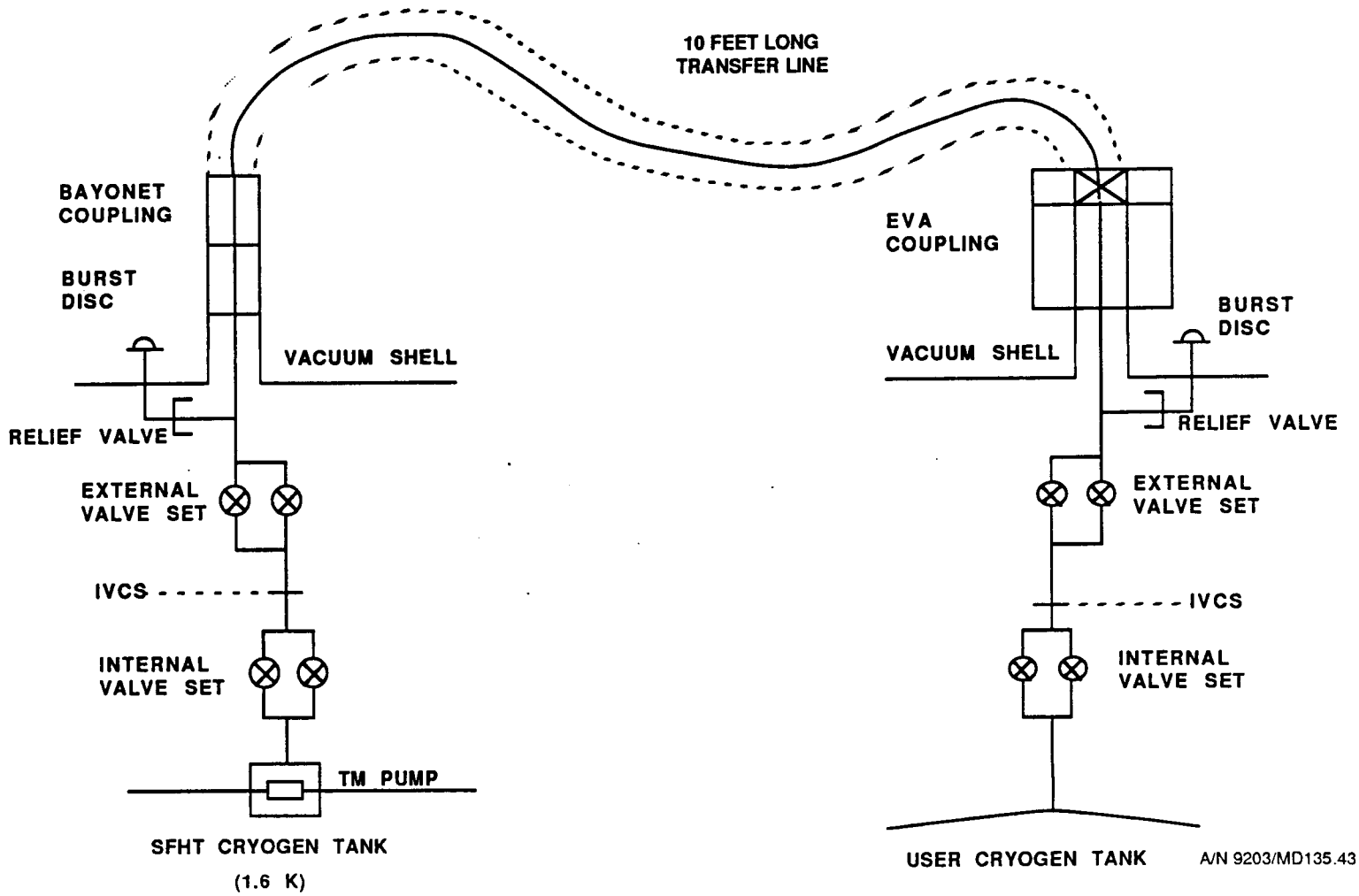


Figure 4-8 Transfer system plumbing schematic

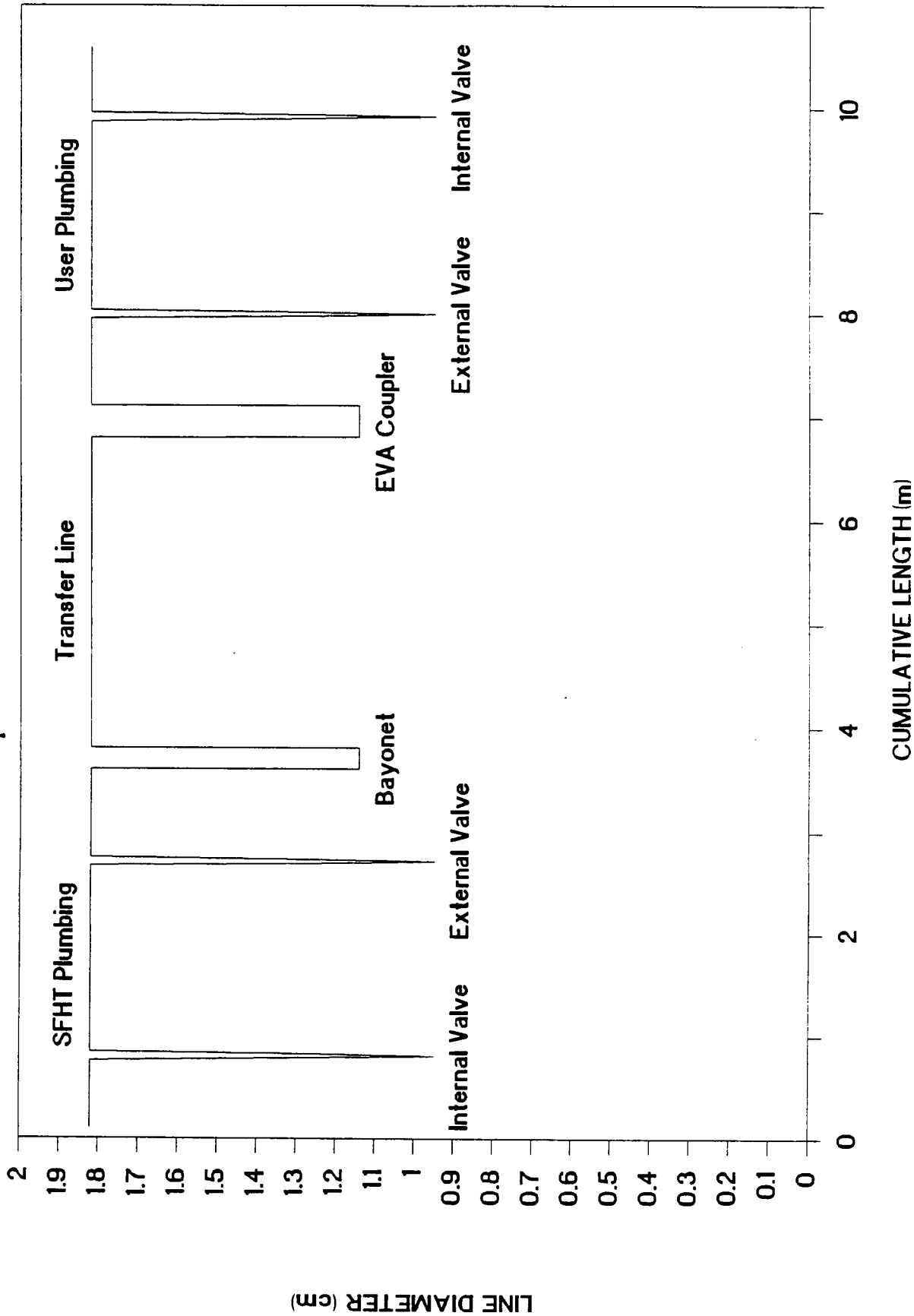


Figure 4-9 Transfer system diameter profile



to the corrugation, the flexible line was modeled as being 10 times longer than its actual length<sup>25,28</sup>. The impedance of the flexible line could be lowered by incorporating a liner inside the corrugated line. As results of the analysis show, however, the pressure drop through the flexible line is a small part of the total, and this may not be necessary. Inside diameters of the EVA coupling and bayonets are 1.12 cm, with appropriate equivalent lengths of smooth 1.8 cm tubing used in the model.

The porous plug modeled is identical to that baselined for the SHOOT experiment with a nominal pore size of 0.5  $\mu$ . The plug surface area is 200 cm<sup>2</sup>, and the thickness is taken to be 1.2 cm. The plug is modeled as a 16 cm diameter disk, although a cylinder with identical surface area would perform essentially the same. The heater section succeeds the porous plug with the electrical element 0.5 mm off the plug face (Figure 4-10). The heater is modeled as a 16 cm diameter section of line tapered down to the 1.8 cm line diameter of the SFHT plumbing with electrical heating over a length of 5 mm.

There are several sources of heat input to the transfer system, as shown below.

