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Superfluid Helium Tanker (SFHT) Study

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Martin Marietta Astronautics Group
Space Systems

FOREWORD

The Superfluid Helium Tanker Study Final Report documents work conducted by Martin Marietta Astronautics Group, Space Systems, Denver, Colorado, under contract NAS9-17854, Superfluid Helium Tanker (SFHT) study. The contract was administered by the National Aeronautics and Space Administration - Johnson Space Center, Houston, Texas. The NASA Project Manager was Mr. William C. Boyd, Propulsion and Power Division. This report summarizes the results of the five SFHT contract tasks:

- Task 1 - Collection of Requirements
- Task 2 - Conceptual SFHT Fluid Subsystem Design
- Task 3 - Conceptual SFHT System Design
- Task 4 - Commonality Assessment and Technology Development
- Task 5 - Program Plan for SFHT Development

This document conforms to the requirements of DRL-6 (DRD-183TJ).

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ABSTRACT

Replenishment of superfluid helium (SFHe) offers the potential of extending the on-orbit life of observatories, satellite instruments, sensors and laboratories which operate in the 2K temperature regime. A reference set of resupply customers was identified as representing realistic helium servicing requirements and interfaces for the first 10 years of superfluid helium tanker (SFHT) operations. These included the Space Infrared Telescope Facility (SIRTF), the Advanced X-ray Astrophysics Facility (AXAF), the Particle Astrophysics Magnet Facility (Astromag), and the Microgravity and Materials Processing Sciences Facility (MMPS)/Critical Point Phenomena Facility (CPPF). We considered a mixed-fleet approach to SFHT utilization -- our 6000 liter tanker concept is compatible with launch on the STS as well as the Delta, Atlas, Titan III or Titan IV expendable launch vehicles. The tanker permits servicing from the Shuttle cargo bay, in-situ when attached to the OMV and carried to the user spacecraft, and as a depot at Space Station.

A SFHT Dewar ground servicing concept was developed which uses a dedicated ground cooling heat exchanger to convert all the liquid, after initial fill as normal fluid, to superfluid for launch. This concept permits the tanker to be filled to a near full condition, and then cooled without any loss of fluid. The final load condition can be saturated superfluid with any desired ullage volume, or the tank can be totally filled and pressurized. The SFHT Dewar and helium plumbing system design has sufficient component redundancy to meet fail-operational, fail-safe requirements, and is designed structurally to meet a 50 mission life usage requirement. Technology development recommendations were made for the selected SFHT concept, and a Program Plan and cost estimate prepared for a phase C/D program spanning 72 months from initiation through first launch in 1997.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
ACE	Alabama Cryogenic Engineering (Huntsville, Alabama)
AFD	Aft Flight Deck
APS	Active Phase Separator
ARC	Ames Research Center
ASE	Airborne Support Equipment
ASTROMAG	Particle Astrophysics Magnet Facility
AXAF	Advanced X-Ray Astrophysics Facility
BASD	Ball Aerospace Division (Boulder, Colorado)
BTU	Bus Terminal Unit
C&DH	Command and Data Handling
C&TDB	Command and Telemetry Data Bus
CITE	Cargo Integration Test Equipment
cfm	cubic foot per minute
cg	Center of Gravity
CPPF	Critical Point Phenomena Facility
CPU	Central Processing Unit
CRT	Cathode Ray Tube
CSF	Customer Servicing Facility
CTS	Cryogenic Technical Services (Boulder, Colorado)
EDP	Embedded Data Processor
ELV	Expendable Launch Vehicle
EMU	Extravehicular Mobility Unit
EOS	Earth Observing Satellite
EVA	Extravehicular Activity
FEP	Fountain Effect Pump
FF	Free Flyer
FIRST	Far Infrared/Submillimeter Space Telescope
FTS	Flight Telerobotic Servicer
GFE	Government Furnished Equipment
GPC	General Purpose Computer
GRT	Germanium Resistance Thermometer
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
go	Acceleration due to gravity at Earth's surface
He	Helium
He-I	Normal Helium
He-II	Superfluid Helium
HLVS	Heater, Level Sensor and Valve System
ID	Inner Diameter
IOC	Initial Operational Capability
IOSS	Integrated Orbital Servicing System
IR	Infrared
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrometer
IRT	Infrared Telescope
ISO	Infrared Space Observatory
IVA	Intervehicular Activity
IWFMS	Integrated Waste Fluid Management system
JSC	Johnson Space Center
J-T	Joule-Thomson

Acronym	Definition
KSC	Kennedy Space Center
K	Degrees Kelvin
LDR	Large Deployable Reflector
LED	Light Emitting Diode
LeRC	Lewis Research Center
LHe	Liquid Helium
LHSF	Liquid Helium Servicing Facility
MDM	Multiplexer-Demultiplexer
MEOP	Maximum Expected Operating Pressure
MLI	Multilayer Insulation
MMPS	Microgravity and Materials Processing Sciences Facility
MRMS	Mobile Remote Manipulator System
MSC	Mobile Service Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NBS	National Bureau of Standards
NHe	Normal Helium
NPSP	Net Positive Suction Pressure
OMV	Orbital Maneuvering Vehicle
OD	Outer Diameter
OPF	Orbiter Processing Facility
ORU	Orbital Replacement Unit
OSCRS	Orbital Spacecraft Consumables Resupply System
P	Pressure
PCR	Payload Changeout Room
PDI	Payload Data Interleaver
PDU	Power Distribution Unit
PGHM	Payload Ground Handling Mechanism
PHSF	Payload Hazardous Servicing Facility
PIP	Payload Integration Plan
P/L	Payload
POCC	Payload Operations Control Center
PP	Porous Plug
PRT	Platinum Resistance Thermometer
RCM	Remote Connection Mechanism
RCS	Reaction Control System
RMS	Remote Manipulator System
RPM	Revolutions Per Minute
RU	Remote Units
S	Entropy
S/C	Superconducting
SC&TB	Serial Command and Telemetry Bus
SFHe	Superfluid Helium
SFHT	Superfluid Helium Tanker
SHOOT	Superfluid Helium On-Orbit Transfer
SIO	Serial Input Output
SIRTF	Space Infrared Telescope Facility
SMCH	Standard Mixed Cargo Harness
SOW	Statement of Work
SRD	System Requirements Document
STICCRS	SIRTF Telescope Instrument and Cryogen Changeout Replenishment Study
STS	Space Transportation System

Acronym	Definition
T	Temperature
TAO	Thermal Acoustic Oscillation
TBD	To Be Determined
TBS	To Be Supplied
TDRSS	Tracking and Data Relay Satellite System
TM	Thermomechanical
TPMS	Temperature and Pressure Monitoring System
TVS	Thermodynamic Vent System
USL	United States Laboratory
V	Specific Volume
VCS	Vapor-Cooled Shields
VLPS	Vapor-Liquid Phase Separator
VPF	Vertical Processing Facility
XRS	X-ray Spectrometer

1.0 EXECUTIVE SUMMARY

Replenishment of superfluid helium (SFHe) offers the potential of extending the on-orbit life of observatories, satellite instruments, sensors and laboratories which operate in the 2K temperature regime. This summary provides a top-level overview of the major program conclusions, analyses/trade study results, recommended fluid, structural, thermal and avionic subsystem conceptual designs and operational considerations for both STS and ELV launch of the SFHT. We have also addressed programmatic issues such as technology development needs and a program plan for SFHT development through delivery of a tanker to NASA-KSC in 1997.

We have considered a mixed-fleet approach to SFHT utilization. Our 6000 liter tanker concept, shown isometrically in Figure 1.1, is compatible with launch on both the STS and a Delta, Atlas, Titan III or Titan IV expendable launch vehicle (ELV). The tanker will also permit servicing from the Shuttle cargo bay, in-situ when attached to the OMV and carried to the user spacecraft, and as a depot at Space Station. We prepared conceptual designs for all the subsystems, and these are discussed in the sections that follow. Technology development recommendations and a Phase C/D program plan were also prepared and they are summarized at the end of this section.

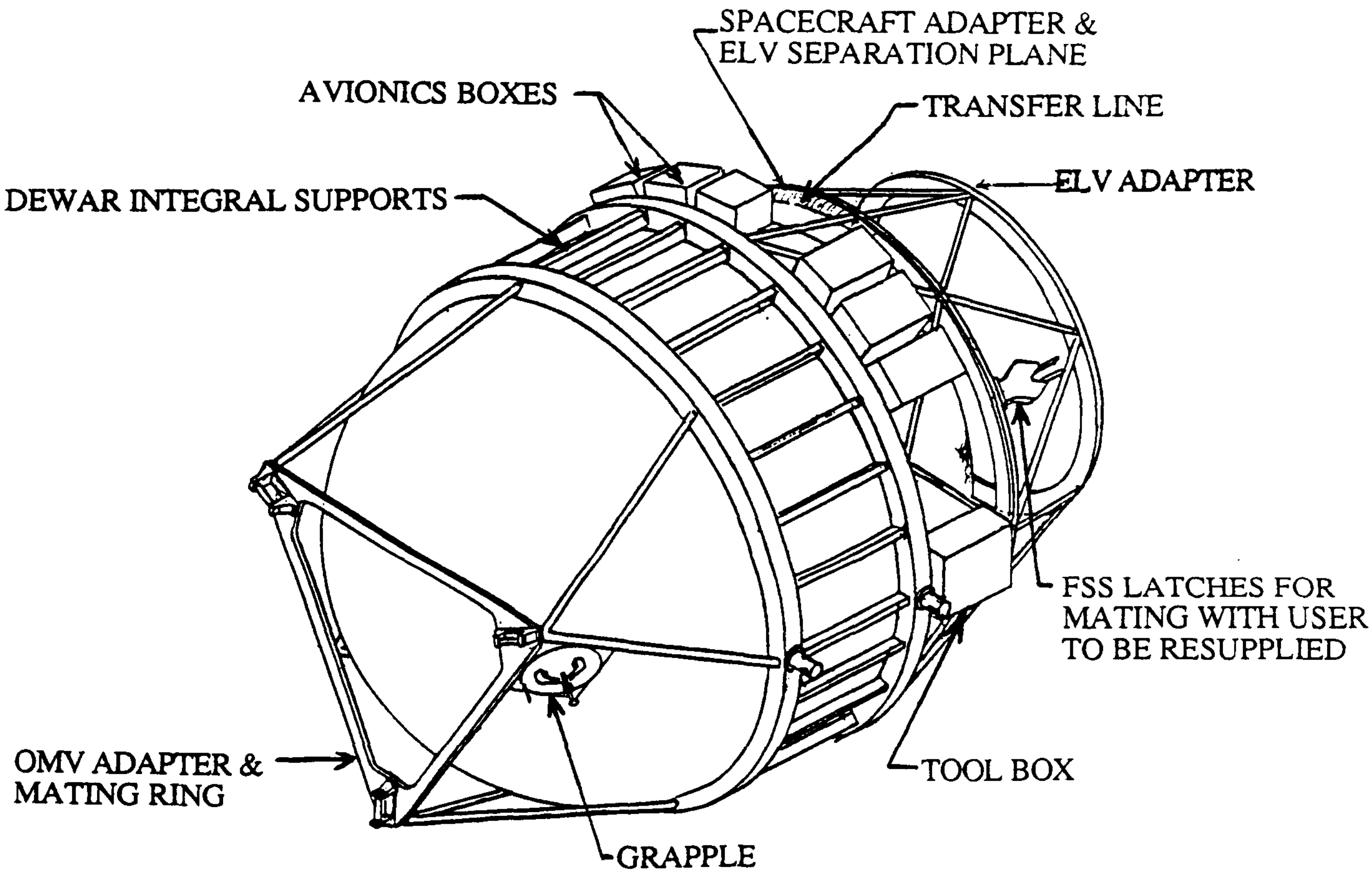


Figure 1.1 Superfluid Helium Tanker Concept

1.1 DESIGN GUIDELINES, GROUNDRULES AND APPROACH

The objectives of the superfluid helium tanker study were to define requirements, prepare a conceptual superfluid helium tanker design, conduct a commonality assessment, recommend technology deficiencies, and prepare a development program plan and cost estimate. The first two tasks in this effort were to collect the user requirements and prepare a fluid subsystem conceptual design which would then be incorporated, following trade studies, into a tanker conceptual design. Task three resulted in SFHT conceptual designs for all tanker subsystems. Tasks four and five involved technology development recommendations and phase C/D program planning and cost estimating activities. We have taken a systems approach to requirements analysis and trade studies to be sure that all system and programmatic design drivers are included, not just those that are fluid-related.

The use of conclusions and recommendations from previous superfluid helium tanker studies, and the technical interaction with workers actively advancing the state-of-the-art of associated technologies, was key to our approach in conducting the tasks documented in this report. We had technical interchange meetings with NASA-GSFC, ARC, MSFC and JPL regarding past experience and current work. Many of those contacted have documented extensively in the technical literature. We visited NASA-KSC to discuss ground servicing, and operational design drivers and constraints, related to handling tanker capacities of 6000 to 10000 liters, and greater.

One of the key features of our approach to conducting this study has been the use of two well-recognized experts in the areas of superfluid helium fluid management and hardware design. Dr. Glen McIntosh of Cryogenic Technical Services contributed significantly to the trade studies on Dewar design and ground servicing. Dr. John Hendricks of Alabama Cryogenic Engineering contributed in the areas of venting system design as it relates to transfer techniques, and fountain effect pump characterization.

A number of design guidelines influenced the results of our trade studies and analysis. We used the baseline SFHT requirements in the Contract SOW, and the System Requirements Document Attachment A of the SOW as our basis. In addition, the following design guidelines and assumptions were developed during the course of conducting this study.

1. The baseline concept is to transfer superfluid helium to the user; options were open as to the condition of fluid at launch and how we obtained the superfluid to be resupplied.

2. There is no requirement to relocate the SFHT within the Orbiter once we reach orbit.

3. The maximum storage time on-orbit prior to resupplying SIRTF, the reference user dictating the 4000 liter capacity design goal, is 3 months.

4. The capability to service "warm" users is a requirement. Big advantages, however, are obtained in terms of cost per usable kilogram of helium to orbit if the users are serviced "cold." Evaluation criteria in our trade study thus considered mixed user thermal conditions and this led to evaluation of modular tanker approaches.

5. We assumed that Delta, Atlas Centaur and Titan Expendable Launch Vehicles (ELVs) were all candidates for providing ELV boost capability for the SFHT. A minimum payload diameter of 9 feet was selected as a trade study parameter.

6. Helium liquefaction and refrigeration were not considered part of the initial SFHT capability (they were also not part of the SHOOT/STICCR baselines). Our designs, however, are configured so that this capability can be added as growth potential to work boil-off/venting issues when the SFHT is used on orbit as a Space Station depot.

7. Flight Telerobotic Servicer (FTS) is an option; we're designing to be compatible if the user specifies its use.

8. We're not relying on a servicing facility being available at Space Station; it's not in the IOC design. The only interfaces we are assuming at Station are power, a control station similar to the Shuttle AFD capability, and debris/meteoroid protection.

1.2 SFHT REQUIREMENTS DEFINITION

A review was made of all superfluid helium users which might require on orbit helium resupply to define the requirements for the SFHT in order to maximize flexibility and to ensure that all user requirements were addressed in subsequent conceptual design tasks.

Based on the results of the SFHT user literature search, time-phased helium requirements were compiled. Based on current requirements, the Space Infrared Telescope Facility (SIRTF) requires the largest amount of superfluid helium (4000 liters). However, some of the smaller users, such as the Critical Point Phenomena Facility (CPPF) require helium resupply every 90 days, which also results in significant yearly quantities. If all the identified users become funded programs in the currently planned time span, the helium requirement would peak at approximately 12000 liters in the 2004 time frame.

Because of the uncertainty involved with many of the users, particularly on their likelihood of being funded in the time schedule currently planned, a reduced user complement was defined to determine the sensitivity of the helium resupply requirements. This was done by considering those users that are the best defined and furthest along in their development phase. These users were AXAF, SIRTF, Astromag, and CPPF. CPPF was considered since it is representative of a payload designed to be placed inside the U.S. Laboratory Module on the Space Station. The helium required for the reduced user complement is shown in Table 1.1. The requirements are significantly reduced; however, SIRTF remains the design driver due to its large capacity. These representative helium resupply requirements were used in the SFHT fluid subsystem sizing trades conducted during Task 2 and discussed in Section 4.1.2.1.

Table 1.1 SFHe User Database - Reduced User Complement

User	Helium Volume (liters)	Service Interval (days)	Service Time (days)	Orbit (km)	Launch Date	Mission Lifetime (years)
SIRTF	4000	730	3 to 14	700	1997	6 to 12
AXAF	200-400	730	TBD	600	1996	8
ASTROMAG	3100	730	TBD	at SS	1998	6 to 8
MMPS/CPPF	200	30-90	1 to 7	at SS	1997	5

Three orbital SFHT resupply options were evaluated for impacts to the SFHT design. These were resupply from the Orbiter cargo bay, resupply in-situ while attached to the OMV, and resupply at the Space Station Servicing Facility. Another major design requirement impacting SFHT design is designing the SFHT to accommodate launch by an ELV as well as by the Shuttle. This adds to SFHT manifesting flexibility, particularly if ELV's are used in the future for Space Station logistics resupply missions. Existing ELV's were examined to evaluate their capabilities of payload weight to orbit, payload shroud geometry, and cost. These are summarized in Table 1.2. Each of the launch vehicles listed has sufficient payload capability to place the SFHT in a useful orbit. The limiting factor in using an ELV to launch the SFHT is payload shroud diameter. Designing the SFHT to accommodate both a Shuttle and ELV launch requires the SFHT structure to be reconfigurable unless the SFHT is launched on the Titan IV vehicle. Reconfiguration is also required to be performed on-orbit if the SFHT is to be returned to the ground by the Shuttle following launch on any expendable vehicle but Titan IV. The Delta launch vehicle has the smallest payload fairing while the Titan IV can accommodate Shuttle-sized payloads with little or no structural reconfiguration.