0.8 W -	EVA coupling
0.5 W -	Bayonet coupling
0.5 W/m -	Flexible transfer line (3 m)
0.5 W -	External valve (each)
0.5 W -	Inner VCS (each)
0.15 W -	Warm relief line (each)
<u>5.1 W</u>	Total heat input

The levels of heat input shown are low, but achievable. The 0.8 W for the EVA coupling is the goal of the on-going coupling development program under contract from NASA/JSC. The 0.5 W for the bayonet is about twice as good as currently available commercial units; this level of heat leak is achievable with careful design and construction. The transfer line heat leak of 0.5 W/m is about twice as good as currently available vacuum-jacketed flexible lines. A heat leak of 0.5 W/m is achievable for a carefully fabricated vacuum-jacketed line or for a flexible line that is foam-insulated rather than vacuum-jacketed. With ground and flight operations as we envision, the SFHT transfer line need work only in a vacuum environment and that a heavy vacuum jacket is therefore not required. The last three heat inputs shown depend on configurational details of the plumbing system.

#### 4.4.3 Transfer Analysis Results

The transfer model was run for two operating conditions: full flowrate (1,000  $\ell$ /hr) and minimum flowrate (70  $\ell$ /hr). A maximum flowrate of 1,000  $\ell$ /hr was established as a study goal by the statement of work. Our analysis indicates that even higher flowrates are achievable with no deleterious impacts on the SFHT cost or development risk. The minimum flowrate is defined to be either (1) that existing with no pump heater power, as long as the flow remains superfluid or (2) that required to prevent the flow from going normal, using pump heater power. The minimum flowrate level is dictated by the overall flow impedance and heat input of the transfer system. Although transition to normal flow within the transfer system is physically



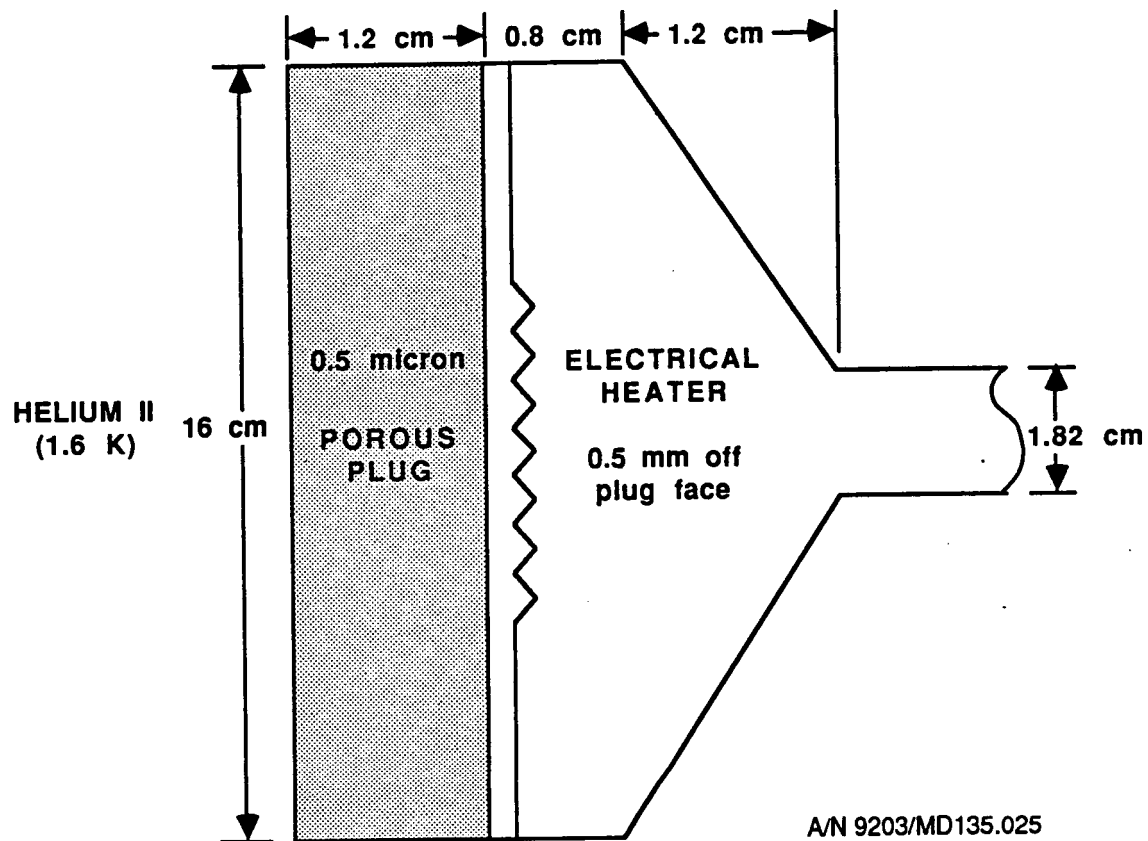


Figure 4-10 Thermomechanical pump configuration



possible, it is difficult to analyze and may be an unstable condition. The minimum achievable flowrate is of interest because low flowrate is desirable for efficient user cooldown and for fill of small users.

Full-Flow Condition - A summary of the predicted full-flow condition is given in Table 4-6. The most direct indicator of transfer efficiency is the fluid temperature rise, which is 0.20 K; this is adequate considering that the user fluid mass loss during the subsequent bath pumpdown is about 1 percent for each 0.1 K of bath temperature reduction. For example, if helium is transferred to the user at a temperature of 1.8 K, then 2 percent of the bath is lost in pumping down to 1.6 K. The pump heater power required to generate the 1,000  $\ell$ /hr flowrate is 28.5 W.

Profiles of temperature, pressure, and conducted heat flux along the transfer system are shown in Figures 4-11, 4-12, and 4-13. Slightly more than half of the total temperature rise takes place in the pump plug. Most of the remainder takes place from the SFHT external valve to the user external valve; almost all the transfer system heat input is along this section. The sharp temperature rise at the exit to the user vessel reflects heat input to the transfer system due to condensation of gas in the user vessel as the liquid volume increases and the ullage shrinks.

The total transfer system pressure drop is about 34 torr; 24 torr of this occurs in the four valves, and most of the remainder is in the corrugated transfer line. Since a TM pump can produce a driving pressure of several hundred torr, pressure drop is an issue only because of the corresponding temperature rise.

The heat flux shown is that described by the Gorter-Mellink relationship; it is zero for a normal fluid. The heat flux to the pump is about 0.5 torr, which is small compared to the electrical heater power. At lower flowrates its effect on the pump operation and the heater power required to produce a given flowrate becomes greater. As may be seen, the heat flux into the transfer system from condensation of vapor in the user vessel is about 2.5 W, corresponding to a flowrate of 1,000  $\ell$ /hr. This is actually a specified boundary condition of the model.

Minimum-Flow Condition - Heat conducted to the TM pump through the fluid from the warm transfer system is sufficient to initiate flow; this has been observed by experimenters at BASG and by others during superfluid helium transfer testing. If the impedance and heat input of the transfer system are small enough, superfluid helium can be transferred to a receiver vessel without applying electrical heater power to the pump. This might be thought of as a "self starting" capability, which is desirable, but probably not necessary. Self starting will occur if the heat conducted upstream to the pump produces a flowrate high enough to prevent the parasitic heat input from raising the temperature of the fluid in the transfer system above the lambda point.

The model was run with successively lower heater power until the fluid temperature at the user came up to the lambda point. The condition at which this occurred is shown in the heat flux, temperature, and pressure profiles of Figures 4-14, 4-15, and 4-16. A summary of pump operating parameters is given in Table 4-6. The resultant electrical power required is 1.1 W, and



Table 4-6  
RESULTS SUMMARY

	<u>FULL-FLOW CASE</u>	<u>MINIMUM-FLOW CASE</u>
• FLOWRATE	1,000	70ℓ/hr
• SUPPLY TEMPERATURE (SFHT)	1.6	1.6 K
• RECEIVER TEMPERATURE	1.80	2.177 K
• PUMP HEATER POWER	28.5	1.1 W
• HEAT INPUT TO PUMP	28.9	1.9 W
• PRESSURE RISE AT PUMP	41.5	29.4 torr
• BACKFLOW FROM PUMP	4.1	0.4 W
• SFHT VENT RATE	1.4	0.1 g/s

the flowrate is 70 ℓ/hr. The transfer system pressure drop in this case is a relatively small 0.16 torr, corresponding to the low flowrate.

Results indicate that it may be difficult to design a system of this size to be self starting. When operation evolves to automatic, the commercial bayonet and transfer line would be eliminated. This would result in reduced heat input to the transfer system and secondarily in reduced flow impedance. These changes would promote self starting, which would simplify the startup operation somewhat. The alternative is to power the electrical heater to a predetermined low level at some appropriate point of the start-up process. Without further analysis, the difficulties involved in the start-up process, especially regarding the control system, are not well understood.

#### 4.4.4 Conclusions from Transfer Analysis

Although a major objective of the modeling effort has been accomplished with the verification of the recommended transfer system, it should in no way be construed as an optimum design. It is, in fact, a step on the way to understanding the behavior of superfluid helium during the course of the transfer operation. The modeling effort has provided considerable insight into the parameters that impact system performance. It has also opened the door to some unanswered questions that are beyond the scope of this particular task.

The following conclusions can be drawn:

- It is feasible to establish a 1,000 ℓ/hr flowrate (and greater) in a system of this size. It would actually be easier if the system were smaller.
- Minimizing parasitic heat input to the transfer system is important. It not only minimizes the fluid temperature at the receiver; it also sets the lower limit on superfluid flowrate. This second point is important because a low flowrate is desirable to achieve high efficiency during user cooldown. If a high flowrate must be used during cooldown, there will likely be a resultant fluid mass penalty.
- The start-up process must be better understood. It appears that if the parasitic heat input to the transfer system is



TEMPERATURE  
System

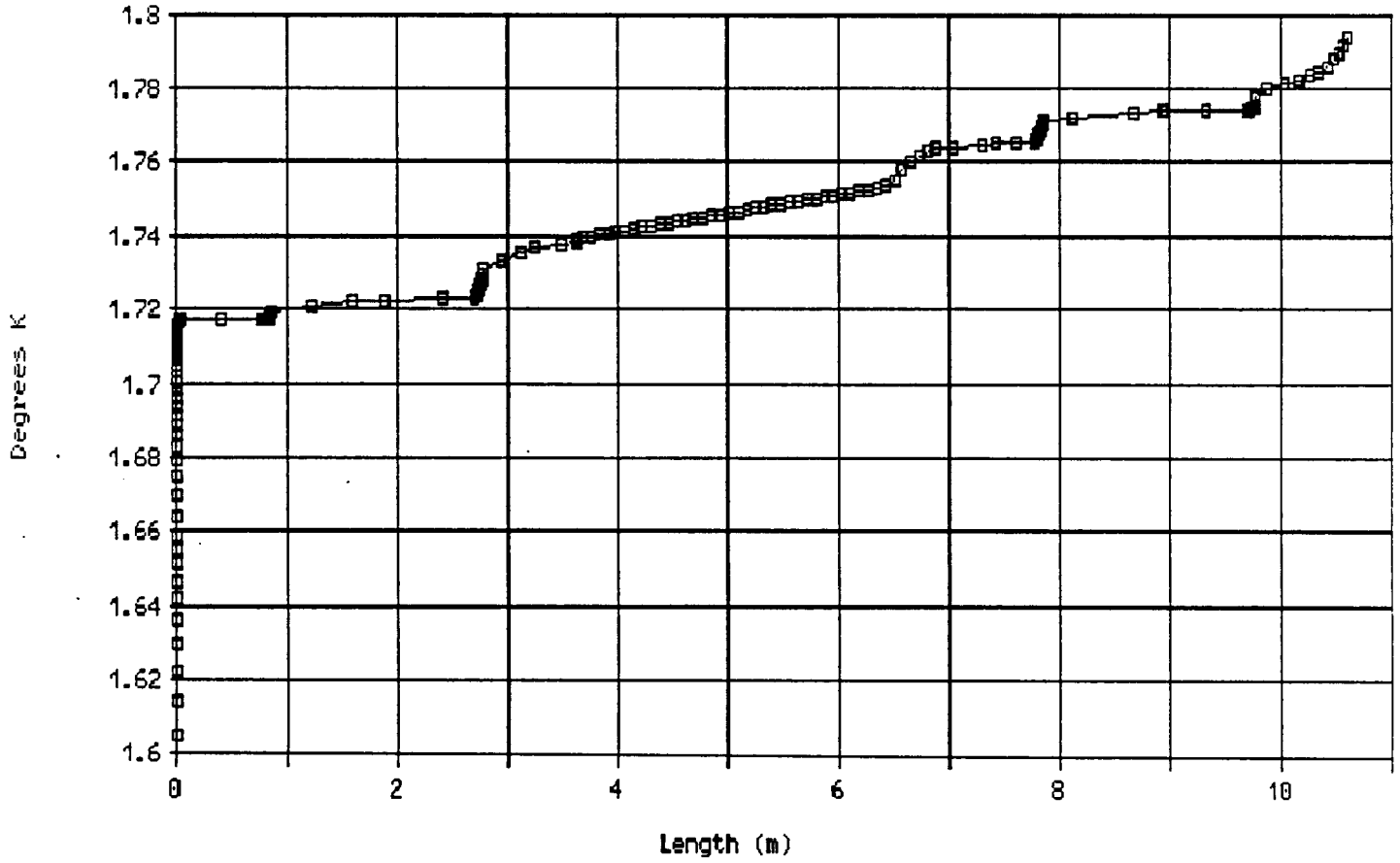


Figure 4-11 Full-flow (1,000 l/hr) temperature profile

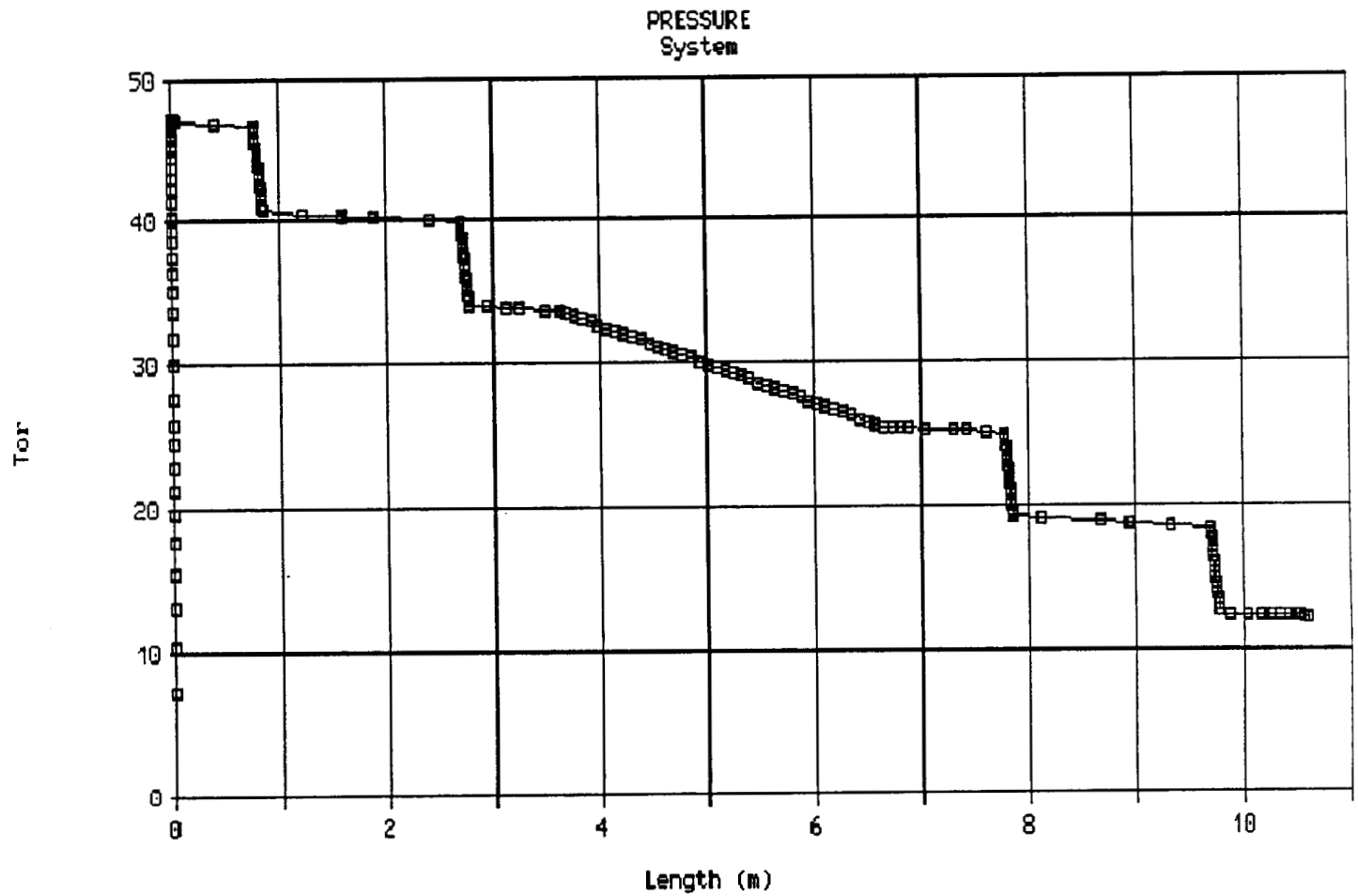


Figure 4-12 Full-flow (1,000  $\ell$ /hr) pressure profile

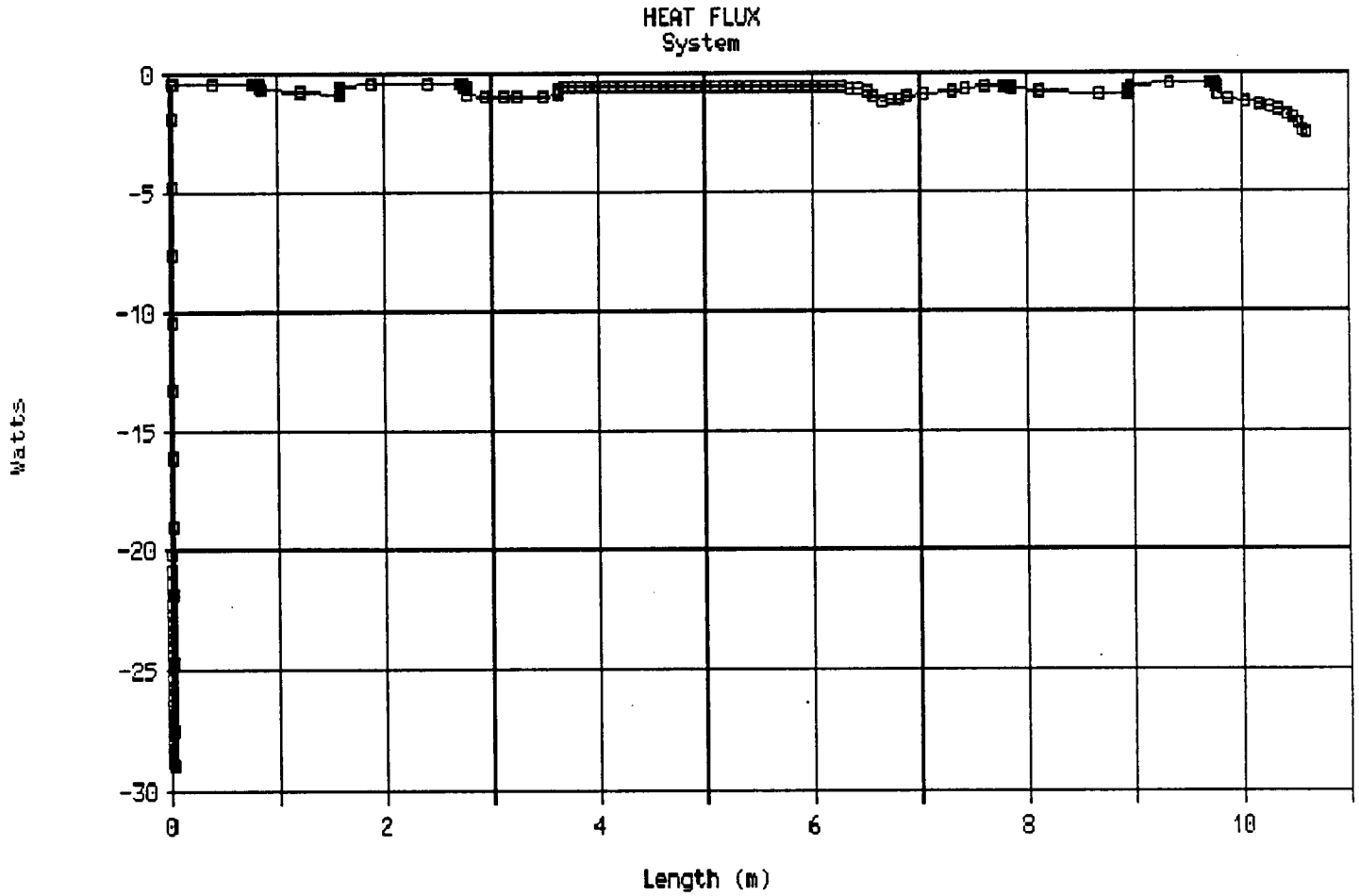


Figure 4-13 Full-flow (1,000 l/hr) heat flux profile

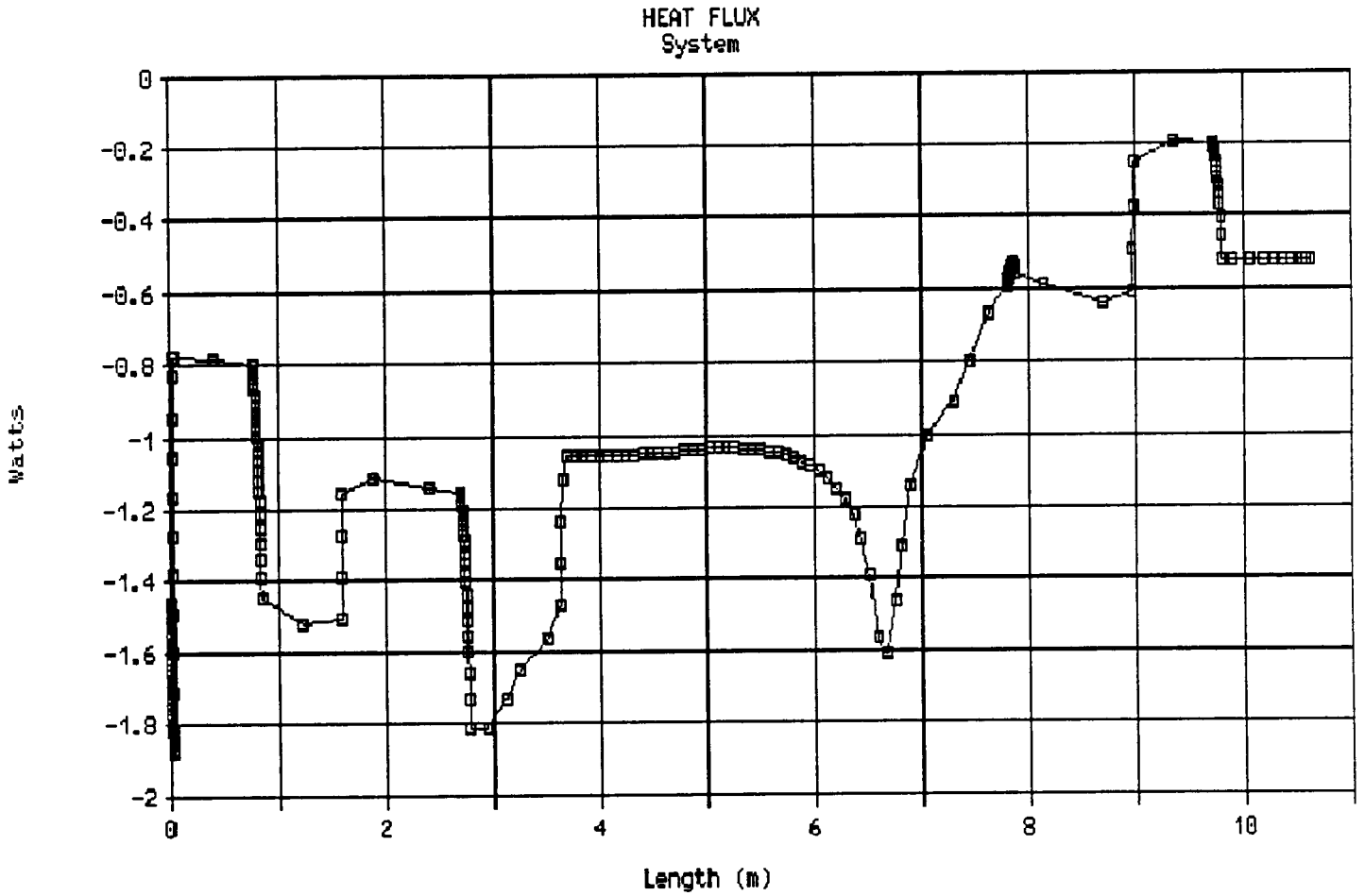


Figure 4-14 Minimum-flow (70 l/hr) heat flux profile

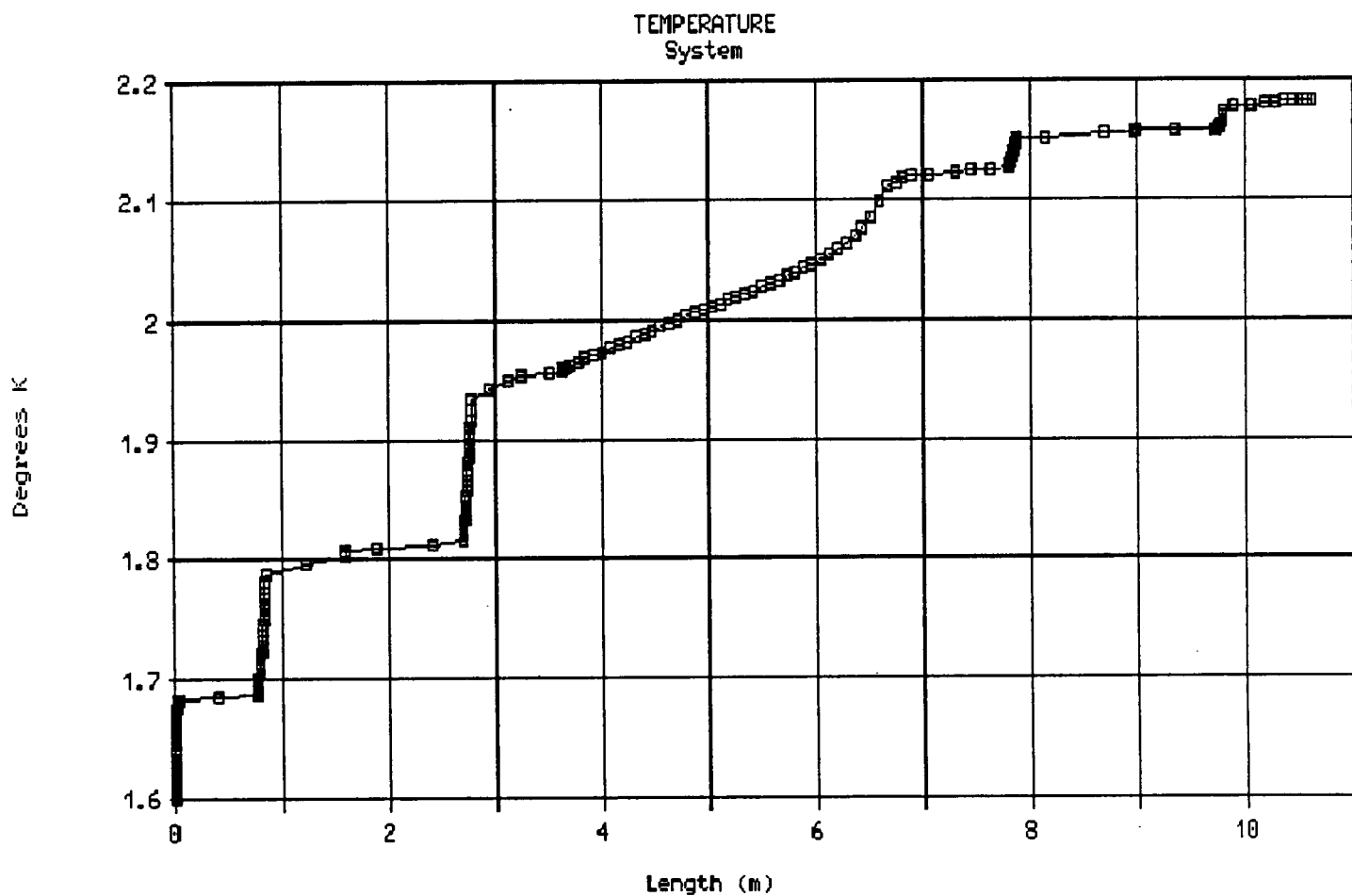


Figure 4-15 Minimum-flow (70 l/hr) temperature profile



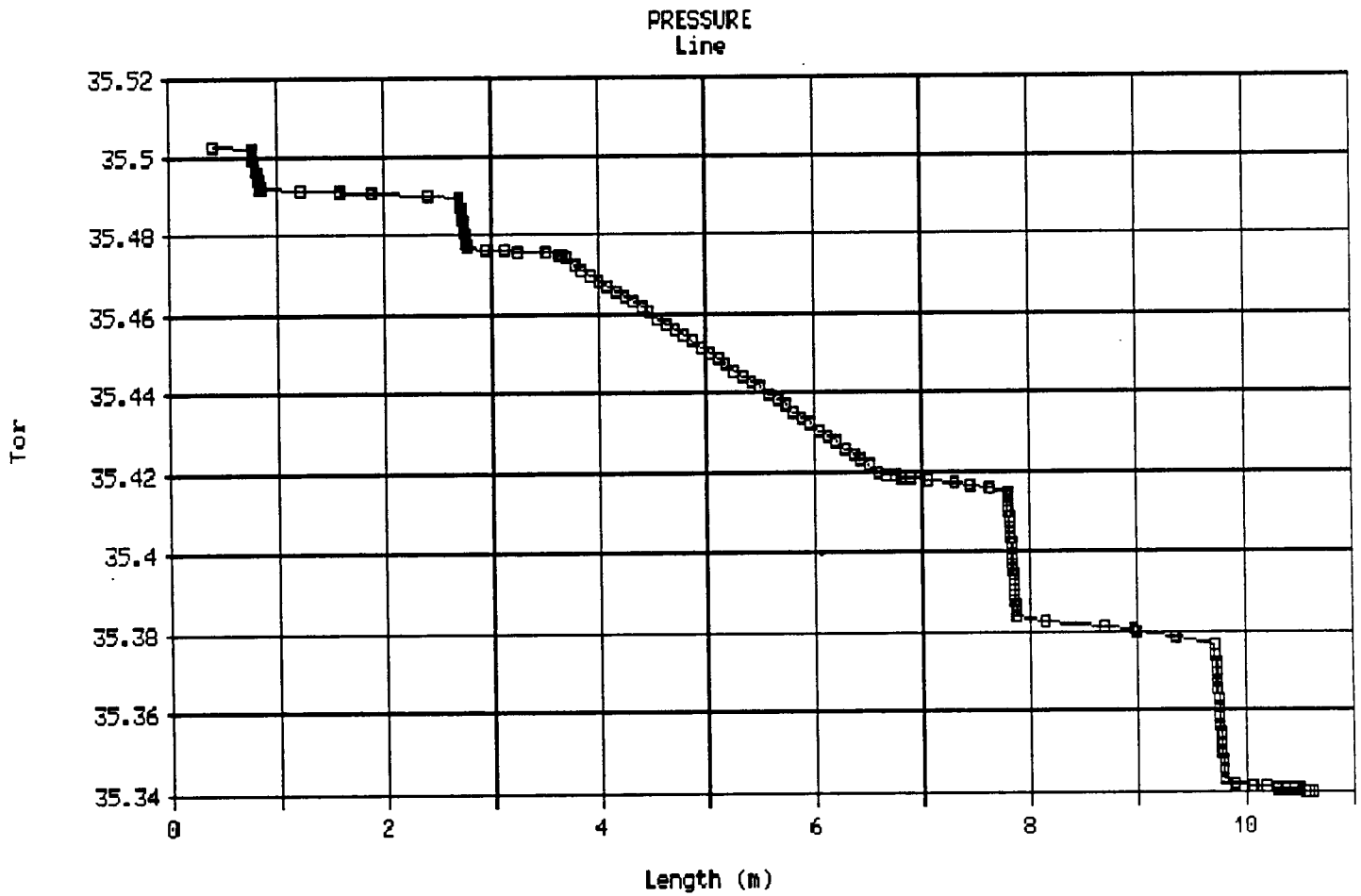


Figure 4-16 Minimum-flow (70 l/hr) pressure profile



below a certain threshold, then start-up will happen without pump heater power. However, for greater parasitic heat input, the pump heater must be turned on at some point of the start-up process. Exactly when this should be done and how critical the timing is remains uncertain without further analysis.

Section 5  
COMMONALITY ISSUES

Table 5-1 lists all the components used in the SFHT. An evaluation was made to determine if these components could be used as is or modified for use in tankers for other cryogenes. Many components would not be compatible without modification or unless a course of action was taken to accommodate the other cryogenes in the initial design of the SFHT.