Table 1.2 Launch Vehicle Comparison

PARAMETER	DELTA II	ATLAS/CENTAUR	TITAN III	TITAN IV	STS
LAUNCH COST	\$45M*	\$59M*	\$110M*	\$160M**	\$140-\$245M
PAYLOAD TO 250 NM ORBIT, LBS	8000 (6920) 10000 (7920)	10500	29500	~39000	48000***
DOLLARS PER POUND (TO ABOVE ORBIT)	5625	5619	3729	4103	2917-5104
PAYLOAD FAIRING I.D., IN.	110	115,143.7	143.7	180.0	180.0
PAYLOAD ADAPTER INTERFACE DIAMETER, IN.	32.5,60	32.5	32.8-70.0	111.77	N/A

*FROM DATA SUPPLIED BY NASA LeRC FOR COLD-SAT PROGRAM
** HARDWARE COSTS ONLY, NO MISSION SUPPORT/INTEGRATION INCLUDED
***WITH PERFORMANCE UPGRADES

Other issues involving an ELV launch of the SFHT are stabilization of the SFHT once it is delivered to orbit, and telemetry and power interfaces between the SFHT and the ELV. If the SFHT is not launched attached to an OMV, then either the SFHT or the ELV must provide a means of stabilization to allow subsequent pick-up by the OMV or Shuttle for transport to the user spacecraft or the Space Station. The Delta II, Atlas/Centaur and Titan III contain reaction control propulsion systems to provide payloads with three axis stabilization prior to deployment. The Titan IV currently has no such capability. Telemetry and power interfaces between the ELV and the SFHT during launch and on-orbit deployment are expected to be minimal since the SFHT is a passive payload.

1.3 TANKER OPTIMIZATION

Superfluid helium tanker configuration is influenced by user requirements, launch vehicle options and the spectrum of on-orbit resupply scenarios. A summary of trade study results and operational concepts is discussed in the following paragraphs; this system optimization allowed us to proceed effectively with the liquid helium subsystem design trades.

1.3.1 SFHT Fluid Storage Sizing Trades

Trade studies were performed to optimize the capacity of the SFHT fluid system based on the reduced set of user requirements presented in Section 1.2. While SIRTF is the chief design driver for the SFHT, the trade studies were performed to ensure that users with capacities different from SIRTF (particularly smaller users) could be efficiently resupplied without incurring unreasonable cost and weight penalties. Key variables that were examined included the number and type of users, SFHT launch costs, SFHT boiloff losses, and SFHT weight.

The first step in evaluating tanker capacities was to determine the number of times a given tanker size would have to be flown to satisfy the time-phased resupply requirements. A spreadsheet was developed to parametrically evaluate different SFHT capacities versus the user requirements. The user requirements were laid out quarterly beginning in 1997. Each user could be individually specified as being either cold or warm at the initiation of resupply. If the user was specified as warm, then the user capacity was multiplied by 2.5 to account for chilldown losses. If the user was specified as being cold, it was conservatively estimated that the user contained no residual helium and would require its full resupply quantity.

The quantity of helium in the tanker versus time was estimated by subtracting a representative boiloff rate of 1.5% per month along with the user requirements for that quarter. When the helium in the tanker reached a level that was insufficient to meet the user requirements for the next quarter, another tanker was flown. In this way, the number of tankers required to satisfy the total user requirements could be determined and key variables such as the number of users, their initial state, and the tanker capacity could be examined.

The penalty associated with on-orbit boiloff became a key driver in SFHT Dewar sizing. As mentioned above, boiloff was estimated assuming a loss rate of 1.5% per month. Cumulative boiloff losses were compared with the Cumulative resupply requirements for the various tanker sizes. Figure 1.2 shows the results for both a 15000 liter capacity tanker and a 6000 liter capacity tanker, assuming the same user requirements. The boiloff losses for the 15000 liter capacity tanker can exceed the user requirements, depending on the type of users. Ideally, the amount of transported helium should be as close to the user requirements as possible for the most efficient resupply system.

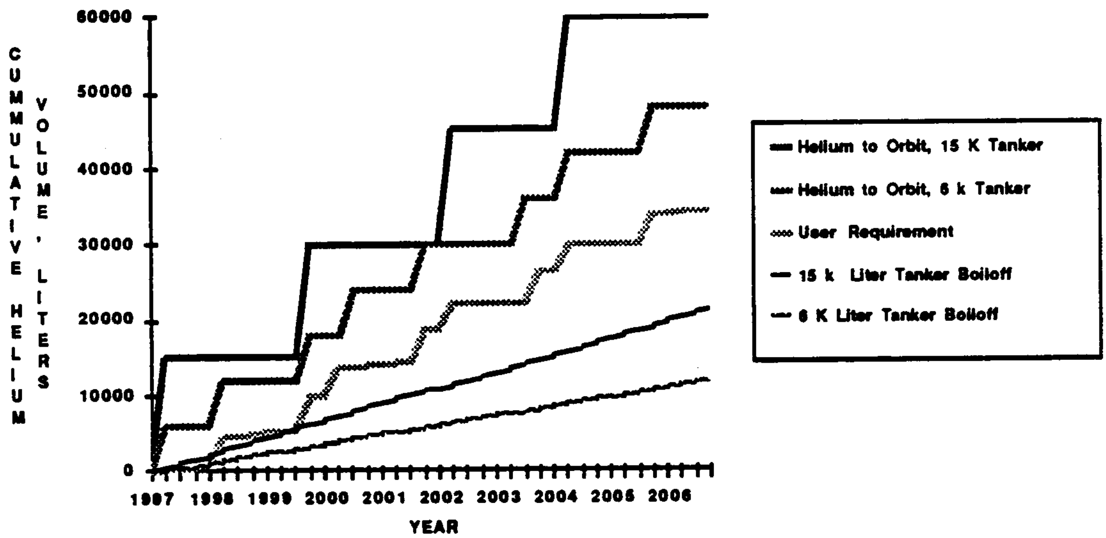


Figure 1.2 Tanker Capacity Sensitivity to Boiloff Losses in Meeting a Specified User Resupply Scenario

Based on the above results and a number of other similar trade studies performed, we feel that a 6000 liter capacity SFHT satisfies the mission requirements in the most efficient manner. It is sufficient in size to resupply SIRTF under normal conditions without an undue penalty for the smaller users. Also, this capacity makes packaging into smaller ELV payload fairings a practical option. However, an important conclusion reached during the sizing studies was that the optimum SFHT size is heavily dependent on the user requirements in terms of both user capacity and resupply frequency. Therefore, it is recommended that the sizing issue continue to be readdressed as the user requirements mature.

1.3.2 Launch Vehicle Options

An objective of this study was to determine design impacts to the SFHT of launch both on an ELV and the Shuttle. A mixed manifesting approach, using both ELV's and the Shuttle, is being considered for Space Station logistics resupply. Early in the study, we established the requirement to examine all ELV's, not just the Titan IV. This was done to ensure that compatibility with a maximum number of ELV's was examined. Designing payloads such as the SFHT to accommodate both ELV and Shuttle launch must necessarily impose some compromise in the design. Specifically, the dual launch requirement involves compromising the SFHT's length since most ELV payload fairings are smaller than the 15-foot diameter of the Shuttle cargo bay.

A benefit of the selection of the smaller capacity 6000 liter SFHT is that it provides easier packaging within the smaller payload fairings. Designing the SFHT to a nine-foot diameter to package within the Delta II payload fairing dynamic envelope results in a slightly longer length tanker which penalizes it somewhat for a Shuttle launch. This penalty is minimized, however, by the smaller capacity tanker. Therefore, due to the selection of the 6000 liter SFHT, we chose to maximize compatibility and design the SFHT to fit within the Delta II fairing. The length penalty associated with this design diameter for a Shuttle launch is two to three feet. The packaging of the nine-foot diameter, 6000 liter SFHT in the various ELV fairings is shown in Figure 1.3 for comparison. The SFHT uses most of the payload fairing volumes for the Delta II and Atlas/Centaur vehicles. For the Titan vehicles however, significant payload weight and volume margins remain, indicating that the SFHT would be part of a multiple payload launch for these vehicles.

1.4 OPERATIONS

The SFHT Systems Requirements Document (SRD) defined the types of resupply operations that the SFHT must perform. Helium replenishment operations can take place from the Orbiter cargo bay, Space Station, and while attached to the OMV. Satisfying each of these cases requires a thorough definition of the operations for each to determine what hardware and design features are required. In developing these operational scenarios, SIRTF was used as a representative user spacecraft since data on its configuration is more readily available. Discussions with NASA Ames Research Center personnel were conducted to obtain the latest data on the SIRTF configuration and mission. On-orbit instrument change-out is not planned and it is desirable to always resupply SIRTF when helium is remaining to avoid warming up the instruments. Resupply of a warm SIRTF therefore is a contingency operation only.

Resupply from the Orbiter cargo bay is considered the baseline operational case for the SFHT. The IOC Space Station configuration does not include the Servicing Facility; therefore, the current plans are to perform servicing from the Orbiter. The baseline SIRTF resupply mission calls for a dedicated Shuttle flight. The Orbiter would transport the SFHT, an A' cradle, and an OMV to a 500 km orbit. The OMV would then be used to retrieve the SIRTF from its 900 km orbit and transport it to the Shuttle.

The combined weight of the fueled OMV, A' Cradle, and the SFHT is summarized in the table accompanying Figure 1.4. A plot of Shuttle payload capability versus altitude with the SSME's at 104% power and with performance enhancements is also shown in Figure 1.4. The payload weight required for the STS-based SIRTF resupply mission is highlighted in the figure and shows that ~90% of the Shuttle payload capability is required for the mission for the 104% power case and ~70% for the performance enhancement case. Use of a larger tanker or the requirement to launch two of the 6000 liter SFHT's to perform a resupply of a warm SIRTF would require the performance enhancements, using 90% of the payload capability.

Servicing of the SIRTF begins by placing it in the A' cradle. EVA astronauts would then connect and disconnect the SFHT fluid and electrical couplers to SIRTF. The configuration for these operations is shown in Figure 1.5. Orientation of the SIRTF in the cargo bay is not critical except that it is desirable to keep the telescope opening pointing away from the direction of flight to minimize contamination. The SIRTF could be rotated down into the cargo bay using the A' cradle to minimize the distance between it and the SFHT. This helps to minimize the required length of the flex transfer lines. Although the OMV is shown restowed in the cargo bay following SIRTF retrieval, it has not been established within NASA that this is acceptable; an alternate means of temporarily "stationing" OMV prior to its use in returning SIRTF to orbit may need to be identified.

To replenish the SIRTF without using EVA, the SIRTF would be directly attached to the SFHT, and the fluid and electrical couplers mated by an automatic coupler mating mechanism, as shown in Figure 1.6. Even though EVA astronauts would be required to perform ORU changeout on

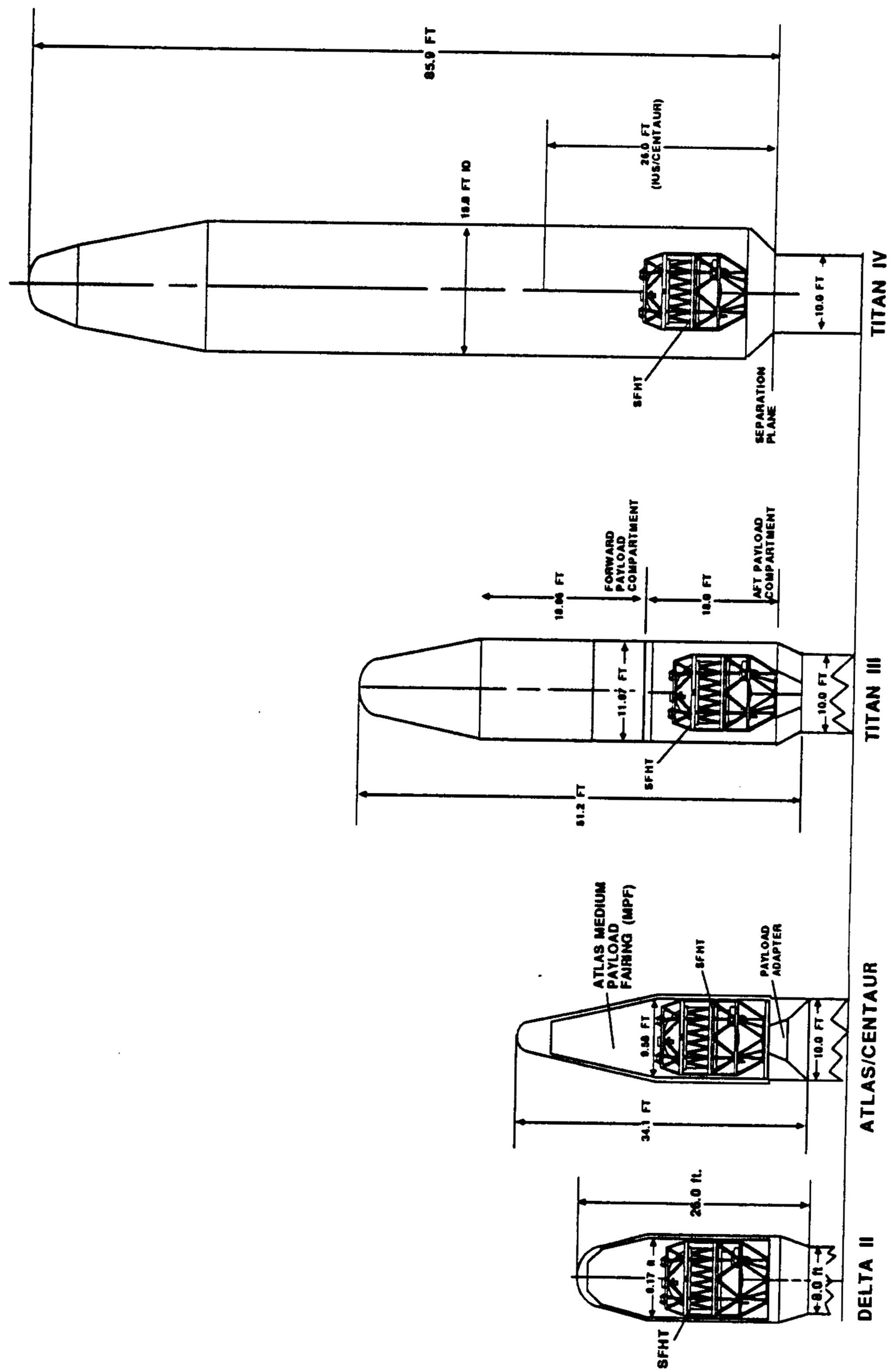
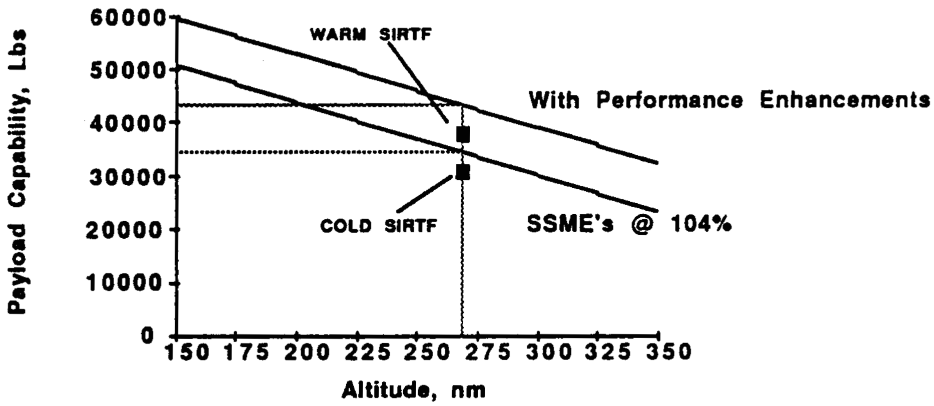


Figure 1.3 ELV Payload Fairing Comparison - SFHT



ITEM	WEIGHT TO ORBIT, LBS
A' CRADLE	4906
OMV	18304
SFHT	7200*, 14400**
TOTAL	30410*, 37610**

*COLD SIRTF
**WARM SIRTF (TWO SFHT's)