Table 5-1  
ASSESSMENT OF USE OF SFHT ELEMENTS ON SUBCRITICAL/SUPERCritical TANKERS

<u>Item</u>	<u>Component</u>	<u>Applicable To Other Cryogenes</u>	<u>Technical Difficulties With Using With Other Cryogen</u>
1.	Thermomechanical Pump	No	Will only work with SfHe
2.	Motor operated Valve	Yes	Acceptable for use, operating pressure may be an issue
3.	Transfer Lines	Yes	Acceptable for use, operating pressure may be an issue
4.	Bayonets	Yes	Acceptable for use, operating pressure may be an issue
5.	Mass Quantity Sensor - Heat Pulse	No	Will only work with SfHe
6.	Flowmeter-Standby Vent	No	Measurement of flow heat capacitance works best at very low temperature. Method might work for low pressure systems such as solid hydrogen or neon. Will only work with SfHe
	Flowmeter-Transfer	No	
7.	Liquid Level Sensor -Superconducting Wire	Yes	Redesign required for use with other cryogenes (use of higher temperature superconductor required)
8.	Liquid Acquisition Device	Yes	Redesign required for use with other cryogenes because of different capillary action
9.	Porous Plug Phase Separators	No	Use TVS with other cryogenes
10.	Avionics	Yes	Acceptable for use with software modification
11.	Relief Valve	Yes	Acceptable for use, operating pressure may be an issue



Table 5-1

ASSESSMENT OF USE OF SFHT ELEMENTS ON  
SUBCRITICAL/SUPERCritical TANKERS (Continued)

<u>Item</u>	<u>Component</u>	<u>Applicable To Other Cryogen</u>	<u>Technical Difficulties With Using With Other Cryogen</u>
12.	Burst Disc	Yes	Acceptable for use, operating pressure may be an issue
13.	Electrical Connector	Yes	Acceptable for use, operating pressure may be an issue
14.	Electrical Feedthrough	Yes	Acceptable for use, operating pressure may be an issue
15.	Low Thrust Vent	Yes	Acceptable for use provided size is right for flow rate