Figure 1.4 STS Payload Assessment for SIRTF Resupply Mission

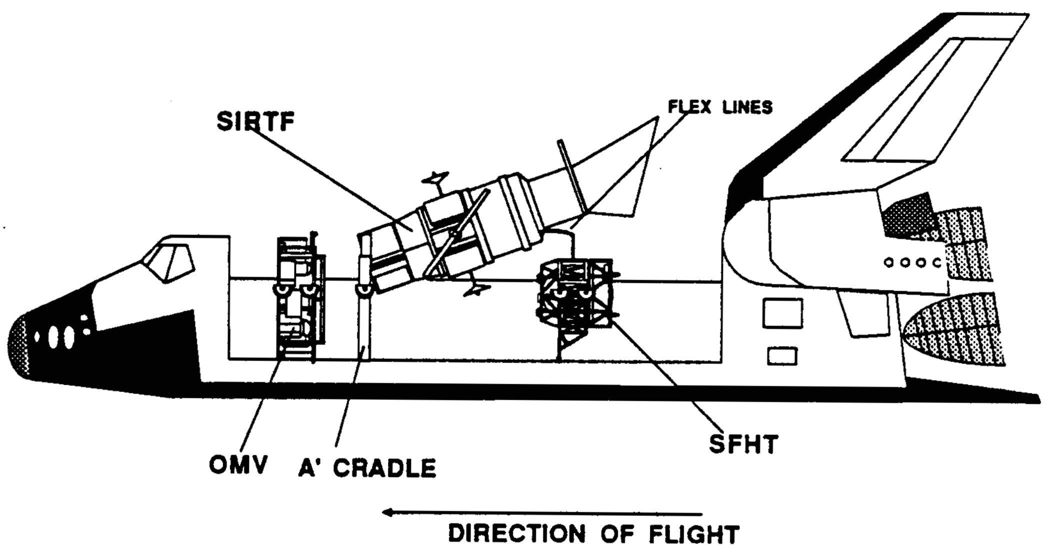


Figure 1.5 Manual Resupply of SIRTF in Cargo Bay

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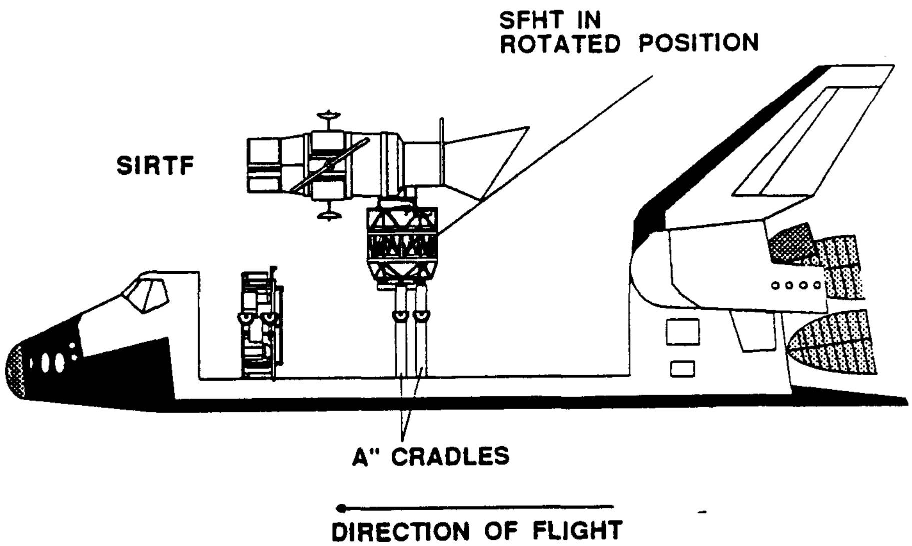

Figure 1.6 Automatic Resupply of SIRTF from STS Cargo Bay

the SIRTF, automatic resupply would provide benefits for the helium transfer operation by eliminating the long transfer lines and their associated flow losses and heat leak. To implement the attractiveness of this automated interface attachment, the SFHT would be rotated out of the bay so the forward interface of the tanker, which would contain a structural docking interface such as the FSS latches and the automated umbilicals, can interface with the corresponding umbilical connectors and couplings on the SIRTF. Once docking is complete, the active half of the automated coupler mating mechanism would mate the fluid and electrical couplers. Two electrical connectors and two fluid couplers would satisfy mission success requirements. Power, and command and data handling would be provided to the user via the SFHT, with monitoring and control of the SFHT being accomplished from the Orbiter AFD or the ground. With automatic resupply of a user from the STS cargo bay, EVA always is available as a backup approach for servicing if the automatic mechanisms can be manually operated.

One of the design requirements for the SFHT is that it be capable of resupplying helium to a user at a remote orbital location. Such operations would be performed while the SFHT is attached to the OMV. This requires the SFHT to incorporate structural and utility connections for attaching to both the OMV and the user spacecraft. The SFHT would require an automatic coupler mating mechanism to attach the fluid and electrical couplers. A concept for replenishing SIRTF with helium in-situ is shown in Figure 1.7. A television camera and light system on the SFHT is required to perform the docking procedure. Power, and command and data handling, would be provided to the user spacecraft from the OMV via the SFHT, with the resupply process being monitored and controlled if necessary from the ground. Upon completion of the replenishment operations, the SFHT would be detached from the user spacecraft and returned either to the Space Station or to the STS.

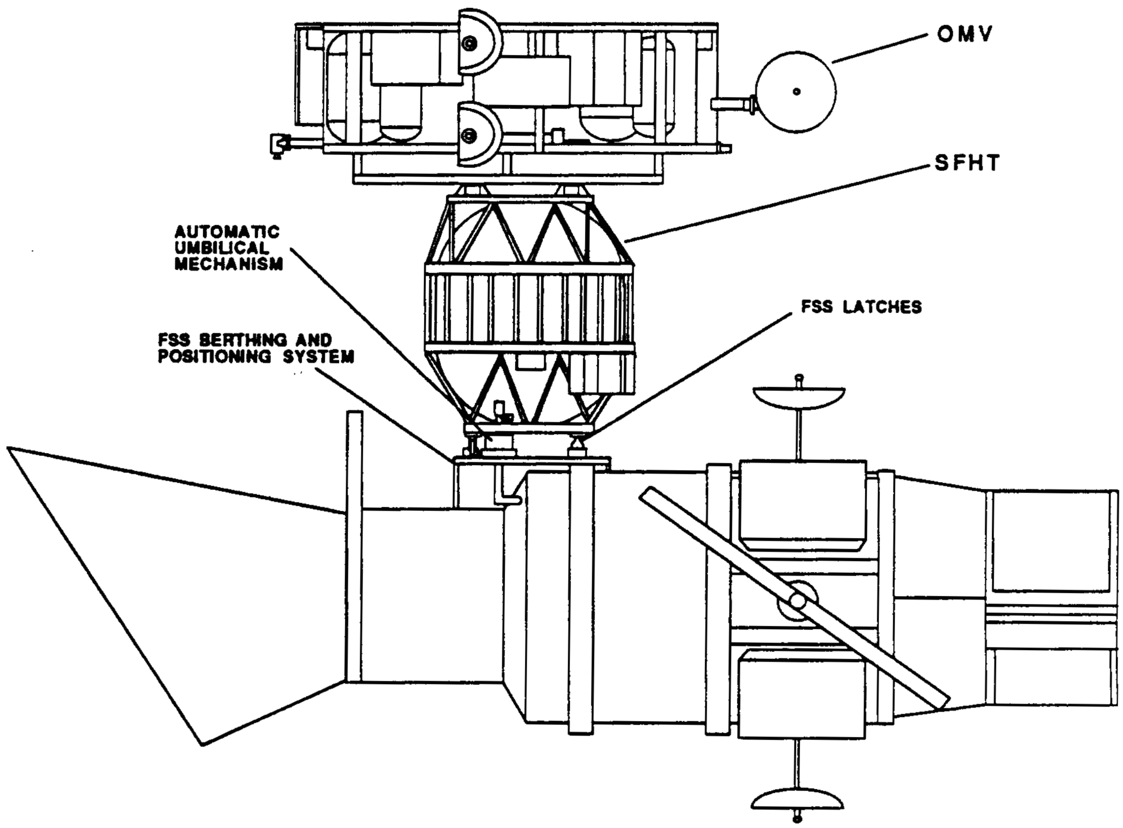

Figure 1.7 SFHT/SIRTF In-Situ Automatic Resupply Interfaces

1.5 FLUID SUBSYSTEM DESIGN

The SFHT mission will vary as user vehicle requirements vary, and cannot be programmed far in advance. Ability to service a variety of user vehicles in any sequence is a desired capability. Basic to this goal is the ability of the SFHT to maintain superfluid helium on orbit for a long period with minimum boiloff losses. Another design goal is to minimize ground operations, particularly after installation in the launch vehicle. This is of particular importance when the SFHT is launched along with other payloads, which vary from flight to flight. These objectives were addressed, along with considerations of weight, cost, and complexity, in the development of our fluid subsystem conceptual design.

1.5.1 Ground Servicing Techniques

Ground servicing of the SFHT will be a lengthy process dictated by the thermal conditioning and fill procedures involved with superfluid helium. Since these operations and the limitations of the KSC facilities involved are critical to the design of the SFHT, ground servicing issues must be considered early in the design process. While superfluid helium payloads have flown on the Shuttle before, they were relatively small in capacity compared to the SFHT. In order to make use of the procedures developed for these payloads and to better understand the facility capabilities and ground processing flow for the SFHT, a technical interchange meeting was held at KSC.

A discussion with KSC personnel on the current capabilities of the processing and launch facilities revealed that no equipment (e.g., vacuum pumps, supply Dewars, etc.) exists for the servicing of a superfluid helium payload. Previous hardware used to service the Spacelab superfluid helium payloads is no longer at KSC. Therefore the SFHT project would need to supply the necessary GSE hardware. Review of the capabilities of the Payload Changeout Room

(PCR) shows that there are significant physical limitations for the SFHT GSE. KSC stated that a 750 liter capacity supply Dewar is probably as big as could be handled in the PCR. This size limit is dictated by the limited volume in the PCR work areas and the weight capabilities of the Payload Ground Handling Mechanism (PGHM) platforms which are limited to 1500 lbs maximum.

An important groundrule relative to ground servicing is the period that the SFHT will be required to maintain superfluid helium at a satisfactory state for launch without benefit of ground servicing. A lockup period of ten days has been established as the maximum time from removal of ground connections and closure of the Shuttle payload bay doors until launch. During this period, the liquid helium must remain sufficiently below the lambda point temperature so that on reaching orbit, control of the fluid condition can be maintained by the space vent system without transition to the normal state. In addition, 24 hours must be allowed for a launch scrub turnaround. At that time, the cargo bay doors can be reopened and the SFHT reconnected to ground support equipment (GSE) and recooled to the launch-ready state.

A fixed requirement for the SFHT is the ability to deliver helium to the receiver tank being serviced in orbit as superfluid. Options exist, however, for the state of the fluid at the time of launch, and these options permit alternatives in the ground servicing procedures. Three fluid states were identified as possible alternatives, and trade studies were conducted to identify the most promising of these in view of ground servicing requirements. These are 1) normal helium, to be converted to superfluid in space, 2) saturated superfluid helium, and 3) pressurized superfluid helium. Alternate 1 was eliminated early in the trade studies due to the large helium losses for conversion to superfluid once on-orbit. The remaining ground servicing trade studies then focused on the preferred concept for obtaining and maintaining the fluid as superfluid at launch.

The selected approach for converting normal helium initially loaded into the tanker to superfluid at the desired launch temperature is illustrated in Figure 1.8. Normal helium is loaded into the vented tanker at about one atmosphere until the desired fill condition is reached. All valves are then closed. An independent cooling system is then placed into operation to cool the fluid to the superfluid state and reduce its temperature to the desired launch condition. The independent cooling system is an open loop refrigeration cycle. Normal helium is admitted from an external supply tank, through a flow restrictor to reduce the pressure, into a heat exchanger mounted in the tank. This heat exchanger exhausts into a vacuum pump that operates to reduce the pressure to a low value (that varies with time), finally reaching a pressure somewhat lower than the vapor pressure of the superfluid at its final temperature. The liquid flowing through the restrictor partially flashes, its temperature is reduced corresponding to the saturation temperature at the reduced pressure, and a temperature difference is created such that this two phase mixture is at a temperature lower than the liquid being cooled. Heat is removed from the contained liquid, causing the coolant fluid to fully vaporize, and the tank temperature is reduced as long as the temperature difference is maintained.

The conceptual design for the SFHT thus provides an independent, isolated open loop cooling system to condition liquid helium from its initial loaded condition of about normal boiling point (4.22 K) to superfluid at 1.6 K or below. Referring to the SFHT schematic diagram, Figure 1.9, the fluid conditioning system includes normal helium supply piping from a ground support Dewar, a throttling device to restrict flow of normal helium into a tank heat exchanger, and piping from the tank heat exchanger through one or more VCS heat exchangers to an external connection to a GSE vacuum pumping system. As the helium flows from the normal supply piping through the restrictor, pressure is reduced, and the fluid partially vaporizes. At the lower pressure, the temperature of the two phase fluid will correspond to the saturation temperature at the reduced pressure in the tank heat exchanger. By regulation of the throttling valve, this pressure will be maintained so that a small, but adequate differential temperature exists between the helium in the SFHT inner vessel and the fluid in the heat exchanger. Because of the

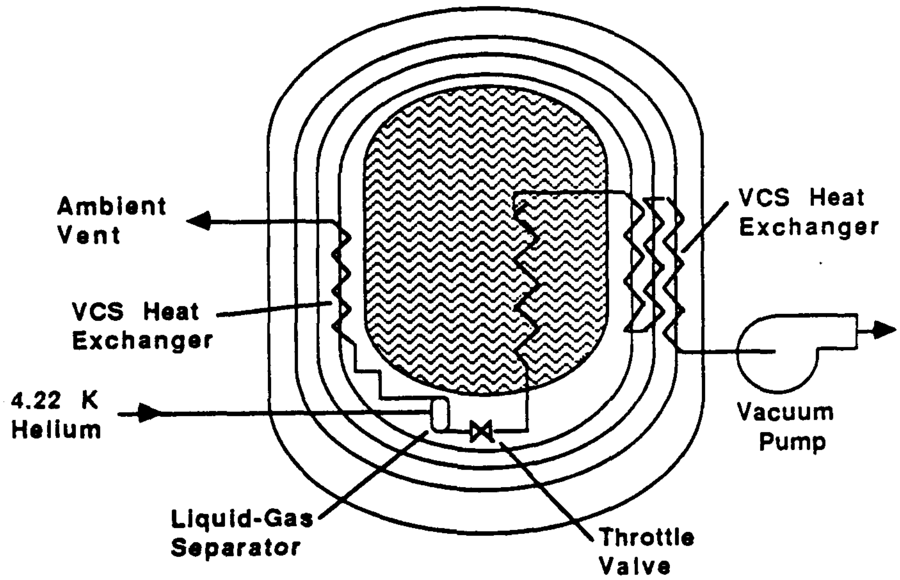

Figure 1.8 Simplified Schematic of Ground Servicing Concept

temperature difference, heat will be extracted from the loaded liquid as it cools, and vaporization will occur in the heat exchanger. The heat exchanger will be adequately sized so that all liquid vaporizes, and only vapor exits the tank boundary.

As the liquid being conditioned cools, the pressure will need to be reduced in the heat exchanger to provide the required temperature difference to drive the heat transfer. This will require gradual closing of the throttling valve. Flow through the heat exchanger is limited by the flow resistance through the total piping system and the capacity of the vacuum pump. The flow will decrease as the tank fluid cools and pressure is reduced in the heat exchanger, since density of the exiting vapor will also decrease. Therefore, the rate of cooling will begin at whatever can be sustained by the pumping and piping systems, and will decrease periodically as the pressure and flow are adjusted. The time required to achieve the cooldown from the initial normal boiling condition to superfluid at 1.6 K or less will depend on the vacuum pump capacity and the size, length, and other features of the flow circuit through the system.

As the tank and fluid cool, the liquid helium flow through the restrictor will decrease to the point that it will not be adequate to absorb the heat leak through the transfer line from the external supply Dewar, and this flow will become two-phase. It is imperative, however, that single phase liquid be supplied to the tank heat exchanger inlet metering valve. To accomplish this function, a liquid-gas separator or "keepfull" is installed in the cold region beneath the inner vapor cooled shield. This simple gravity separator is controlled by a vapor outlet valve actuated by a level sensor to maintain it partly filled with liquid. The vapor is vented to atmosphere through a heat exchanger on the inner vapor cooled shield. The keepfull not only provides liquid on a continuous basis, but also assists in reducing the heat leak to the tank during ground operations by maintaining the VCS at or near 5 K, much lower than its normal operating temperature (during space operation) or about 45 K.