16.	Plumbing	Yes	Acceptable for use, operating pressure may be an issue
17.	EVA Coupler	Yes	Acceptable for use, operating pressure may be an issue
18.	Germanium Resistance Thermometer	Yes	Acceptable for use up to a temperature of 40 K (hydrogen and neon)
19.	Silicon Diode Thermometer	Yes	Operating temperature range is probably acceptable for most applications with other cryogen
20.	Pressure Transducer	Yes	Acceptable for use, operating pressure may be an issue
21.	Triaxial Accelerometer	Yes	Acceptable for use, operating range may be an issue
22.	Strain Gauges	Yes	Acceptable for use, operating range may be an issue
23.	Ion Gauge	Yes	Acceptable for use
24.	Cryogen Tank Support Straps	Yes	Other cryogen, except hydrogen, are more dense requiring stronger support straps
25.	Cryogen Tank (CT)	Yes	Supercritical cryogen may require a CT with a much heavier wall because of higher operating pressures. Required quantities of other cryogen may be much different



Table 5-1  
 ASSESSMENT OF USE OF SFHT ELEMENTS ON  
 SUBCRITICAL/SUPERCritical TANKERS (Concluded)

<u>Item</u>	<u>Component</u>	<u>Applicable To Other Cryogen</u>	<u>Technical Difficulties With Using With Other Cryogen</u>
26.	Vacuum Shell	Yes	Must be beefed up for heavier CT
27.	Mechanical cooler	Yes	Potential system mass benefit unknown without thermal analysis. Ground lock-up not a major issue with other cryogens
28.	Pyrotechnic Umbilical Cutter	Yes	Acceptable for use providing line sizes are the same

### 5.1 LIQUID ACQUISITION DEVICE

As part of the commonalty investigation, the LAD configuration appropriate for a 10,000 liter spherical tank containing either liquid oxygen or hydrogen has been determined. This analysis was performed for the study by McDonnell Douglas Astronautics Division, who have extensive experience in the design and use of channel capillary LADs.