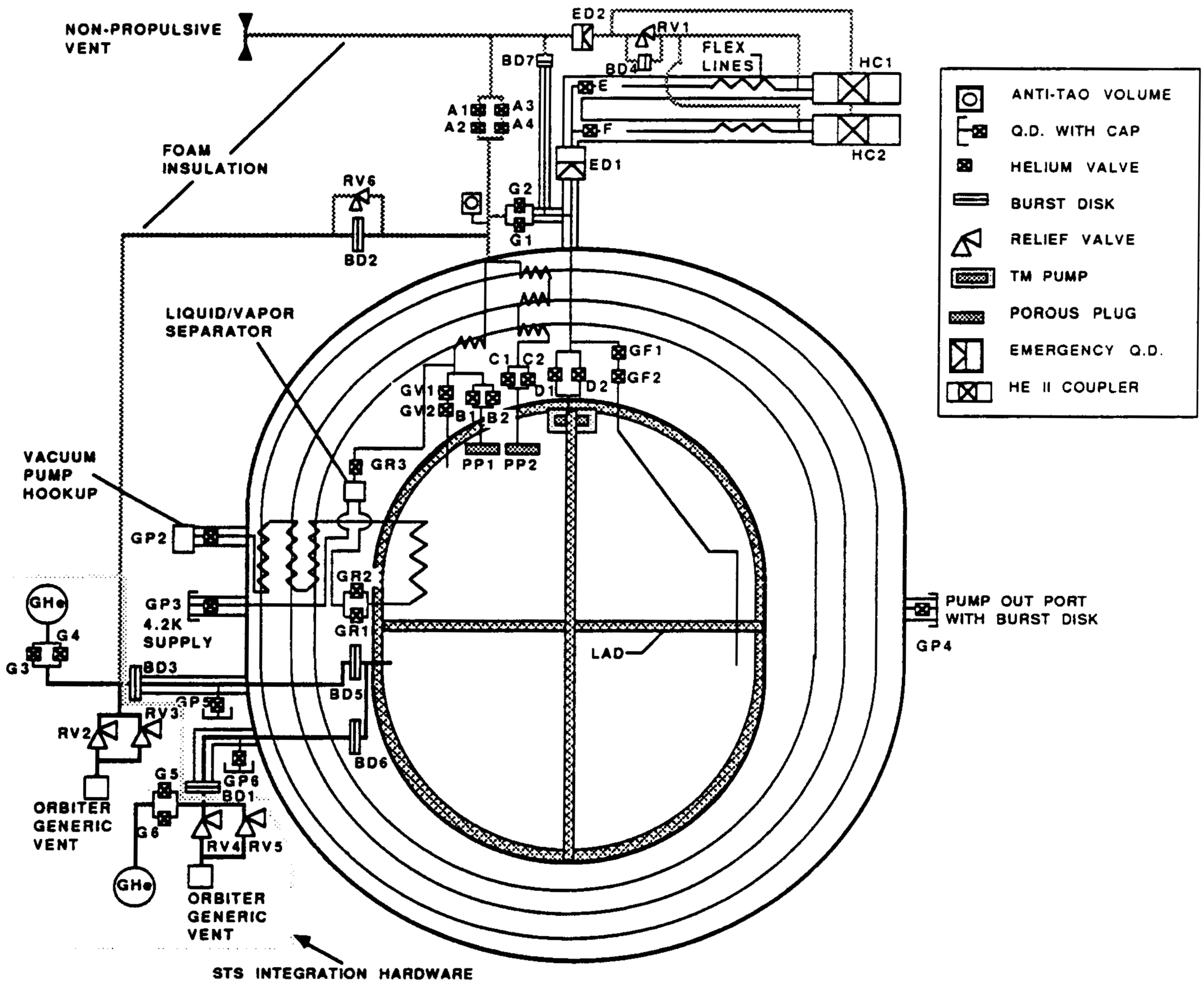

Figure 1.9 Schematic of Baseline Superfluid Helium Tanker

Ground servicing of the SFHT will consist of a vented fill of the tank with normal helium, following a normal purge and chilldown operation. The tank remains at approximately one atmosphere during load. When the tank is filled with the normal helium to near full, 85% or more, it is temporarily locked up and the open loop refrigeration cooling system is connected to the GSE and operation is started. As the fluid cools to below 4.22 K, the pressure in the tank reduces to below atmospheric. Additional liquid is then slowly added, without the need for venting. If the tank is to be launched in a pressurized (subcooled) condition, a final fill operation will pressurize the tank to about one atmosphere at the time the temperature of the fluid just reaches the lambda point, 2.17 K. At this point, the tank is 100 percent full of liquid with a density approximately that of saturated fluid at the Lambda point temperature. All valves communicating to the fluid in the tank are then closed, and no fluid enters or exits the tank thereafter. As the tank is cooled below the lambda point, the pressure increases because of the reversal of the coefficient of thermal expansion at the lambda point. The maximum pressure that can be reached from this starting condition is about 2 atmospheres, or less depending on the volume expansivity of the tank with pressure. If the launch condition is to be saturated superfluid, then the same procedure is followed, but a small ullage is left in the tank. This will require an accurate method for loading to the desired fill if a small ullage is desired. It may also be necessary to remove some fluid after the tank has reached a low pressure, probably requiring a vacuum pump to remove some helium as a vapor. Because of the simpler procedure, the pressurized state at launch appears more desirable, and is recommended. It is noted, however, that either pressurized or saturated load can be accommodated with the recommended ground servicing system.

A detailed analysis was performed which showed that for the baseline system, with a 1/2-inch heat exchanger tube and connecting piping, the SFHT can be cooled from 4.22 K to 1.5 K in about 20 days. The time to recycle from a (conservative) temperature of 2.1 K after a maximum delay launch scrub is approximately 10 days. These times appear to be acceptable. If a faster operation is required, the piping size, and/or the vacuum pump capacity, can be increased. This analysis will of course need to be repeated in more detail, and some parameters determined by test.

To determine the lockup capability, steady state temperatures of the vapor cooled shields and the multilayer insulation were determined by the system optimization program for various coolant flow rates. Using these temperatures as initial conditions, the Cryogenic Systems Analysis Model (CSAM) program was used to perform a transient analysis to determine the rate of temperature rise of the liquid. The starting liquid temperature was held at 1.6 K for this analysis, although overcooling may also reduce that temperature. The results are presented in Table 1.3, in the form of the number of days to reach various temperatures, assuming the coolant flows were maintained long enough to reach steady state. Coolant flow was varied on the basis of percent of normal onorbit vent rates. The results show that the 11 day lockup requirement can be easily met, since the nominal space vent rate is approximately 0.21 L/Hr.

Table 1.3 Estimated Liquid Temperature After Hold Period for Various Overcool Conditions

	Hold Time After Lockup No Coolant Flow (Days)		
Coolant Flow Rate Prior to Lockup	To Reach 1.9 K	To Reach 2.0 K	To Reach 2.1 K
0.21 L/Hr (Nominal Space Vent Rate)	6	7.5	9
0.26 L/Hr (125% of Nominal Space Vent Rate)	8.5	10	12
0.31 L/Hr (150% of Nominal Space Vent Rate)	9.5	11	13
0.27 L/Hr (175% of Nominal Space Vent Rate)	11	12.5	14.5
0.42 L/Hr (Double Nominal Space Vent Rate)	11.5	13	15
SFHe Temperature at Lockup - 1.6 K Vacuum Jacket Temperature - 300 K			

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1.5.2 Liquid Acquisition Techniques

A study was conducted to determine which liquid acquisition techniques would be most practical for use in the SFHe tanker. There are only two acquisition system concepts that appear feasible, open sheet metal systems or channel systems fabricated from fine mesh screen. Both of these are capillary systems in which the surface tension of the fluid is used to orient the liquid and provide a barrier to vapor flow.

The main environmental factor affecting surface tension liquid acquisition system design and performance is the acceleration environment in which the acquisition system must operate. In general, the open sheet metal systems are limited to acceleration environments of 10^{-4} g or less. If the acceleration environment exceeds 10^{-4} g, the hydrostatic force produced exceeds the surface tension force of the liquid and displacement of the liquid occurs. This displacement can be such that liquid outflow from the tank during transfer is interrupted. Re-establishment of flow requires reorientation by the surface tension forces which could require a lengthy time period. Channel systems provide a continuous path between the bulk liquid and the tank outlet regardless of liquid orientation or displacement. Several channels are typically employed so that continuous communication between the bulk liquid and tank outlet is provided even if liquid moves in the tank. If the helium transfer process from the SFHT to the using space system is always accomplished at the Space Station, where the acceleration typically will be less than 10^{-4} g, then the open system would be preferred. However, since some of the transfer may be from the Shuttle to the using system, some Shuttle transient accelerations as high as 10^{-3} or 10^{-2} g may be imposed on the SFHT. Therefore, the recommended system considering all orbital locations and environments is a channel system fabricated from fine mesh screens.

A study was made to evaluate the residuals that would be left in the helium tank at the end of the transfer process. It was assumed that the acceleration environment was directed so as to locate the bulk liquid residual between the channels. For an acceleration of 10^{-5} g, the Bond number for the fluid in the tank was calculated to be approximately 70. This large a Bond number indicates a very flat liquid interface that could result in a maximum quantity of liquid located between the channels. This quantity was estimated to be 360 liters or 5.8% of the total tank volume. This volume does not include the liquid contained within the liquid acquisition system channels which is also considered to be an unusable quantity. In order to reduce the residual, a horizontal channel was located at the equator of the tank linking the four vertical channels. The general arrangement is shown in Figure 1.10. With this channel design, the maximum liquid residual external to the channels would be located in one quadrant of the tank between the two vertical channels and the horizontal channel.

Consideration was also given to the possible retention of liquid in the gap between the channels and the tank wall. Actually, this gap can support liquid to a varying height depending upon the acceleration environment. This supported height influences expulsion efficiency in two ways. First, it increases the wetted screen area and reduces screen entrance pressure losses and, therefore, the total system pressure loss. The supported liquid also reduces or possibly eliminates the liquid puddle volume in the tank if the puddle Bond number is small. A rigorous analysis of expulsion efficiency was made considering the gap thickness between the channel and the wall and the acceleration environment as variable parameters. The liquid residuals include the total internal channel volume, the puddle volume not in contact with the channels, and the liquid volume in contact with the screen at the time of screen breakdown. These residual volumes were calculated as a function of the gap thickness and the acceleration. The results indicated that a maximum expulsion efficiency of 99.5% could be obtained at an acceleration of 10^{-5} g. If the acceleration were raised to 10^{-3} g, the worst case expulsion efficiency would drop to 96.6 percent with a gap thickness as great as a quarter inch.

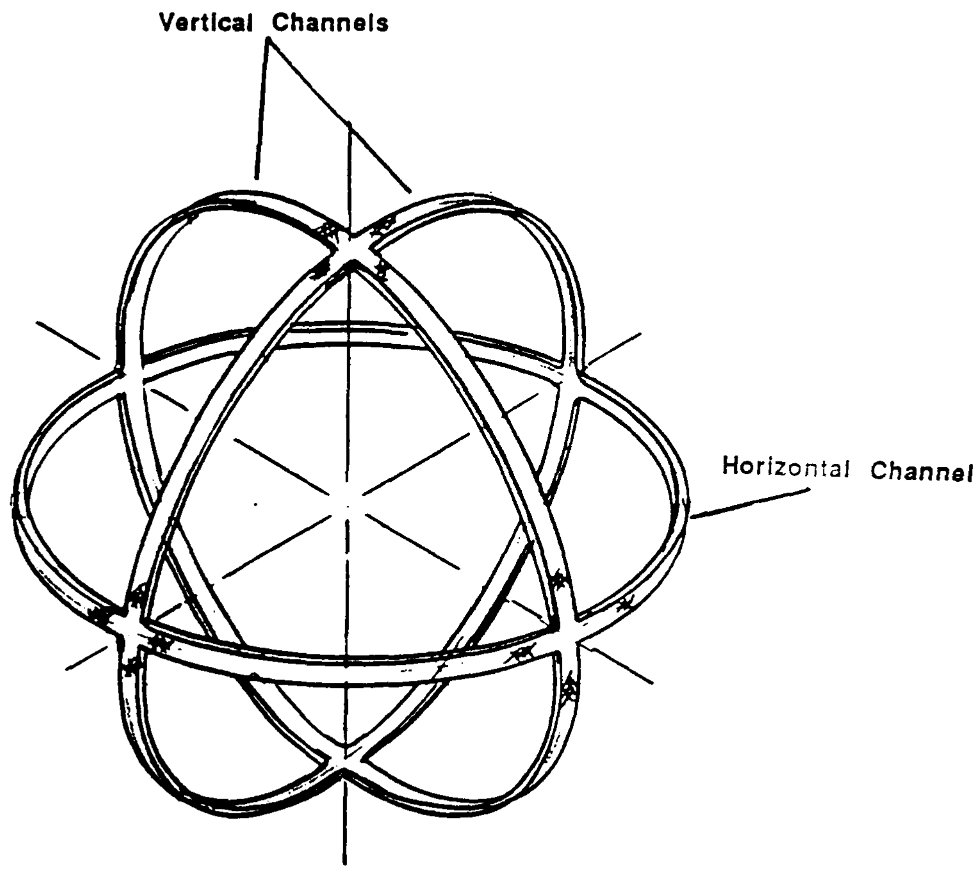


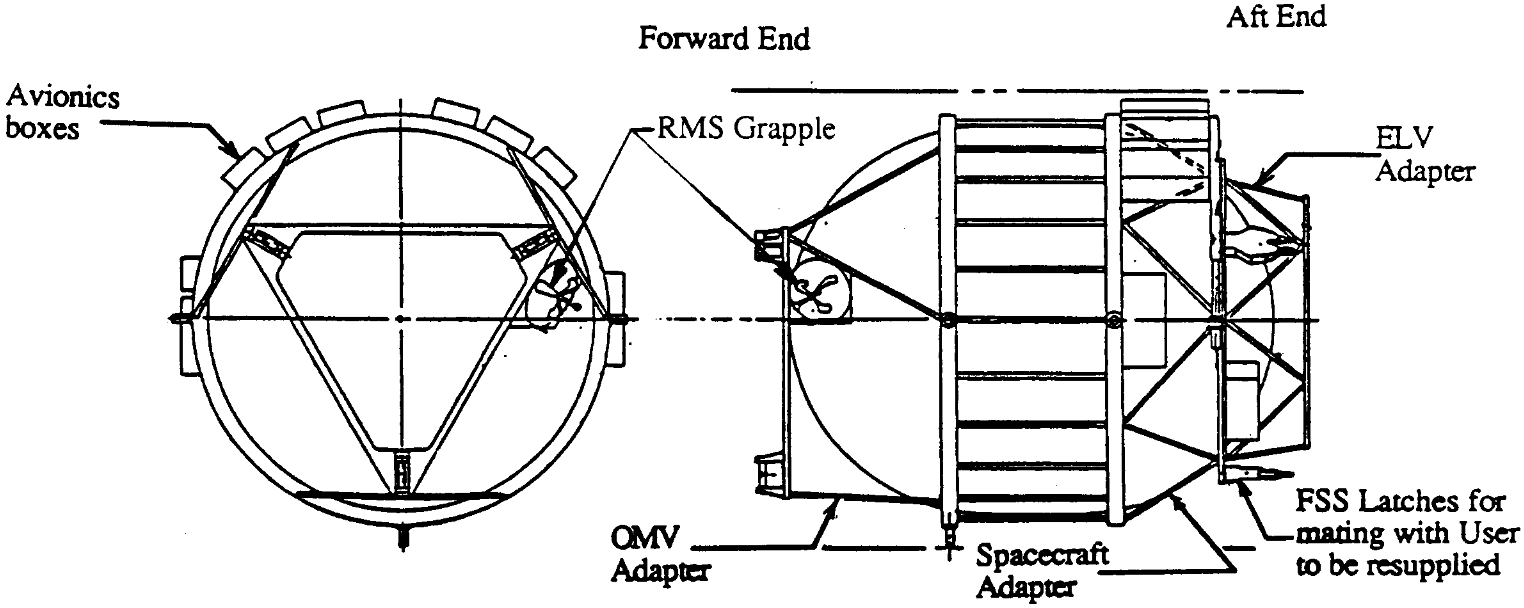
Figure 1.10 SFHT Liquid Acquisition Device with Horizontal Ring Channel

1.6 STRUCTURAL/MECHANICAL/THERMAL CONTROL SUBSYSTEM DESIGN

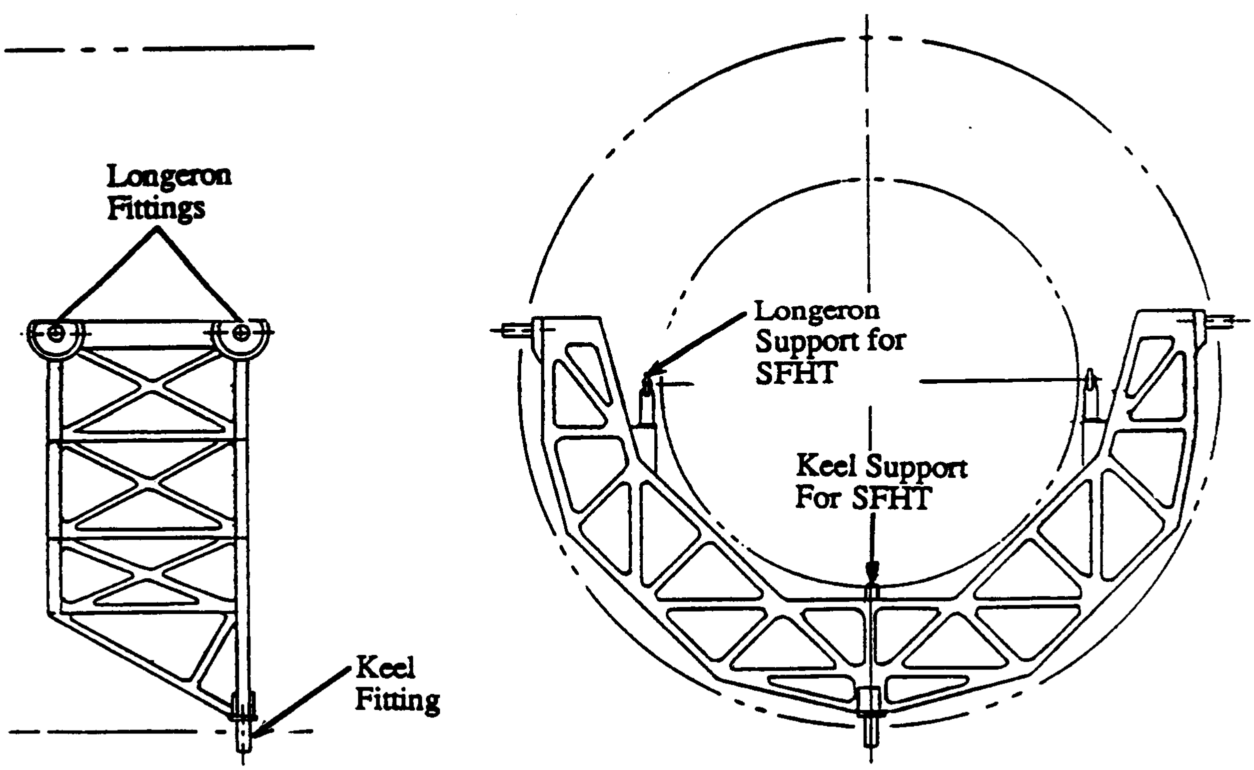
The structural/mechanical and thermal control subsystem design features are discussed in this section. These subsystem designs were configured to permit launch compatibility with both shuttle and ELV launches, and use of the SFHT as a space station depot or with the OMV, as well as servicing from the Shuttle.

1.6.1 Structural/Mechanical Subsystem

The SFHT is being designed with the versatility to be launched either on the Space Shuttle (STS) or on an expendable launch vehicle (ELV), in which case it would be returned on the STS. The SFHT structural support concept and STS transport cradle configured to satisfy the design criteria are shown in Figure 1.11. The SFHT structural configuration for STS launch includes the Dewar vacuum jacket structure, an OMV adapter, a spacecraft adapter for docking with the user on orbit, and a cradle that supports the SFHT in the cargo bay. The ELV scenario includes the Dewar vacuum jacket structure, OMV and spacecraft adapter structures, and an ELV adapter, all of which fits into the 110-inch diameter envelope of the Delta. When the SFHT is launched on an ELV, a cradle will have to be launched on the STS simultaneously for SFHT return to Earth. All the structure shown is aluminum although approximately 50 pounds could be saved by using graphite/epoxy struts for the adapters instead of aluminum.



a) SFHT Configuration for ELV Launch (or placement in Transport Crade for STS Launch)



b) SFHT Transport Cradle for STS Launch and/or Return

Figure 1.11 SFHT Structural Support Concept

The Dewar vacuum jacket structure weighs approximately 1290 pounds, although roughly 150 pounds could be saved by using a more expensive chem-milled skin structure which would require development testing. The two hemispheres (wall thickness t = 0.125 inches) are sized for collapse, and to support valving and vapor-cooled shields. A short cylindrical barrel (wall thickness t = 0.188 inches) connects the two hemispheres. Longerons are machined into the barrel to transfer axial load from one ring at the aft end of the barrel to a similar ring at the other end. The rings are key to the structure in that they support the inner Dewar, stiffen the vacuum jacket, hold five pins that attach to the cradle, interface with the OMV adapter and the spacecraft adapter, and support an avionics platform.

The Orbital Maneuvering Vehicle (OMV) adapter weighs approximately 283 pounds. It mounts to the forward ring with six struts that separate FSS/OMV latches from the hemisphere. At the forward end the struts attach at 3 places to a machined triangular frame, on which the latches and two RMS grapple fixtures are mounted. Note that the latches make up 67% of the subsystem weight.

On the aft end of the Dewar vacuum jacket is mounted the spacecraft adapter, weighing 328 pounds. It is sized for ELV loads since it connects the vacuum jacket to the ELV adapter. Twelve struts space the aft ring from the vacuum jacket. Six separation fittings and three FSS fittings are attached to this ring. Additional equipment, including tool boxes, are mounted on this truss. The redundant vacuum-jacketed transfer lines are also mounted to the spacecraft adapter structure. These lines are flex lines which are not easy to handle, particularly with regard to stowing and unstowing by an EVA astronaut.

The ELV adapter, which stays with the ELV after separation, interfaces at six points to the spacecraft truss. This will be a mechanical, as well as electrical, separation. It weighs 138 pounds and can be built to adapt to any ELV interface diameter and number of discrete attachment points. A Delta adapter is shown in the sketch.

Finally, the transport cradle will be mounted in the Orbiter to support the SFHT at four longeron and one keel latches. Each of these fittings weighs 44 pounds. The transport cradle itself also mounts to the Orbiter with four longeron and one keel fitting. The cradle weighs approximately 1200 pounds based on similar designs we've fabricated and qualified.

1.6.2 Thermal Control Subsystem

A thermal control design has been selected to be compatible with the Orbiter, OMV, and Space Station. The design allows flexibility in orientation so that mission constraints imposed by other vehicles do not occur. The key features of our thermal control concept are shown in Figure 1.12. The external surfaces on the Dewar and its supporting structure are painted white to limit their temperature excursions in the orbital environments. The avionics equipment is enclosed in two thermally controlled spaces covered with multilayer insulation. Temperature control in these spaces is provided by a movable shade which varies the equipment baseplate's view to space in response to a temperature sensor. This approach allows the avionics equipment to operate over a wide range of orbital environments. The control volumes are designed to 1) allow full power avionics operation in a hot environment with direct solar input to the heat rejection surface, and 2) to minimize heater power in a cold, deep space environment with no external heat fluxes. The shade was selected over louvers based on heat rejection area requirements to allow efficient operation under conditions of direct solar input.

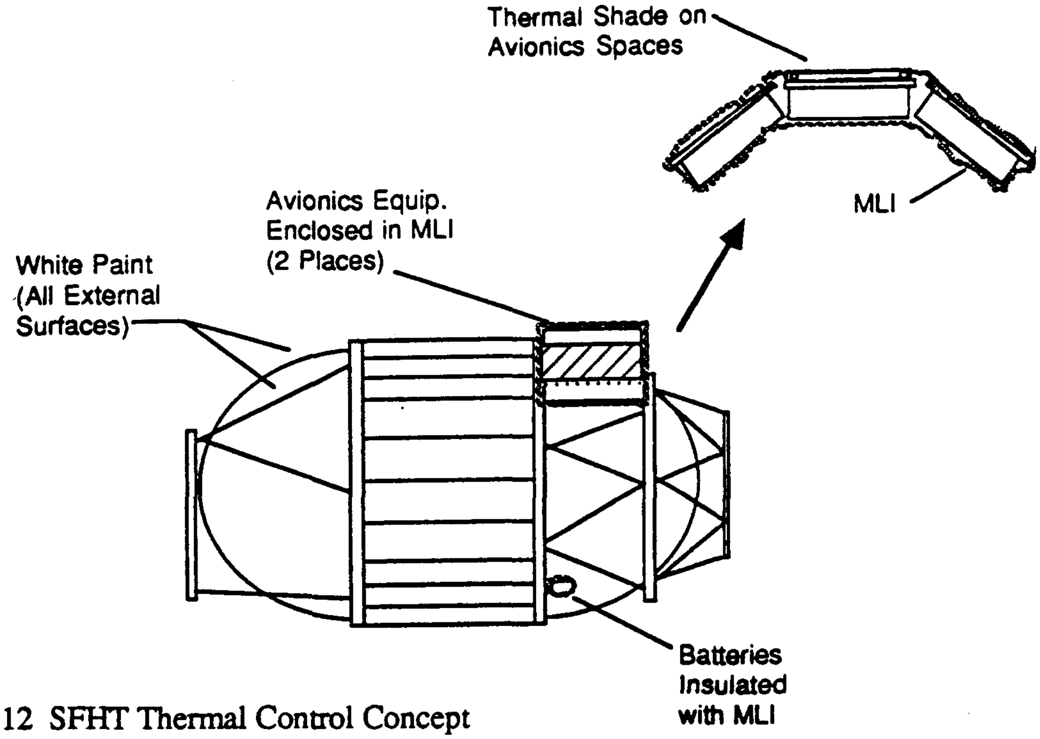


Figure 1.12 SFHT Thermal Control Concept

Standard components which are space qualified are available for this design. The thermal shade, which is somewhat unique, has been flight qualified on another Martin Marietta program. Film heaters of etched nichrome metal laminated between Kapton film will be used. Mechanical thermostats will be used with an arc suppression circuit on each thermostat to assure long life. The insulation blankets on the two avionics volumes will be comprised of double aluminized Mylar film, Dacron net spacers, filter cloth, Kapton facing, and Gortex Ortho cloth. The Mylar will have an acrylic overcoat to protect the aluminization from water vapor damage which can be experienced during earth atmosphere return. The exterior Gortex Ortho cloth was selected because of its optical properties (a/e = .18/.84) and its toughness. Standard stitching and grounding straps will be used.

1.7 AVIONICS SUBSYSTEM

The first activity conducted relative to the avionics subsystem was to identify the user avionics requirements and interfaces, and identify the SFHT instrumentation needed to monitor and control the superfluid helium transfer process. We then addressed the potential for using the previously defined OSCRS avionics to maximize commonality. The safety critical aspects of the superfluid helium tanker relative to the OSCRS storable tankers turned out to be relatively less safety intensive, allowing some simplification of the SFHT avionics as compared to OSCRS.

1.7.1 Instrumentation

To properly monitor and maintain the superfluid helium in its desired state, both on the ground and during a refueling operation on orbit, the tanker must provide the capability to accurately monitor the temperature, pressure, and mass of the liquid. To accomplish this the instrumentation baselined for the SHOOT experiment was baselined for the superfluid helium tanker. The particular sensors identified for the SHOOT experiment provide the accuracy necessary to manage the fluid in storage and during a refueling process as well as providing a proven design concept certified with flight experience. A list of instrumentation within the tanker system is provided in Table 1.4. Figure 1.13 indicates sensor position.

Temperature measurements will be obtained using Germanium Resistance Thermometers (GRT) and Platinum Resistance Thermometers (PRT). The GRTs provide excellent accuracy in the temperature range of superfluid helium (1.3 K to 2.2 K) and will be used to monitor liquid

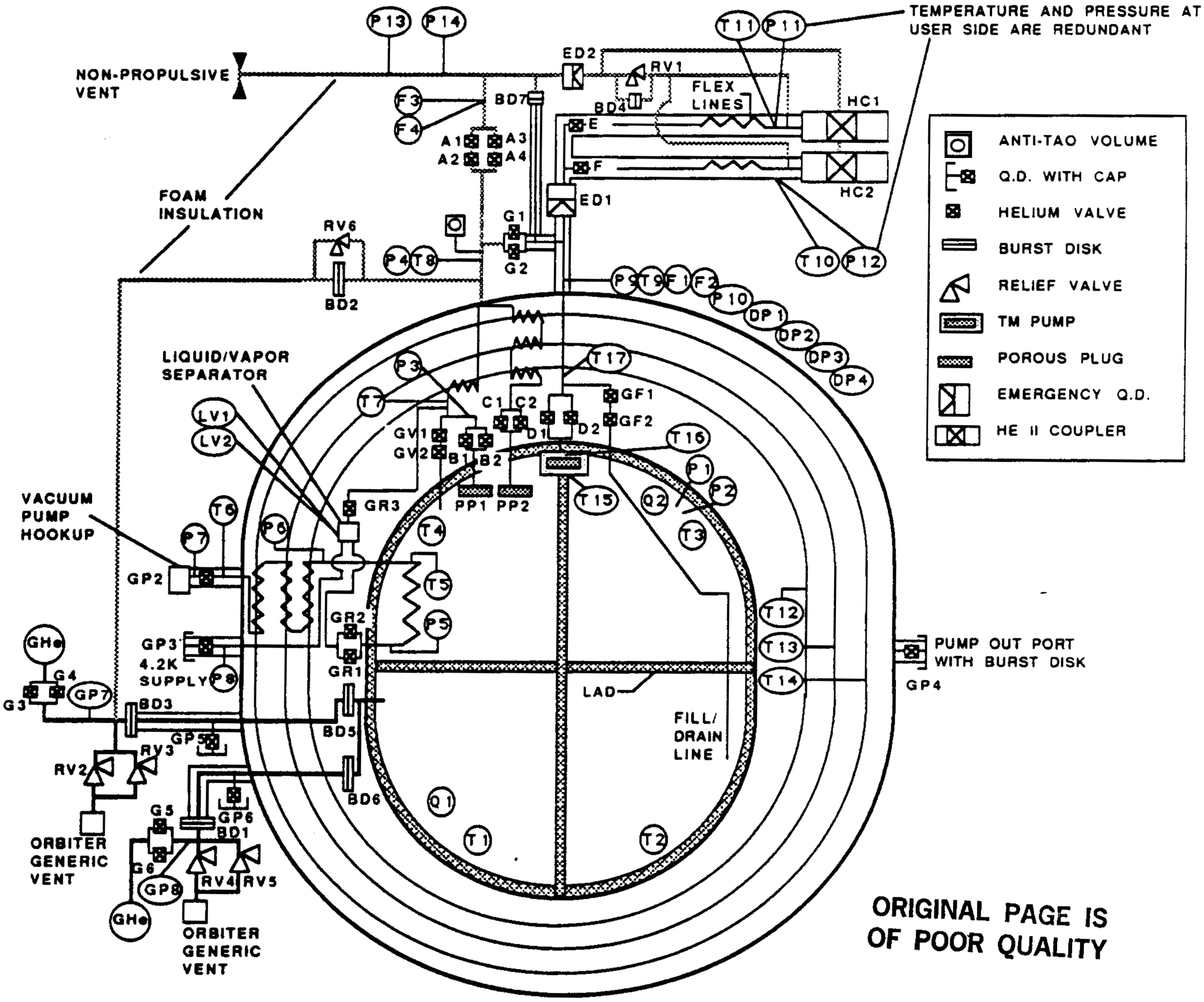


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Figure 1.13 Baseline SFHT Fluid System Schematic Showing Instrumentation

temperature up to 50 K. To monitor the temperature of subsystems or subelements above 50 K to room temperature (312 K), PRTs will be utilized. Each GRT and PRT will be in a four wire configuration, two wires for excitation and two wires for sensor output. We propose using the Temperature and Pressure Measurement System (TPMS) units developed for the SHOOT experiment to provide the excitation and monitor the sensors.

Pressure measurements will be performed with a diaphragm type differential pressure sensor. The diaphragm is of steel construction which allows usage of the pressure sensors in a cryogenic environment. Each pressure sensor will be in a four wire configuration with excitation and sensor monitoring being performed by the TPMS. An AC voltage source will be used for excitation. The AC excitation provides a balanced drive signal to the transducer to reduce the effects of cable characteristics on the transducer signal and to improve the accuracy of the TPMS in monitoring the transducer output signal. Accuracy of the TPMS is expected to be 0.1% of full scale. Multiple pressure sensors will be provided to ensure system reliability.

Table 1.4 SFHT Instrumentation List

MEAS. ID.	MEASURES	RANGE	SAMPLE RATE	FUNCTION	REMARKS
P1	Tank Press	0-100 Torr	.1/sec	On-Orbit tank pressure	redundant if necessary
P2	Tank Press	0-3 ATM	.1/sec	tank press during gnd/launch ops	redundant if necessary
P3	Phase separator, down stream pressure	0-20 Torr	.1/sec	monitor vent phase separator ops	
P4	VCS exit pressure	0-20 Torr	1/sec	monitor TVS ops	
P5	Ground refrig tank Hx pressure	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P6	Inlet to gnd refrig VCS	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P7	gnd refrig exhaust press	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P8	Gnd refrig line supply pressure	0-3 ATM	1/sec	used during fill, conditioning & gnd hold	
P9	fill/drain line press	0-3 Torr	1/sec	used during fill, conditioning, gnd hold, & xfer	(monitor locked-up volume)(may need dual range for xfer)
P10	fill/drain line press	TBD	TBD	monitor locked-up	if required
P11	press in trapped volume (flex line-to-spacecratf)	TBD	TBD		if required
P12	press in trapped volume (flex line-to-spacecratf)	TBD	TBD		if required
P13	overboard vent pressure	0-200 PSI	1/sec	monitor xfer operations	
P14	overboard vent pressure	0-200 PSI	1/sec	monitor xfer operations	redundant sensor
DP 1	pressure drop in F1	0-2.0 psid	1/sec	monitor xfer operations	
DP 2	pressure drop in F1	0-0.125 psid	1/sec	monitor xfer operations	
DP 3	pressure drop in F1	0-2.0 psid	1/sec	monitor xfer operations	
DP 4	pressure drop in F1	0-0.125 psid	1/sec	monitor xfer operations	
T1-T4	internal tank temps	0-5K	1/sec	monitor He temp during gnd & flight ops	
T5	gnd tank Hx exit temp	0-5K	1/sec	monitor loads cooldn & gnd hold operations	
T6	gnd refrig VCS exit temperature	100-300K	1/sec		
T7	VCS inlet temperature	100-300K	1/sec	monitor TVS/VCS performance	
T8	VCS exit temperature	200-300K	1/sec	monitor TVS/VCS performance	
T9	transfer line temp	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T10	temp at disconnect	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T11	temp at disconnect	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T12	VCS #1 temp	0-100K/tbd	.1/sec		
T13	VCS #2 temp	0-200K/tbd	1/sec	monitor VCS perform	redundancy as req-tbd
T14	VCS #3 temp	100-300K	1/sec	monitor VCS perform	redundancy as req-tbd
T15	FEP inlet temp	0-5K	1/sec	monitor pump pressure	
T16	FEP outlet temp	0-10K	1/sec	monitor pump pressure	
T17	transfer line temperature	0-5/0-300K	1/sec	mont chilldn/xfer temp	redundancy
Q1	quantity of SFHe in tank	0-1000Kg	1/sec	tank gauge	
Q2	quantity of SFHe in tank	0-1000Kg	1/sec	tank gauge	redundancy-if required
V1	FEP heater voltage	0-30VDC	1/sec		HLVS data
V2	FEP heater voltage	0-30VDC	1/sec		HLVS data
I1	FEP heater current	0-1.44 Amp	1/sec		HLVS data
I2	FEP heater current	0-1.44 Amp	1/sec		HLVS data
F1	transfer flow rate	TBD	1/sec	monitor xfer operations	venturi flowmeter
F2	transfer flow rate	TBD	1/sec	monitor xfer operations	venturi flowmeter
F3	overboard vent flow rate	TBD	1/sec	monitor vent system operations - backup to mass gauge	
F4	overboard vent flow rate	TBD	1/sec	monitor vent system operations - backup to mass gauge	redundancy

Liquid mass will be determined by inputting a heat pulse into the helium and monitoring selected GRTs to determine the change in temperature. The rise in temperature is then related to liquid mass through the helium specific heat characteristics. This technique is proven and provides the desired accuracy to know liquid mass; it is being specified by the SHOOT experiment. With calibration of the GRTs, accuracies of 3% (SHOOT's goal is 1%) have been obtained in testing by the SHOOT personnel. GRT excitation and monitoring will be via the TPMS units as described for the temperature sensors. For a superfluid helium state only one GRT is required to determine the liquid mass; to ensure system reliability multiple sensors will be included. Flow measurements will be provided by redundant venturi flow meters. Each flow meter contains two differential pressure sensors for determining the pressure drop within the meter, a low range sensor (0-0.125 psid) for flow rates of 25 l/hr to 200 l/hr and a high range sensor (0-2.0 psid) for flow rates of 200 l/hr to 1000 l/hr.