The LAD configuration consists of four channel legs, the same as recommended for our baseline SFHT concept, which is discussed in 2.1.4. The legs are joined by a manifold to the pump inlet. The channel cross-section forms an isosceles triangle, 7.5 cm in height and 7.5 cm in basewidth. The base of the triangle, which faces the wall, is made of standard 325x2300 DDTW screen. The screen is 2 cm from the tank wall at all locations.

Figure 5-1 shows the expulsion efficiency of the LAD as a function of adverse acceleration level for storage of oxygen or hydrogen. Performance with both fluids is insensitive to flowrate over the range from 10 to 100 percent of tank fluid capacity per hour. A residual of 2 percent is achieved for acceleration levels up to 0.1 g, well above the expected frequent disturbances of the resupply environment. The slightly lower performance with oxygen is attributable to the lower ratio of surface tension to density of oxygen (i.e.,  $1.27 \times 10^{-5}$  compared to  $1.95 \times 10^{-5}$ ).

In summary, the overall configuration of the LAD for use with liquid oxygen or hydrogen can be very similar to the device needed for SfHe. Therefore, with careful thought the mounting bracketry and overall structural design of the LAD could be identical for the three fluids. However, as discussed in 2.1.4, the physics behind operation of the LAD with SfHe, and therefore the details of the screen (or porous material), are unique compared to normal fluids.

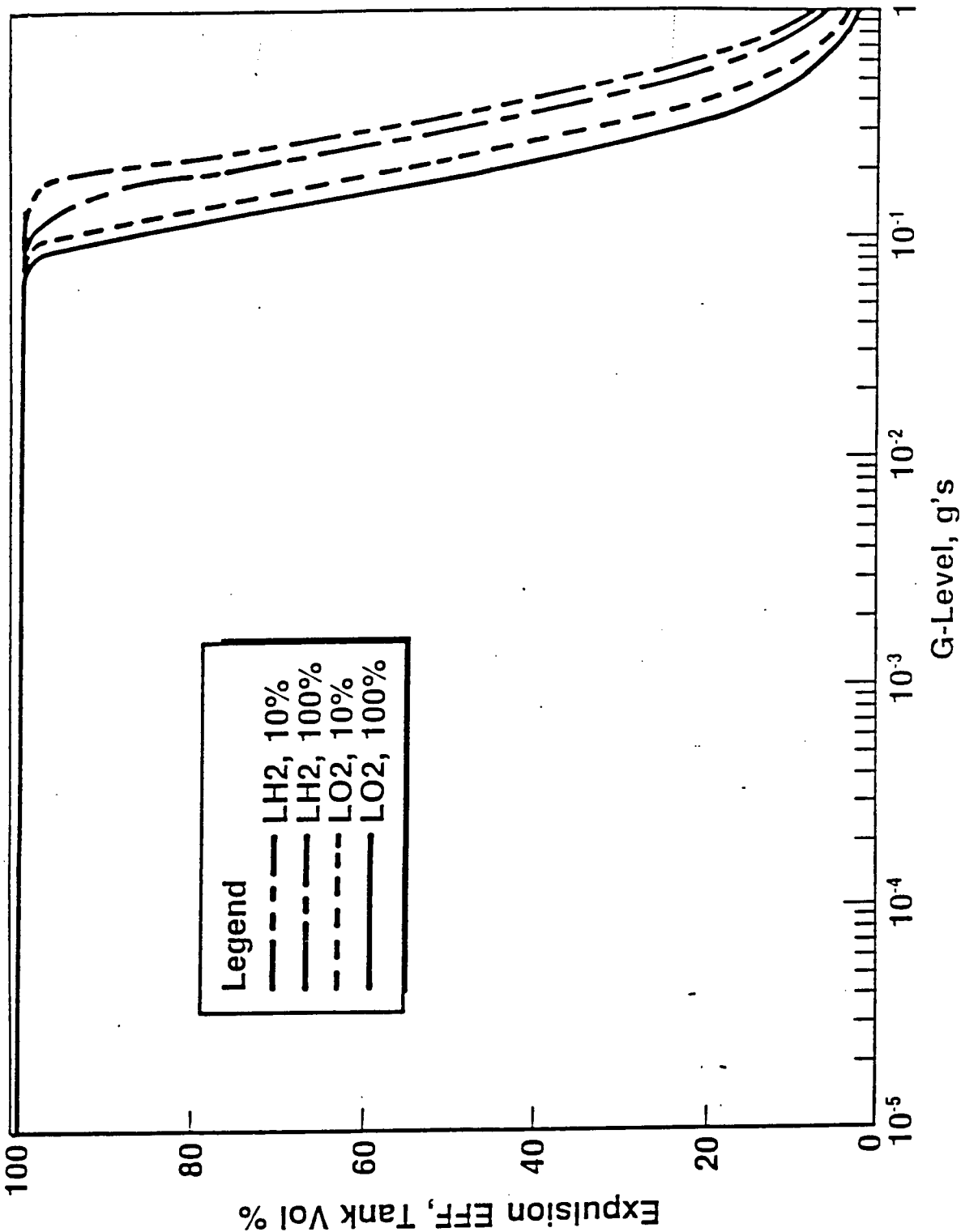


Figure 5-1 LAD performance in oxygen and hydrogen for outflow rates of 10 and 100 percent of tank volume per hour



Section 6  
TECHNOLOGY DEVELOPMENT

An assessment was made to determine the technology development status of all the components used on SFHT. This assessment is presented in Table 6-1. The development status is based on the criteria for Development Status and Criticality shown at the bottom of the table. Criticality is a judgment based on the need for that component to complete the mission. The cost and schedule has been noted for those hardware items requiring further development. Comments have been included to explain why development is required and to give a history of successful use of the proposed components.



Table 6-1  
DETERMINING SFHT TECHNOLOGY DEVELOPMENT REQUIREMENTS

<u>ITEM</u>	<u>COMPONENT</u>	<u>ORBITAL TESTING REQUIRED</u>	<u>DEV. STATUS</u>	<u>DEV. COST</u>	<u>DEV. SCHED</u>	<u>EXPLANATORY/COMMENTS</u>
1.	Thermomechanical Pump	Yes	2A		SHOOT	Learn more about auto control and operational limitations.
2.	Motor-operated Valve	No	5A		SHOOT	SHOOT 3/4-in. and 1/2-in. valve acceptable.
3.	Transfer Lines	No	3B	\$200K	6 mo	Lower heat leak than 1 W/m planned for SHOOT desirable.
4.	Bayonets	No	3B	\$100K	6 mo	Lower heat leak than 1.0 W of IRAS/CODE desirable.
5.	Mass Quantity Sensor - Heat Pulse	Yes	4B		SHOOT	SHOOT design needs to be sized for SFHT.
6.	Flowmeter-Standby Vent	No	3C	\$100K	6 mo	Steady-state heat capacity design (at 2 K) should work well.
	Flowmeter-Transfer	No	4C		SHOOT	Flowmeter not baselined. Flow determined from temperature in and out of TM pump and downstream pressure. SHOOT is using venturi-type meter.
7.	Liquid Level Sensor - Superconducting Wire	No	4C			Same as IRAS/CODE.
8.	Liquid Acquisition Device	Yes	1A		SHOOT	Major technology development item. Baseline is distributed porous medium using TM effect to draw Sflle in. Analysis and ground test will help, but orbital testing is a must. SHOOT may not provide all the answers.





Table 6-1  
DETERMINING SFHT TECHNOLOGY DEVELOPMENT REQUIREMENTS (Continued)

<u>ITEM</u>	<u>COMPONENT</u>	<u>ORBITAL TESTING REQUIRED</u>	<u>DEV. STATUS</u>	<u>DEV. COST</u>	<u>DEV. SCHED</u>	<u>EXPLANATORY/COMMENTS</u>
9.	Porous Plug Phase	No	4A	\$300K	1 yr	Flown on IRAS and on two Spacelab experiments, but high flow vent of SFHT must operate at much higher flow rates. Ground test verification needed. SHOOT should verify.
10.	Avionics	No				Current state-of-the-art technology can be used during SFHT development. Considerable software development needed, specifically for SFHT
	• Flat panel display and switch panel		2B			
	• Dewar computer, expert system software and valve drive unit		3A			
	• APD computer software and majority vote unit		4A			
	• Switch panel and power distribution unit		5A			
11.	Relief Valve	No	5A			
12.	Burst Disc	No	5A			CODE/SHOOT design.
13.	Electrical Connector	No	5A			
14.	Electrical Feedthrough	No	5A			
15.	Low Thrust (LTV)	No	4A			Loose requirement, should be simple design.
16.	Plumbing	No	5A			
17.	EVA Coupler	Yes	2A		SHOOT	JSC developing coupling for SHOOT.
18.	Germanium Resistance Thermometer	No	5A			
19.	Silicon Diode Thermometer	No	5B			



Table 6-1  
DETERMINING SFHT TECHNOLOGY DEVELOPMENT REQUIREMENTS (Continued)

<u>ITEM</u>	<u>COMPONENT</u>	<u>ORBITAL TESTING REQUIRED</u>	<u>DEV. STATUS</u>	<u>DEV. COST</u>	<u>DEV. SCHED</u>	<u>EXPLANATORY/COMMENTS</u>
20.	Pressure Transducer	No	5B			PT part of transfer rate measurement. Siemens KPY12 (piezo-electric) and Validyne DPI0 (reluctance) gages have been used at 2K in laboratory and SHOOT is using Validyne in venturi flowmeter.
21.	Triaxial Accelerometer	No	5C			
22.	Strain Gages	No	5C			
23.	Ion Gage	No	5C			
24.	Pressure Vessel Support Straps	No	3A			Fiberglass/epoxy straps have been flown on IRAS/COBE. Alumina/epoxy straps have been fabricated and tested for fatigue strength and thermal conductivity. Development of flight items is straightforward.
25.	Cryogen Tank (CT)	No	4A			
26.	Vacuum Shell	No	4A			
27.	Mechanical Cooler	No	3B	\$2M	1 yr	British Aerospace Stirling cycle cooler with 1 W @ 93 K cooling power is space qualified for flight on VARS. Same units are baselined for AXAF/XRS. Direct technology extension will provide three times greater cooling power, as baselined for SFHT. Re-qual needed.