1.7.2 SFHT-Orbiter Avionics

The SFHT avionics is divided into two sections, AFD subsystem and tanker (cargo bay) subsystem. Figure 1.14 shows a block diagram for the SFHT flight system, assuming that we retain much of the redundancy and fault tolerance put into the OSCRS avionics design.

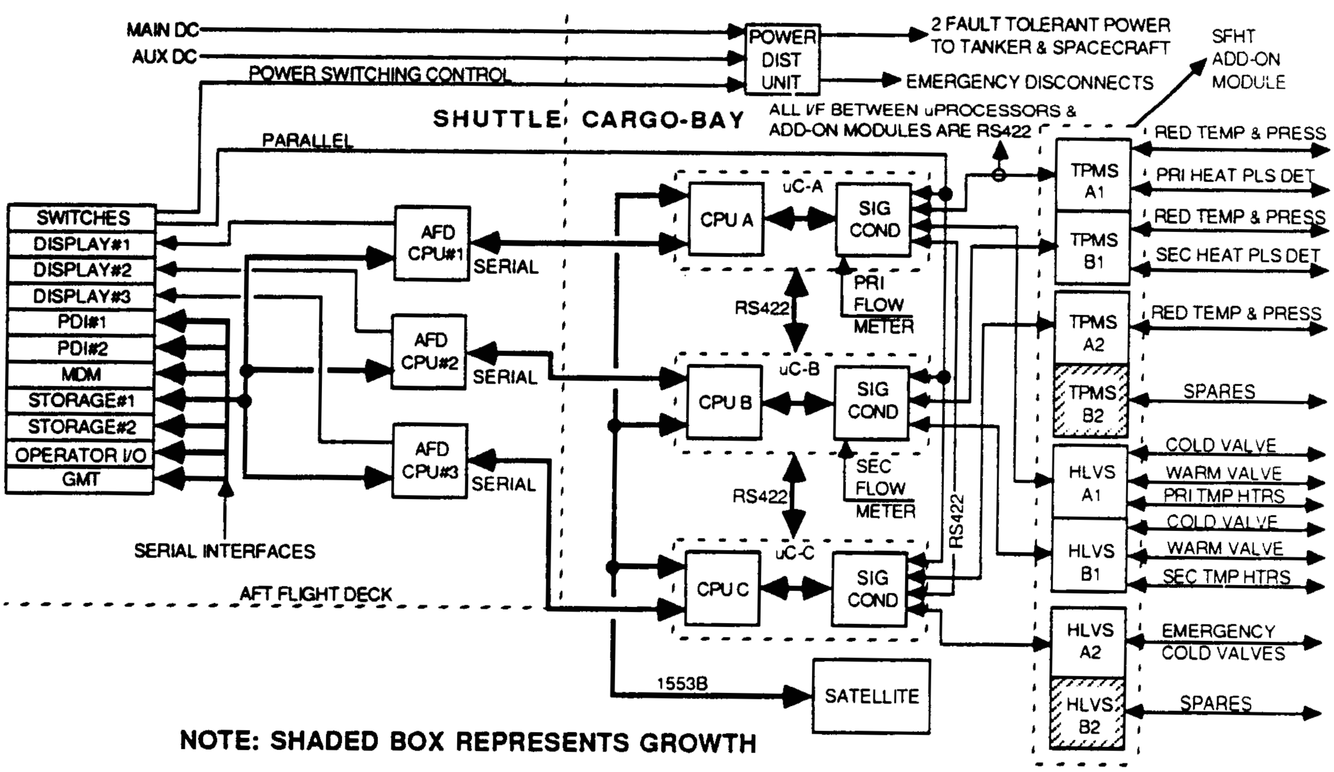


Figure 1.14 SFHT Avionics System Diagram Assuming Maximum Commonality with OSCRS Avionics

The AFD subsystem provides the man-machine interface for crew monitoring and control of the resupply operation. The subsystem is triple redundant and provides two fault tolerance to commanding and monitoring SFHT and the satellite. The control of the SFHT and the display of data is performed on flat panel color displays with touch-screen command capability. An overlay film (resistive, capacitive, or LED-matrix) on the surface of the display provides the touch-screen capability. The crew controls the resupply process by actuating commands from software generated graphics shown on the displays. Each CPU, hardwired to a dedicated display, monitors and processes signals from the displays and transmits the appropriate command or commands to the tanker subsystem through a dedicated serial interface (RS422). To prevent inadvertent valve operations by the crew, command actuation is a two stage process (validate/correct) before transmitting the command to the tanker.

Monitoring of SFHT and satellite data, and providing the information to the crew, is controlled by the CPUs. The CPUs acquire data from the tanker subsystem through the serial interface, and process the data and control the display of data on the three flat panel displays. Since each display is controlled by a dedicated CPU, data displayed on a given screen can be the same or independent of data displayed on the other screens. Interconnections exist between the CPUs for sharing of SFHT and satellite data, and CPU housekeeping data. This provides the capability to warn the crew of a CPU malfunction if one of the CPUs is having difficulty. The crew can then take the necessary action to correct the problem or shut down the problem CPU. Caution and warning is provided for selected tanker and satellite parameters. The CPUs compare monitored parameters to set points stored in memory. These set points will indicate when a parameter is approaching an out-of-limit condition and/or is actually out-of-limits. A visual warning is shown on the display screens indicating to the crew the problem parameter(s) and, if required, procedures to correct the problem. The touch-screen displays will also provide the capability for the crew to review and change, delete or add set points on parameters any time during a mission.

Since the Challenger accident, NASA-JSC safety and mission integration has reassessed the desirability of having all safety-critical operations be monitored and controlled by the GPC. This is possible because the SFHT has a significantly less safety-critical design and operational scenario than does the OSCRS. One of the options we investigated using the Orbiter GPC is shown in Figure 1.15. In this configuration the GPC controls the tanker avionics, with the GRiD computer providing display of tanker and satellite data. The GPC interacts with the tanker avionics through two interfaces, the data bus and a SIO channel. Two GPC links are via Bus Terminal Units (BTUs) with the third GPC link via the Multiplexer-demultiplexer Serial Input-Output (MDM SIO) channel. This combination of GPC links keeps the tanker within payload allocations, which are two BTUs and one SIO channel. The BTU links are the primary link, with one BTU on each data bus. The MDM SIO channel is used in the event of a failure of both data bus links. The GRiD system has the capability to display data in graphic form (instead of tabular form) like the original AFD display system, but without touch-command capability. The GRiD is flight qualified and can interface to the tanker avionics through several standard interfaces without any hardware changes required.

1.8 CONCEPTUAL DESIGN SUMMARY

One of the major questions we addressed following the conceptual subsystem design activity was the margin we had on the 6000 liters of our baseline SFHT conceptual design to accomplish resupply of the reduced set of users, particularly the resupply of 4000 liters of helium to SIRTF. We itemized all of the cooldown, venting, and transfer losses associated with the superfluid helium resupply operation and determined that we had greater than 16 percent margin on available helium to supply 4000 liters of helium to SIRTF after a 90-day on-orbit hold period. The helium allocation and capacity margin tabulation is presented in Table 1.5.

Following the SFHT conceptual subsystem design effort, we also tabulated the SFHT weights to see if we met the mass fraction goal of 0.25. The resulting SFHT weight summary is presented in Table 1.6. As indicated in the table, we meet the mass fraction goal specified in the SOW Design Requirements Document. It should be noted that the STS support cradle only flies with the SFHT on STS launches. It must, however, fly on the STS separate from the SFHT when the SFHT is launched on an ELV, in order to return the SFHT to Earth. The ELV adapter would not fly on STS launches.

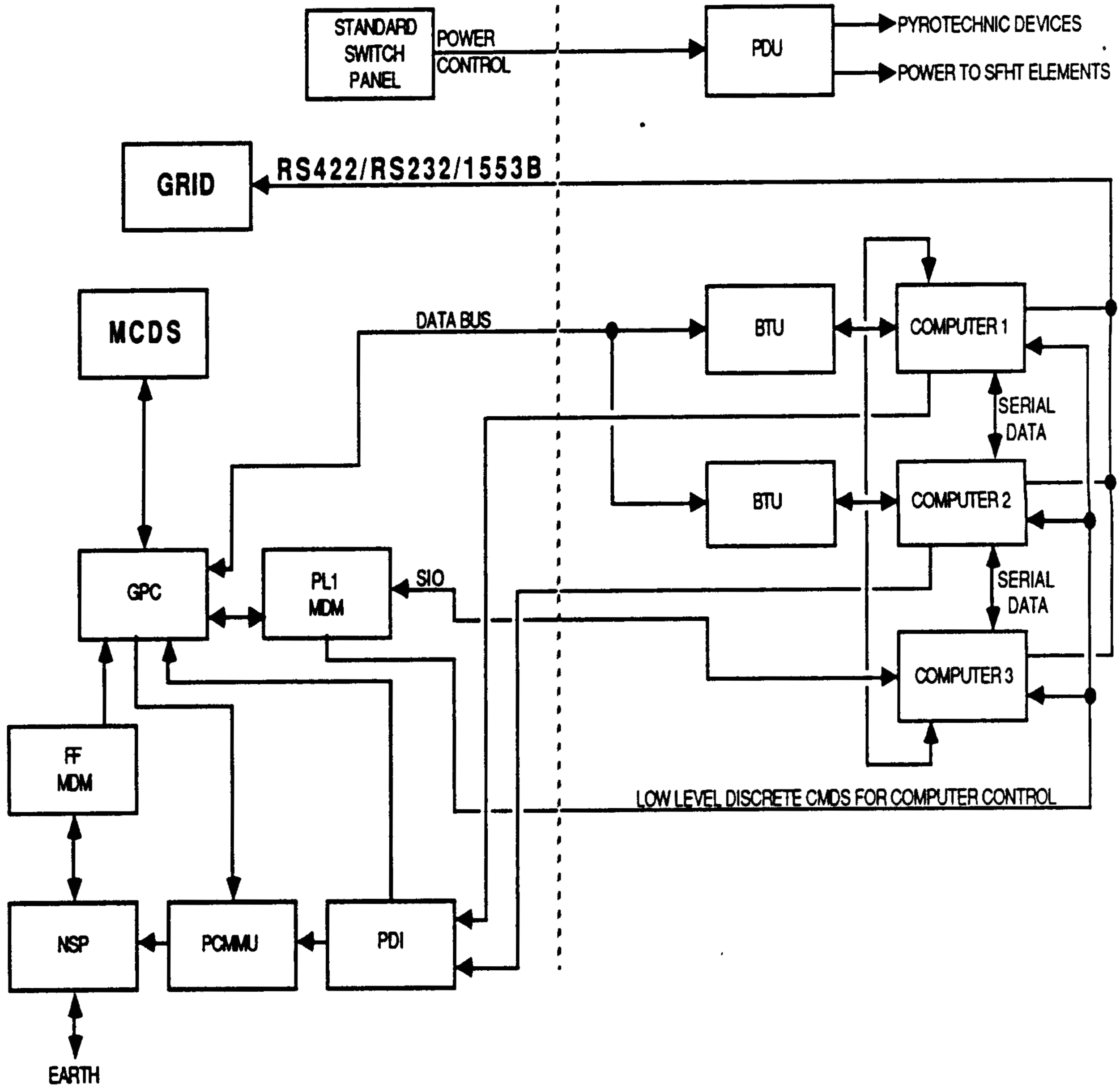


Figure 1.15 SFHT Simplified Avionics Using Orbiter GPC for Safety-Related Monitoring and Control

Table 1.5 SFHT Dewar Superfluid Helium Allocation and Capacity Margin

Ts = 2.0 K Tr = 1.5 K	Transfer Time = 5.5 Hours Transfer Rate = 1000 Liters/Hr
Loaded Volume	6000 Liters
Losses	
• Boil-Off (1.5%/Month, 90 Days)	270 Liters
• Transfer Line Cooling	20 Liters
• Supply Tank Venting (Mechanocaloric Effect, Parasitic Heating)	466 Liters
• Receiver Tank Venting (Reduce to 1.5 K, Parasitic Heating)	368 Liters
• Residual at Depletion (Assuming 10^{-3} g environment)	204 Liters
Volume Available for Transfer	4672 Liters
Margin for Supplying 4000 Liters to SIRTF, Conditioned to 1.5 K	672 Liters

Table 1.6 SFHT Weight Summary

SUPERFLUID HELIUM TANKER EQUIPMENT LIST

SUBSYSTEM	NUMBER	WEIGHT PER ITEM (LBS)	WEIGHT (LBS)
DEWAR			
VACUUM JACKET	1	1200	1200
INNER TANK	1	700	700
VAPOR COOLED SHIELD	3	75.3	226
MLI	1	80	80
STRUCTURE			
SPACECRAFT ADAPTER	1	289	289
OMV ADAPTER	1	224	224
STS SUPPORT CRADLE*	1	1200	1200
FSS LATCHES	7	63	441
CRADLE PINS	1	90	90
FLUID SYSTEM	1	180	180
INSTRUMENTATION	1	25	25
AVIONICS**	1	350	350
THERMAL CONTROL	1	100	100
TOTAL DRY WEIGHT			**5105**
HELIUM (6000 LITERS)			1945
TOTAL WET WEIGHT			**7050**
MASS FRACTION			**0.28**

* STS LAUNCH ONLY

** 60 LBS FOR STATION-BASED SFHT

NOTE: An ELV Adapter (Weight - 138 lbs) required for ELV Launch. Total ELV Launch Weight is 5988 lbs.

1.9 FACILITIES AND GSE DESIGN

Facility capabilities and limitations are an important consideration in the design of the SFHT fluid subsystem and GSE, and the planning of the ground processing flows. Early in the study, our discussions with KSC personnel established some basic groundrules on what facilities could be used to process the SFHT for an STS launch, and these facilities were toured for familiarization. The Payload Hazardous Servicing Facility (PHSF) was identified by KSC as a potential servicing and storage facility for the SFHT. The PHSF is capable of supporting hazardous operations including assembly, testing, propellant transfer, and explosive system operations. It consists of a hazardous operations service high bay connected to an airlock with overhead cranes for handling of payloads. Storage, maintenance, check-out, and helium servicing of the SFHT could be performed in this facility.

The Payload Changeout Room (PCR) at the Shuttle launch pad is a facility designed to install payloads into the Orbiter cargo bay in a protected environment. The Payload Ground Handling Mechanism (PGHM), inside the PCR, is used to insert and access payloads within the cargo bay. The SFHT would be transported vertically to the PCR from the PHSF using the Payload Cannister and Transporter, and then inserted into the cargo bay. The SFHT GSE would then be brought to the PCR and placed at the level closest to the SFHT bay location. The layout of the PCR and the relative locations of the PGHM and the Orbiter bay are shown in Figure 1.16.