Table 6-1  
 DETERMINING SFHT TECHNOLOGY DEVELOPMENT REQUIREMENTS (Concluded)

<u>ITEM</u>	<u>COMPONENT</u>	<u>ORBITAL TESTING REQUIRED</u>	<u>DEV. STATUS</u>	<u>DEV. COST</u>	<u>DEV. SCHED</u>	<u>EXPLANATORY/COMMENTS</u>
28.	Pyrotechnic Umbilical Cutter	No	3A			Similar items are space qualified. (Pyrotechniks, Inc.)
29.	Thermal Switch	No	2B	\$100K	6 mo	The concept of passive thermal switching based on differential thermal contraction is simple and has been demonstrated for levels of heat flow somewhat lower than needed for SFHT.



RANGE OF DEVELOPMENT STATUS

- |    |  |    |        |
|----|--|----|--------|
| 1. | Feasible in Theory                       | A. | High   |
| 2. | Working Laboratory Model                 | B. | Medium |
| 3. | Based on Existing Nonflight Engineering  | C. | Low    |
| 4. | Extrapolated from Existing Flight Design |    |        |
| 5. | Proven Flight Design                     |    |        |



## Section 7 PROGRAM PLAN

This section defines a preliminary program plan for development and certification of the SFHT system and associated GSE described in Section 2. The plan assumes one protoflight SFHT system with spares only at the component level and one set of GSE, also with only component spares.

### 7.1 HARDWARE TO BE DEVELOPED

In addition to the flight hardware and its GSE, special test equipment, training equipment, and production tooling must be developed. The items of development hardware assumed for construction of the program plan are summarized below.

SFHT Flight System - Two major subsystems, the dewar and the avionics, comprise the SFHT, as shown in Figure 7-1. The subassemblies of the two are shown in the figure. Almost all of the technology development risk is associated with the dewar and its operations.

Ground Support Equipment - As described in Section 2.3, the GSE is comprised of three categories of equipment: mechanical (handling), (cryogenic operations), and monitor/control. Development of this complex set of equipment is an important part of the SFHT program. The most significant items of GSE are the 15,000  $\ell$  supply dewars. Two are needed, and they must operate at negative pressure to perform the low pressure toff of the SFHT.

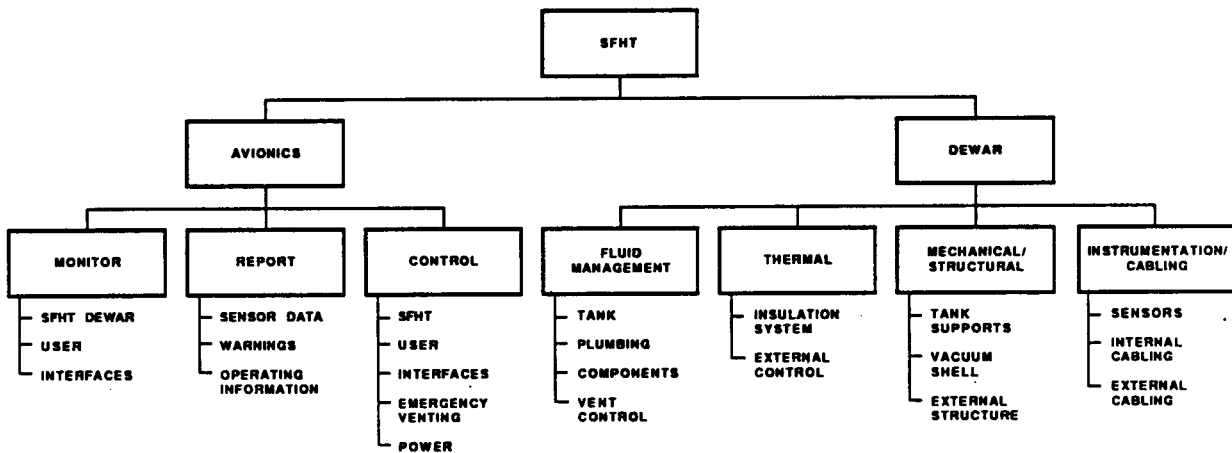
Special Test Equipment (STE) - There are four items of STE. First is a test dewar to be used for verifying the SFHT transfer operations. This dewar may be relatively small (e.g., 500  $\ell$ ) and must interface with the SFHT fluid subsystem. It must have appropriate internal valving and a high conductance vent similar to the orbital resupply users. It is not necessary to include the EVA coupling in the transfer system performance verification, and the fluid couplings of the test dewar will therefore be standard bayonets. GSE transfer lines can probably be used for the test.

The other three items of STE are electronic simulators of 1) the SFHT dewar, 2) the user, and 3) the host vehicle. These will be used for verification of the avionics subsystem before it is mated to the dewar and for final certification of the avionics. These simulators will allow the two SFHT major subsystems, the dewar and the avionics, to be fabricated and certified somewhat independently of each other. The two will be mated and verified as a total system only after they have each been fully verified as a subsystem. This approach will minimize schedule risk factors related to the complex end-item testing required for the two subsystems, especially that of the dewar.

Training Equipment - An avionics simulator will be provided for astronaut training that duplicates human interfaces and control functions of the flight system.



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Figure 7-1 SFHT flight hardware breakdown



Production Tooling - During fabrication and assembly of the dewar, carefully designed production tooling is required. These include holding fixtures for automatic welding, holding fixtures for fabrication of subassemblies such as plumbing manifolds, templates for MLI cutting, fixtures for assembly of vapor-cooled shields, a cryogen tank holding fixture for MLI layup, proof test fixtures, etc.

## 7.2 PROGRAM SCHEDULE

The development program schedule is shown in Figure 7-2. The 5.5 year phase C/D is preceded by a phase B study. The preliminary design review is shown 1 year after contract start. To maintain the planned schedule, it is essential that critical long-lead procurements, such as spinnings for the cryogen tank, be initiated immediately after the PDR. The extensive dewar subsystem testing is reflected by the estimated 9 month test duration.

## 7.3 RISK

Critical technology development issues are discussed in Section 6. The most critical area is the transfer system, especially the liquid acquisition device and understanding of the transient aspects of the transfer operation, particularly the startup process. The SHOOT program will provide many of the answers, but, because the SFHT is considerably larger, it is likely that further development testing guided by the results of the SHOOT experiment will be needed. The schedule of Figure 7-2 shows component development starting during the phase C/D preliminary design stage.

## 7.4 MAKE-OR-BUY PLAN

Preliminary make-or-buy decisions for the major components are shown below:

BUY	Spinnings for the cryogen tank, vacuum shell, and VCSs
BUY	Forging for the vacuum shell girth ring
EITHER	Machining of cryogen tank and girth ring
BUY	Support straps
BUY	Motor-operated valves
BUY	Mechanical cooler and electronics
BUY	EVA coupling
BUY	Electronic parts/instrumentation
MAKE	Thermal switch
MAKE	Low flowrate flowmeter
MAKE	Avionics electronics boxes
MAKE	Dewar exit cable assemblies
MAKE	Liquid acquisition device
EITHER	15,000 ℓ supply dewars
BUY	Transfer lines, bayonet couplings