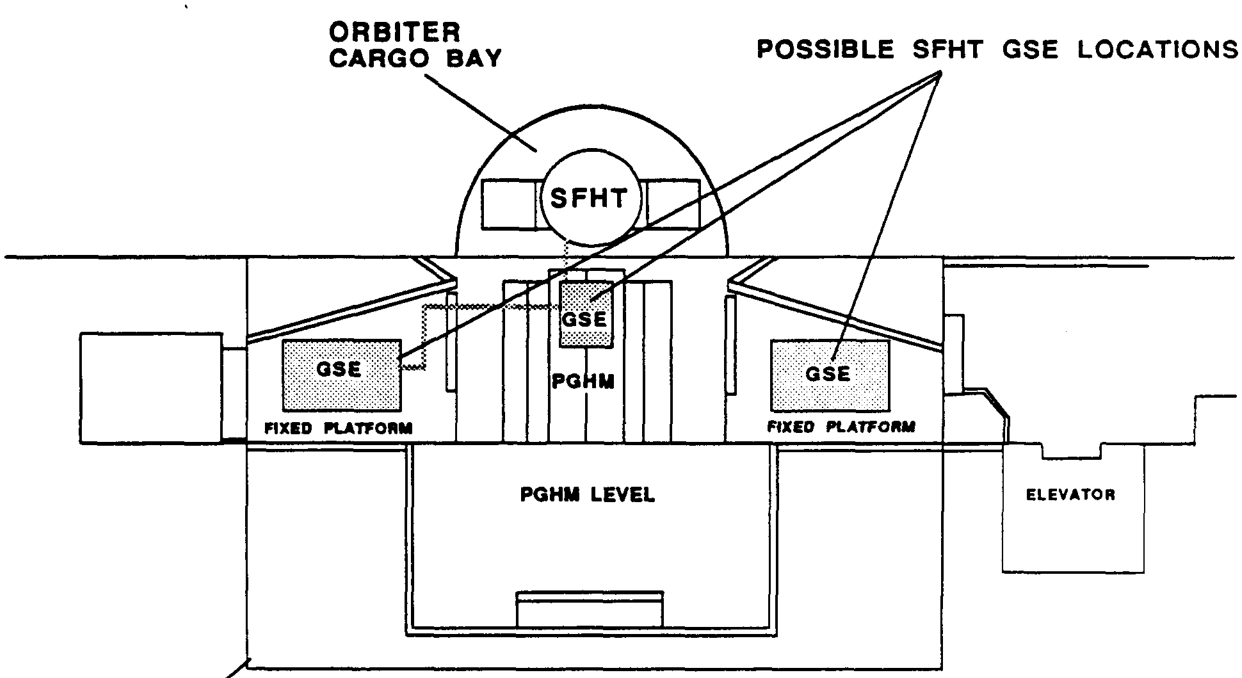


Figure 1.16 Configuration of the Payload Changeout Room Showing SFHT and Associated GSE Relative Locations

The launch sites for the various ELV's all have similar ground accommodations and limitations. For processing of the SFHT, the PHSF could be used regardless of whether the SFHT was being launched on the Shuttle or an ELV. Therefore, the only difference is the accommodations at the launch pad itself. A typical ELV launch pad facility consists of an environmentally controlled work room, work platforms, hoists, and various utility supplies. As with the PCR, there is limited volume for a large amount of payload GSE. However, since the SFHT would be transported to the pad only days before launch, minimal GSE would be required. A concept showing pad facilities required to support the SFHT is shown in Figure 1.17. Work platforms are provided at various levels to allow access to the SFHT and to support the GSE if it is required. Interfaces for overboard venting to the outside of the environmental shelter will be required, particularly for an emergency vent.

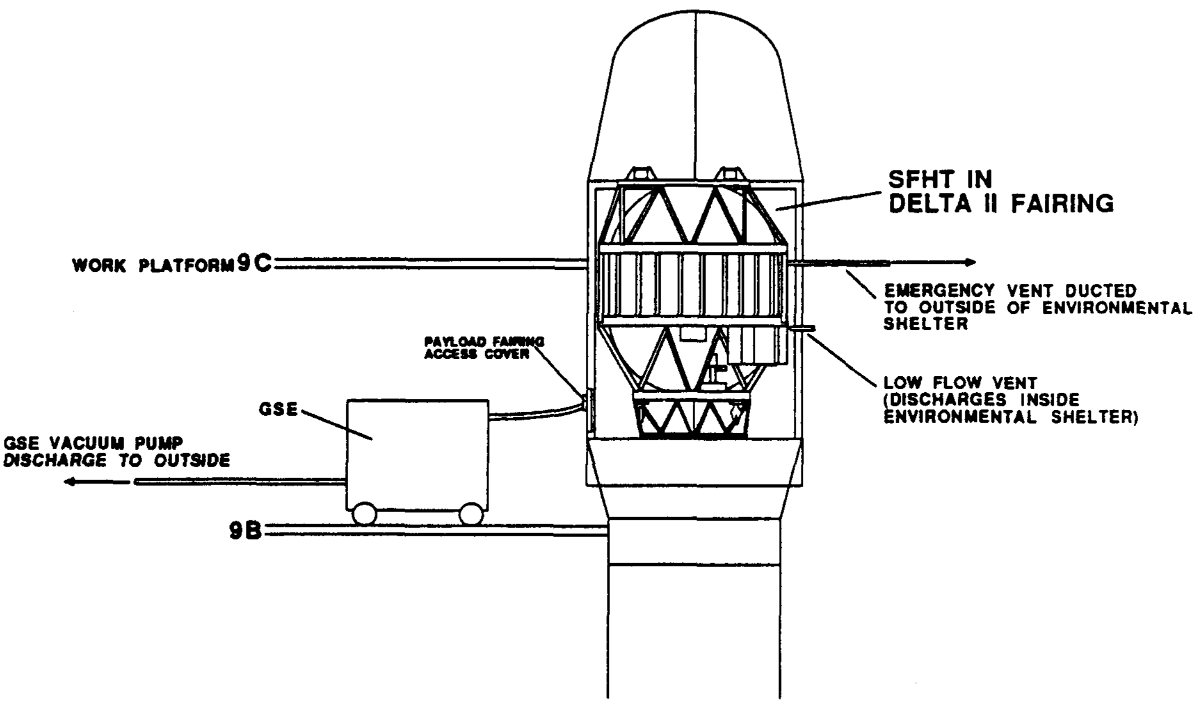


Figure 1.17 ELV Launch Pad Facilities to Support SFHT

1.10 TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

The initial subtask associated with recommended technology development was to assess SFHT design and operational commonality with other subcritical/supercritical cryogen tankers. This task was de-emphasized at the beginning of the program, so we only did a quick review of the SFHT design to identify those elements that might be usable as part of a non-helium cryogenic tanker. Some of the concepts and modeling tools for Dewar thermal optimization might be usable but must be used with the appropriate databases for the fluids under consideration. The vent system (e.g., porous plugs) for SFHe is of course unique to liquid helium and the flow analysis involves two-fluid models and identification of flow regimes where the fluid behaves as a "Quantum" fluid or a "Newtonian" fluid. Design of components, such as valves and the transfer line coupler, suggest approaches for low heat leak but would need a thorough review of the safety aspects, particularly for cryogens such as liquid hydrogen and liquid oxygen. For example, the liquid helium valve being designed by Utah State for SHOOT would not be acceptable in its current configuration for hydrogen usage on the ground since hydrogen in and around the stepper motor could lead to fire and explosion.

Our overall assessment of commonality potential is that there is little that is directly transferable to other cryogenic tankers, particularly in the fluid subsystem. The OSCRS avionics subsystem might have a fair amount of commonality; due to the safety issues with liquid hydrogen and liquid oxygen, however, the avionics redundancy and fault-tolerance would be closer to OSCRS than to the avionics for the SFHT, which is not as safety critical.

In evaluating technology needs for the superfluid helium tanker, we looked at both those items being developed on the SHOOT program, and those tanker-specific items not being developed on SHOOT. In some cases, those items being developed on SHOOT require additional testing for 50 missions usage or to design limits beyond those used for the experiment test bed. Table 1.7 contains our listing of development needs not being addressed by SHOOT. A technology development program schedule and cost estimate to accomplish each is included in a separate cost document submitted with the final report.

1.11 PROGRAM PLAN FOR SFHT DEVELOPMENT

We prepared a program plan for the SFHT development which addressed our approach to the detailed design and development, fabrication and test of the superfluid helium tanker conceptually designed during this study. The phase C/D program, as outlined, runs through post-flight analysis of the first mission and is 6 years in length, ending with a launch in October 1997. The SFHT is designed to meet the requirements of the Systems Requirements Document, Attachment A to the contract SOW. The program consists of detailed design of both the flight equipment and GSE, fabrication and test of a dedicated Dewar Qual article to verify the multimission life capability, fabrication of one flight unit and one set of GSE, testing, delivery to NASA-KSC and support of the mission. We believe that eventually a second superfluid helium tanker would be procured as a backup capability or to permit one tanker to be used as a depot at Space Station while the second one is used for servicing from the Orbiter, and in-situ servicing of a payload when carried to the user spacecraft with the OMV.

The phase C/D master program schedule for the SFHT program is shown in Figure 1.18. Time phasing is based on completion dates for defining requirements, performing design tasks, procuring required components and materials, accomplishing fabrication and assembly, and conducting validation and verification testing. The initial emphasis has been placed on the systems engineering activities necessary to define requirements and firm up the interfaces. Following concurrence with the requirements and specifications reviewed at the Program Requirements Review (PRR) by NASA-JSC, we will authorize major procurements necessary to support the fabrication and assembly activities, particularly for the Dewar qualification test article. Our plan is to fabricate all components and piece parts for both the Qual Dewar and the flight article. We will then assemble the Qual Dewar and conduct the qualification tests. While this is occurring, we will be fabricating the other (non Dewar) subsystems, which are to be tested and then flown, in a protoflight approach. Once Dewar qualification is complete, the flight Dewar will be assembled and integrated with the rest of the tanker subsystems. System level tests will then be performed for flight certification and the tanker delivered to NASA-KSC.

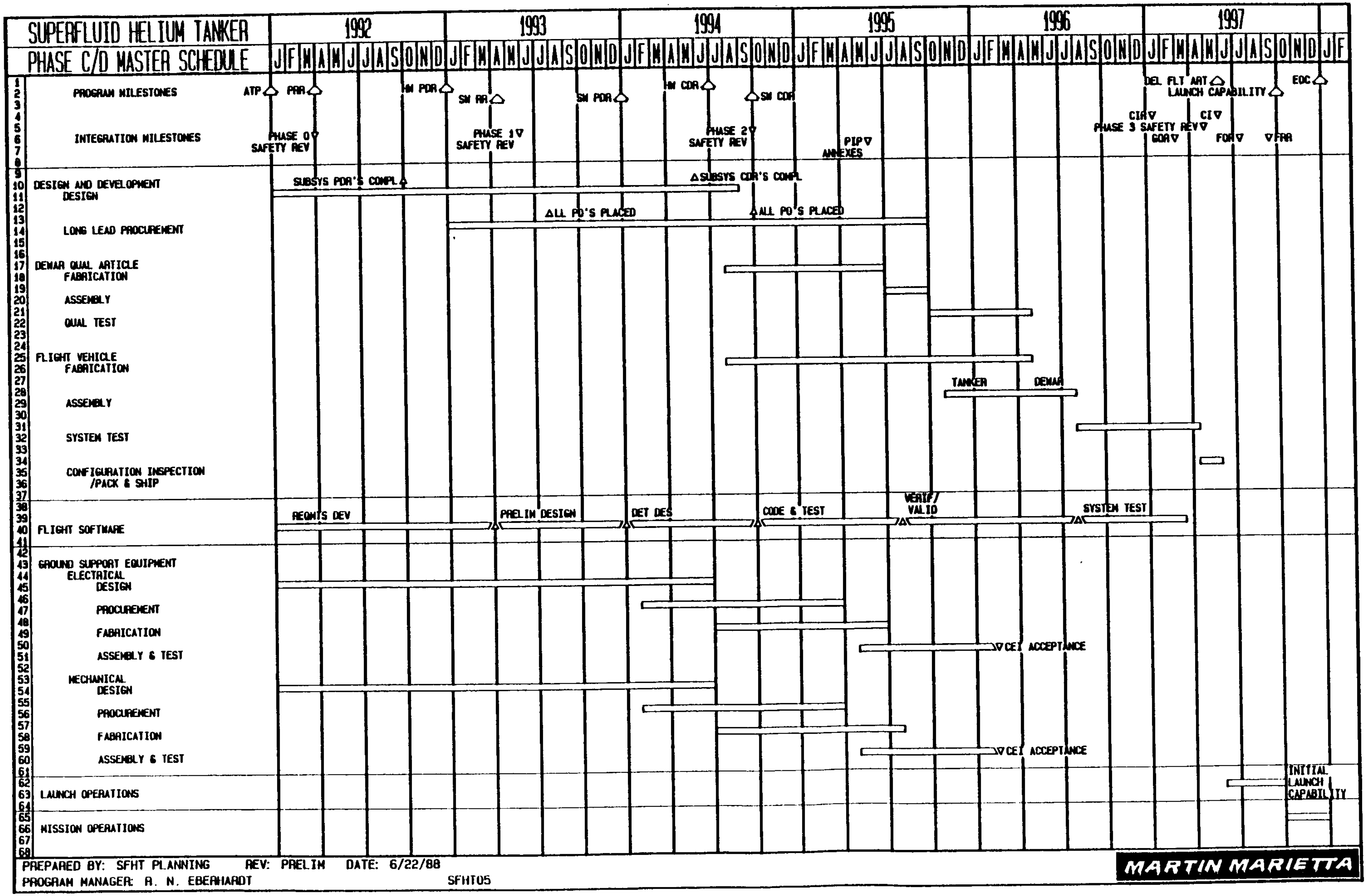
For those elements of the SFHT which are to be protoflight, special care must be taken in their validation and the combination of testing and analysis which shows they're good for the 50 mission design life. For both procured and Martin Marietta-manufactured hardware, our verification test program will be initiated at the component level. These component prototype tests are expected to drive out any problems early and are prerequisite to assembly-level prototype testing. This test approach ensures a systematic validation of performance, personnel, and procedures that minimizes risk and establishes high confidence in the system verification activities.

The tanker system test schedule, which is approximately 9 months in duration, is protected by preplanned schedule reserve and will support delivery to NASA-KSC 65 months from ATP. Launch operations also contains preplanned schedule reserve and supports the first flight of the SFHT. As indicated in the schedule, approximately 2 years at the beginning of the program is allocated for design and development.

Table 1.7 SFHT Technology Development Needs

- Dewar Ground Operations Heat Exchanger Characterization
  - Internal Heat Exchanger Sizing and Design to Condition and Maintain Stored SFHe at Desired State Without Topping
- Dewar Design/Fabrication Technology
  - Structural Design Approach (Supports Piercing Into Inner Vessel)
  - Stiffness of Telescoped Tank Support
  - Effective Thermal Conductance of Telescoped Tank Support System; Thermal Cross-Coupling
  - VCS/Heat Exchanger Fabrication and Thermal Optimization
  - Alumina-Epoxy Straps for Large Dewars
    - Cycle Life To Meet 50 Mission Requirement
    - Thermal Performance
- Transfer Line Coupling
  - Qualifying for 50 Missions
  - Automatic Operation Carrier Interface
  - Heat Leak
- Motorized Throttling Valve
  - LHe Temperatures
  - Use as Thermal Conditioning (JT Valve)
  - Use for High Rate Venting During Transfer
- MLI Blanket Fabrication Technology for Between Flight Maintenance
  - Dewar Component Changeout Considerations
  - Blanket Edge Fabrication and Performance
- High Conductance Valves
  - Handle Fluid Transfer Rates to 1000 L/Hr
  - Reduced Weight
  - Good for 50 Mission Life
  - Low Heat Transfer (Valves Outside)
  - Total Shut-Off (Valves Inside)
- Transfer Line Characterization (Heat Leak Critical)
  - Flex Lines
  - Line Lengths to 12 Feet
  - EVA Compatibility (Including Couplings)
  - Emergency Disconnect Compatibility
  - Two Phase Flow During Transfer (How to Suppress, if Needed)
- Superfluid Helium Vent Relief Valve
- SFHe Transfer System Analytical Model Development and Correlation with Data (Assume One-g Transfer System Tests are Being Done by NASA and/or Industry)
- Liquid Acquisition Device (Post SHOOT)
  - Two-Fluid Flow
  - Pumping to Refill
- Selection/Characterization of Conventional Insulation on Large Tank
  - K vs T
  - Outgassing
  - Ability to Withstand Thermal Shock
  - Use of Reflective Surface (e.g. Tape) or Other Options Such as Direct Aluminum Layer Application
- Superfluid Helium TM Pump Performance (post SHOOT)
  - 500 to 1000 L/Hr Range
- Porous Plug Phase Separators (Post SHOOT)
  - High Capacity Porous Plug Phase Separators for Venting During Transfer
  - Characterization of Normal Vent Porous Plug Phase Separator (Controllability, Flooding, Efficiency as Thermodynamic Vent Element)
  - System Level Ground Demo - Separate Supply and Receiver Vessels
- Instrumentation (Post SHOOT)
  Level Sensors, Mass Quantity Sensors, Flow Meters
- Limited Life Avionics Parts (Post SHOOT)
  - Identification of Piece Parts That May Not Withstand 50 Missions (Examples: Switches, Relays, Motors, Solenoids)
  - Conduct Qual Tests To S Level to Impove Life
- Evaluate TPMS and HLVS for 50 Mission Usage (Post SHOOT)
  - Evaluate Reliability of Piece Parts
  - Examine Repackaging to Increase Reliability
  - Examine Maintainability (Parts Replacement
- Slosh
  - Design Concern? Impact to Liquid Acquisition Device?