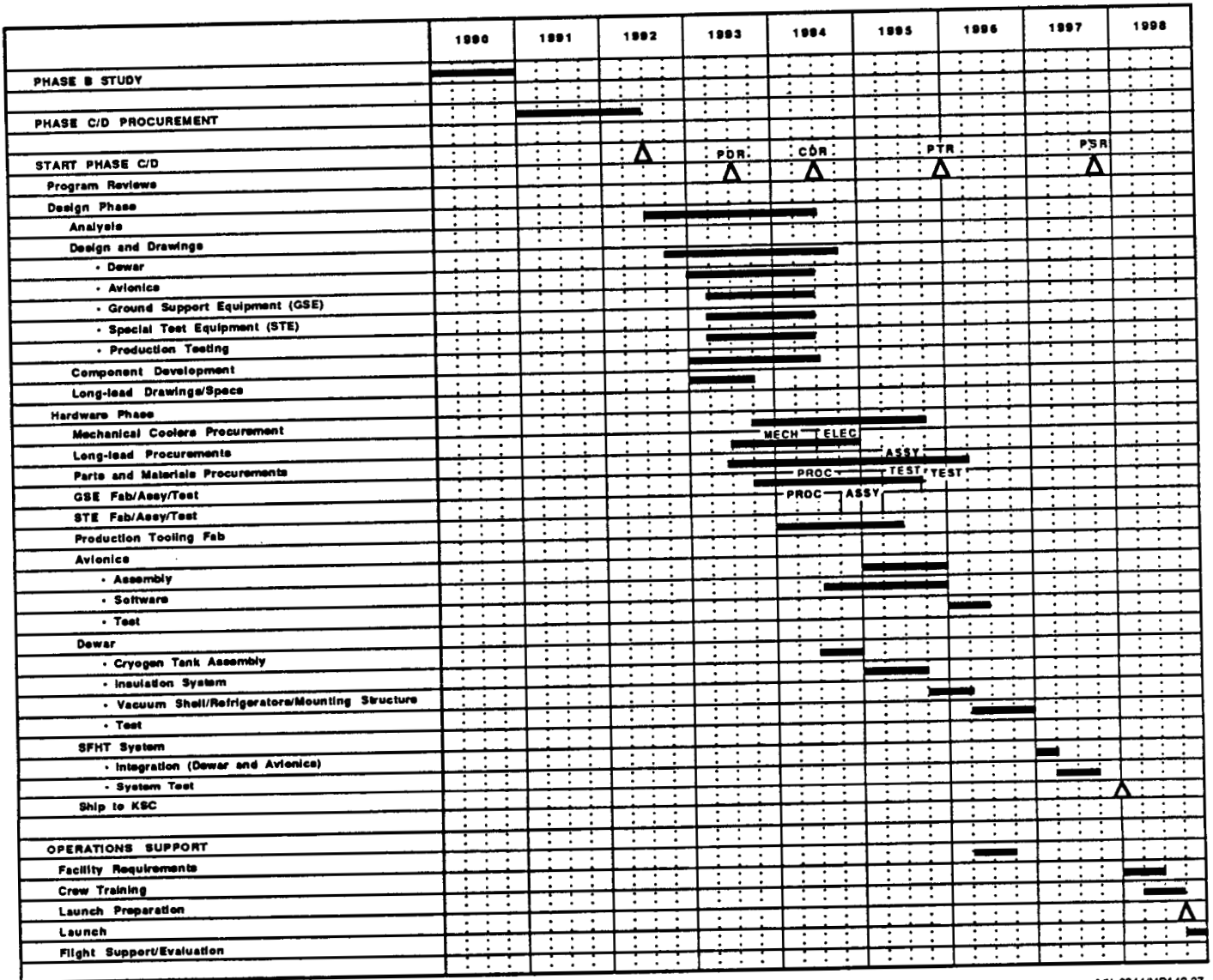
## 7.5 LONG-LEAD PROCUREMENTS

Critical long-lead procurements are:

- Spinnings for the cryogen tank, vacuum shell, and VCSs
- Girth ring forgings/machinings
- Support straps



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Figure 7-2 SFHT program schedule



- Motor-operated valves
- Electronic parts
- EVA coupling
- Mechanical cooler
- 15,000 ℓ supply dewars
- Liquid level sensors

Criticality is based on a combination of estimated delivery schedule and need date in the fabrication schedule. For example, items associated with the cryogen tank, which is the first major subassembly on the program critical path, have high criticality.

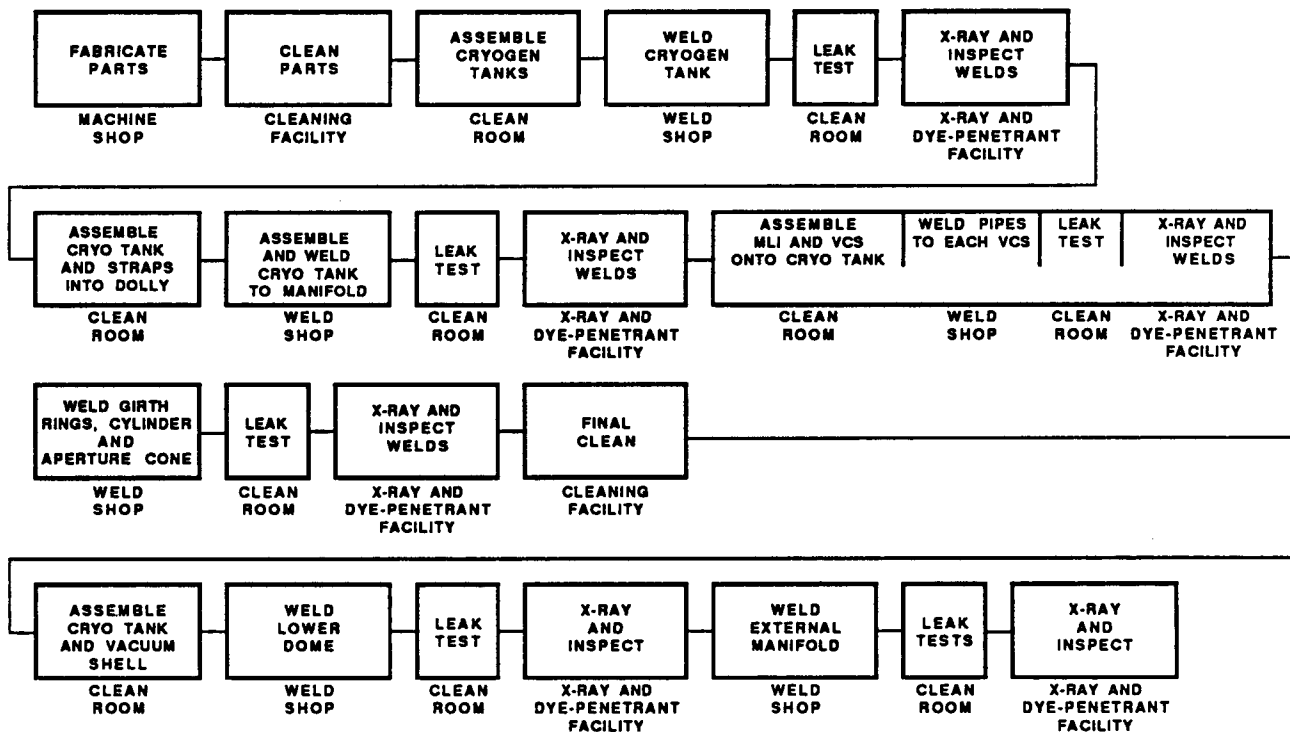
## 7.6 FACILITIES

Figure 7-3 shows the flow of the SFHT dewar fabrication process and the facilities required. BASG has all the facilities needed for fabrication and test of the SFHT system.





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Figure 7-3 SFHT dewar manufacturing process and facility usage



Section 8  
CONCLUSIONS AND RECOMMENDATIONS

A SFHT design concept has been recommended that meets all mission requirements using low-cost and low-risk approaches. The all-aluminum, 10,000 lb spherical dewar will perform a warm SIRTf resupply at either the shuttle or the space station (after a 9-month standby). The insulation system design is optimized to provide minimum launch mass based on the 9-month standby requirement; mechanical coolers are used to cool the dewar outer VCS during the extended SS standby.

An oblate spheroid configuration was investigated to see if it would reduce shuttle launch cost; it has essentially the same launch cost and thermal performance as the spherical dewar, which is 1,600 lb lighter. It requires about 19 in. less shuttle bay length, providing better manifesting flexibility. Although the spherical shape has been selected as the baseline, there is not a strong preference.

The study has emphasized the areas of technology risk, which center around the fluid subsystem design and operations. Technology development is needed for the follow-on automatic system, but only a cursory consideration of those items was appropriate within the scope of this study. When the SFHT hardware is developed, state-of-the-art, space-qualified technology will be used for the avionics. Therefore, little study effort was spent on this topic. Regarding avionics, the study was more concerned with assuring that SFHT power and data requirements are compatible with shuttle and SS resources. Considerable software development will be required for the avionics "smart" computer system.

BASG has a proven capability for designing and fabrication spaceborne dewars with high thermal performance. Although this is not a technology risk area, considerable study effort was spent on providing valid mass and thermal performance estimates for the dewar. This was necessary to make legitimate configuration tradeoffs and plan operations, both ground and flight. Also, minimizing the parasitic heat input to the cryogen tank will minimize the SfHe bath temperature and maximize the transfer efficiency.

The primary technology development area for the SFHT is the transfer system, consisting of the liquid acquisition device, thermomechanical pump, SFHT plumbing, flexible transfer line, and user plumbing. Demonstration of this system is the main function of the SHOOT experiment. However, there are important scaling factors and detailed design impacts that can only be determined through a rigorous analytical understanding of the system. Regardless of ground component testing and SHOOT flight testing, a valid analytical model of the entire transfer system is required to establish the SFHT design with any confidence. That analytic capability does not yet exist.

Our approach has been to take a very careful end-to-end look at a point transfer system design based on the fundamental physics involved, therefore verifying the feasibility of performing on-orbit superfluid helium resupply. We conclude that it can be done within the imposed design constraints, but the system design and operation must be very carefully planned and verified.



The next step is to construct a comprehensive analytic tool for understanding the system better, particularly the transient aspects of the resupply process.



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