Figure 1.18 SFHT Phase C/D Program Master Schedule



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A Program Cost Estimate has been prepared as a separate document (MCR-88-1403) and submitted to NASA-JSC. All costs are reported in constant Government Fiscal Year 1988 dollars. The cost estimates reflect that the design of the SFHT incorporates components of like or similar design to those flying in the SHOOT orbital test. One major area of cost difference from the SHOOT system is the Dewar inner storage vessel, outer vacuum jacket, and alumina/epoxy support straps. We've also costed a dedicated Dewar test article for conducting qualification tests. Our structures, thermal, and avionics subsystem costs have been compared to those of the OSCRS design, with appropriate cost deltas generated per differences in the design.

1.12 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were complied during the course of the SFHT study effort:

- A 6000 liter SFHT appears to be a reasonable size to handle the reduced user complement specified for SFHe resupply through the year 2006. We had selected the 6000 liter capacity during our Task 2 effort using this reduced user complement and found no reason to change that decision.

- We have selected a slightly cylindrical Dewar shape which fits within the fairings of the Delta, Atlas, Titan III and Titan IV launch vehicles, as well as the STS Orbiter. This results in a mixed fleet approach to minimizing total mission launch costs. We recommend that the SFHT be designed for compatibility with only one ELV in addition to the Orbiter since interface hardware and ELV unique GSE, operations and integration can result in significant non-recurring and recurring costs to maintain flight compatibility with all ELVs.

- We have selected a ground servicing concept which utilizes a ground heat exchanger for establishing and maintaining the storage Dewar at the desired temperature without activating flight valves to conduct periodic topoffs. This technique allows us to "subcool" the Dewar thermal protection system and meet the eleven day ground hold period following cargo bay door closure. Either pressurized (subcooled) or saturated superfluid conditions in the Dewar are possible.

- Based on a worst case vent analysis for loss of guard vacuum (where we assumed some stratification could develop within the supercritical fluid at the 80 psi burst level), we selected a conventional insulation (non-MLI) to be applied to the inner storage vessel to reduce the heat flux and minimize the size of the vent line. We configured two totally redundant vent lines within the Dewar to handle loss of guard vacuum conditions.

- Our selected avionics approach ties into the Orbiter GPC for safety-related monitoring and utilizes a redundant computer system on the AFD for superfluid helium transfer monitoring. We baselined the use of the HLVS and TPMS boxes being developed on SHOOT to interface with tanker temperature and pressure sensors, valves, and TM pump heater elements.

- An overboard vent interface, such as a T-O umbilical interface or a "generic" orbiter vent interface, is required to handle nominal and emergency venting when the SFHT is launched in the STS. Automated decoupling is needed in the vent line, as well as the electrical SFHT/STS interface to allow the SFHT to be removed from the Orbiter for its use as a Space Station supply depot.

- We recommend that automatic refueling (transfer line coupling interface) be baselined as the primary method for the SFHT with capability for EVA mating/demating as a backup.

- We can meet the design goal mass fraction of 0.25.

Several recommendations for additional study effort beyond the scope of work on the present contract resulted from our study effort:

- Some follow-on work should be performed to identify approaches for establishing SFHT stability once on-orbit when launched by an ELV. The overall ELV operating concept, including docking and transport scenarios with the OMV, should be more thoroughly investigated.

- Growth provisions for adding helium refrigeration/reliquefaction capability should be investigated as a means of minimizing the adverse boil-off and venting aspects associated with the SFHT when used as a space depot.

- Users desiring superfluid helium resupply should assess receiver Dewar design impacts early in their design process since the ability of the SFHT to adequately accomplish the servicing is coupled to the specific features of the user's design. Developing standardized interfaces is required to minimize the diversity and complexity of the SFHT interfaces to the potential users, but is difficult until user interface requirements are much better defined. User interface definition should also be an early priority in the user design process.

2.0 INTRODUCTION

Replenishment of superfluid helium (SFHe) will extend the on-orbit life of observatories, satellite instruments, sensors and laboratories which operate in the 2 K temperature regime. We have studied the technology associated with SFHe resupply and produced a conceptual design of a Superfluid Helium Tanker (SFHT) which is capable of meeting a wide range of user requirements (helium quantities, launch dates, frequency intervals for resupply, fluid state, and condition of receiver at time of servicing). This report provides a detailed summary of the major program conclusions, analyses/trade study results, recommended fluid subsystem conceptual designs and operational considerations for the SFHT, conceptual designs of the structural/mechanical, thermal control, and avionics subsystems, technology development recommendations and a phase C/D Program Plan for SFHT development and hardware fabrication and delivery.

We have reviewed the previous work on superfluid tankers and have used that as a starting point for our trade studies. This included the STICCR studies (References 2.1 and 2.2), the Fluid Management Study done for STICCR (Reference 2.3), the Swales & Associates, Inc., studies done for NASA-GSFC (References 2.4 and 2.5) related to Space Station-based liquid helium servicing facilities, and numerous technical papers authored by industry, university and NASA personnel. We have both study and research-oriented IR&D tasks that are contributing to our knowledge and data base regarding superfluid helium transfer, and these results are factored into this study contract, as appropriate. Since the Superfluid Helium On-orbit Transfer (SHOOT) experiment is focused on obtaining the needed technology for the SFHT we have been closely following the progress on this program (Reference 2.6-2.9). Our commitment to supplying the fluid acquisition devices for this test bed has kept us closely involved in the details of transfer techniques and component operational capabilities being developed to support this flight experiment. Since we were one of the OSCRS contractors, we are very familiar with the design concepts and approaches, particularly as they relate to servicing at the Space Station (Reference 2.10); we have used our OSCRS database to assess impacts peculiar to the superfluid helium resupply application.

We have contacted all of the known United States users of superfluid helium to ascertain their design requirements. Only a few of these user systems are sufficiently defined to permit a good first cut at interface definition. For other less defined users, these study results will help them define features and operations they'll need to consider in their designs to permit efficient and cost effective resupply.

We have done a thorough assessment of the mixed fleet concept for SFHT launch. We considered all mid-size and larger expendable launch vehicles (Delta, Atlas, Titan III and Titan IV) as possible launch vehicles in addition to the Shuttle Space Transportation System (STS). We attempted to thoroughly address all ground and flight issues of the mixed fleet approach to provide decision makers with an adequate database for realistic assessment of launch concept feasibility and SFHT design and operational impacts.

Three approaches of accomplishing on-orbit resupply were also evaluated: 1) from the Orbiter bay, 2) from an OMV or an OTV/OMV stack carried remotely to a satellite or platform for in-situ servicing, or 3) from Space Station as a Liquid Helium Servicing Facility (LHSF). The initial servicing from the Orbiter would use astronaut control from the Aft Flight Deck (AFD) of the Orbiter, and possibly EVA for umbilical mate/demate. Future servicing will be accomplished remotely using tankers at the Space Station or in conjunction with OMV's, and the Flight Telerobotic Servicer may become a part of the overall automated resupply concept. Our design approaches are selected to be compatible with these interfaces, including evolution to the fully automated capability.

We prepared a SFHT Technology Development Plan and Phase C/D Program Plan, and associated cost estimates, to aid both user spacecraft developers and satellite servicer developers in future planning activities. We believe the results obtained during this study, as documented in the following sections, are sufficiently definitive to allow a Phase B SFHT study to be initiated.

3.0 DESIGN GUIDELINES, GROUNDRULES AND APPROACH

The objectives of the superfluid helium tanker study were to define requirements, prepare a conceptual superfluid helium tanker design, conduct a commonality assessment, recommend technology deficiencies, and prepare a development program plan and cost estimate. The first two tasks in this effort were to collect the user requirements and prepare a fluid subsystem conceptual design which would then be incorporated, following trade studies, into a tanker conceptual design. Task three resulted in SFHT conceptual designs for all tanker subsystems. Tasks four and five involved technology development recommendations and phase C/D program planning and cost estimating activities. A study flow of the five tasks is shown in Figure 3.1. We have taken a systems approach to requirements analysis and trade studies to be sure that all system and programmatic design drivers are included, not just those that are fluid-related.

The use of conclusions and recommendations from previous superfluid helium tanker studies, and the technical interaction with workers actively advancing the state-of-the-art of associated technologies, was key to our approach in conducting the tasks documented in this report. We had technical interchange meetings with NASA-GSFC, ARC, MSFC and JPL regarding past experience and current work. Many of those contacted have documented extensively in the technical literature. We visited NASA-KSC to discuss ground servicing, and operational design drivers and constraints, related to handling tanker capacities of 6000 to 10000 liters, and greater.

One of the key features of our approach to conducting this study has been the use of two well-recognized experts in the areas of superfluid helium fluid management and hardware design. Dr. Glen McIntosh of Cryogenic Technical Services contributed significantly to the trade studies on Dewar design and ground servicing. Dr. John Hendricks of Alabama Cryogenic Engineering contributed in the areas of venting system design as it relates to transfer techniques, and fountain effect pump characterization.

A number of design guidelines influenced the results of our trade studies and analysis. We used the baseline SFHT requirements in the Contract SOW, and the System Requirements Document Attachment A of the SOW as our basis. In addition, the following design guidelines and assumptions were developed during the course of conducting this study.

1. The baseline concept is to transfer superfluid helium to the user; options were open as to the condition of fluid at launch and how we obtained the superfluid to be resupplied.

2. There is no requirement to relocate the SFHT within the Orbiter once we reach orbit.

3. The maximum storage time on-orbit prior to resupplying SIRTF, the reference user dictating the 4000 liter capacity design goal, is 3 months.

4. The capability to service "warm" users is a requirement. Big advantages, however, are obtained in terms of cost per usable kilogram of helium to orbit if the users are serviced "cold." Evaluation criteria in our trade study thus considered mixed user thermal conditions and this led to evaluation of modular tanker approaches.

5. We assumed that Delta, Atlas Centaur and Titan Expendable Launch Vehicles (ELVs) were all candidates for providing ELV boost capability for the SFHT. A minimum payload diameter of 9 feet was selected as a trade study parameter.

6. Helium liquefaction and refrigeration were not considered part of the initial SFHT capability (they were also not part of the SHOOT/STICCR baselines). Our designs, however, are configured so that this capability can be added as growth potential to work boil-off/venting issues when the SFHT is used on orbit as a Space Station depot.

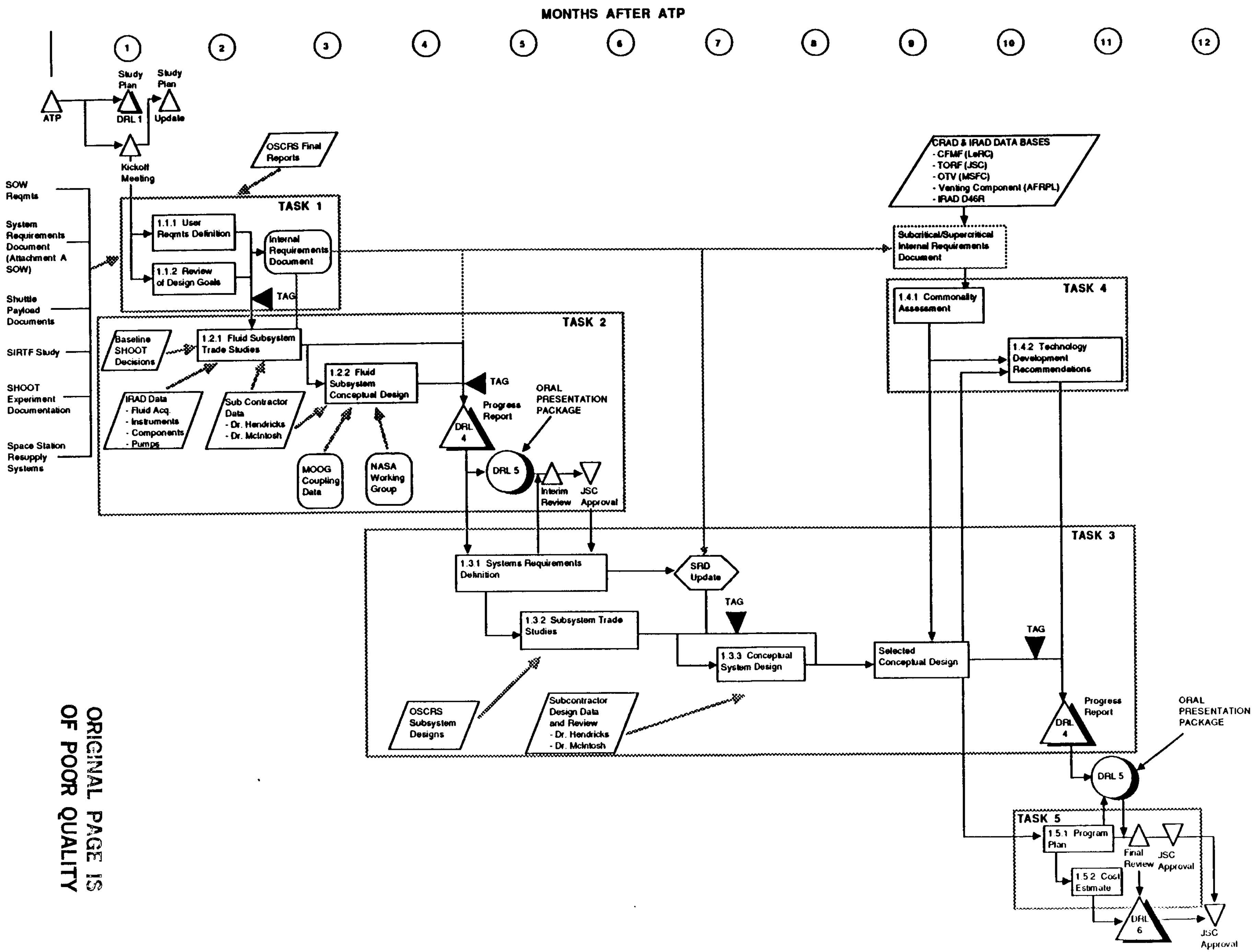

Figure 3.1 SFHT Study Task Flow

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7. Flight Telerobotic Servicer (FTS) is an option; we're designing to be compatible if the user specifies its use.

8. We're not relying on a servicing facility being available at Space Station; it's not in the IOC design. The only interfaces we are assuming at Station are power, a control station similar to the Shuttle AFD capability, and debris/meteoroid protection.

Following our Interim Program Review at NASA-JSC, we updated our design guidelines and assumptions. The following design guideline updates and additions further clarified and bounded our Task 3 conceptual design and Task 4 commonality assessment efforts:

1. A reduced set of resupply customers shall be used; SIRTF, AXAF, Astromag, MMPS/CPPF and LPE.

2. STS is considered the prime resupply site, but the SFHT design is to be compatible with use on Space Station for 9 month orbital stay and station venting requirements.

3. SFHT design impacts and capability should be considered if Space Station on-orbit storage time were to be increased to 12 months.

4. Baseline ground hold capability shall be compatible with closing orbiter cargo bay doors ten days prior to launch.

5. Identify required GSE for emergency venting on the ground prior to installation into Orbiter.

6. A "generic" orbiter inert gas vent will exist in at least one of the orbiters. Vent line sizing and thermal analysis shall be performed to establish SFHT requirements for this generic line.

7. Re-assess need for SFHT servicing capability in both horizontal and vertical positions.

8. Emphasis on SFHT avionics should be placed on tanker-to-user functionality, rather than tanker-to-host (i.e., Orbiter or station). Policy on orbiter payload control by the GPC is indeterminate at this time.

9. Address the weight and complexity impacts to both the user and SFHT of the allocation of servicing hardware to either. The launch cost is only paid once if incorporated into user; complexity probably should be maintained on tanker to permit maintenance.

10. Task 4 commonality assessment should be limited to identification of possible areas of commonality with other cryogen tankers, as opposed to analytical studies of system capabilities and designs.

11. Flow gauging accuracy of ±5 percent and mass gauging accuracy of ±3 percent.

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4.0 TASK 1 - COLLECTION OF REQUIREMENTS

The overall objective of Task 1 was to review and define the requirements for the SFHT in order to maximize flexibility and to ensure that all user requirements were addressed in the subsequent conceptual design tasks. The requirements for resupply from the Space Station or Orbiter cargo bay were to be identified, and constraints imposed by the method of carrying the SFHT to the user (via Orbiter, OMV or ELV) were to be defined. These requirements are discussed below, ending with an assessment of requirement impacts on initial study design goals.

4.1 USER REQUIREMENTS DEFINITION

Numerous potential users had been identified by previous studies (References 4.1-4.2); a summary of their fluid resupply requirements were listed in the Statement of Work for this program. These users are listed in Table 4.1, which presents a summary of the more important requirements for each. The most significant requirement is the amount of helium needed, which ranges from a few hundred liters to several thousand. The resupply frequency of the users also varies over a wide range. Individuals in both NASA and industry were contacted to obtain updated information on each user. Requirements for several of the users have changed since the table presented in the Statement of Work was compiled. As examples of the diversity of the potential users of the SFHT, the following paragraphs present brief summaries of several of the best defined users, highlighting the key design features. Full details of all the users can be found in Reference 4.3, which contains the results of the literature search conducted on each of the users.

Table 4.1 Superfluid Helium User Database

USER	HELIUM VOLUME (liters)	HELIUM PHASE	SERVICE INTERVAL (days)	SERVICE TIME (days)	ORBIT (km)	LAUNCH DATE**	MISSION LIFETIME (years)
AXAF	200 - 400	He II	730	TBD	600	1996	10
IR Telescope in Space	450	TBD	180	7	400-900	1997	2
MMPS/CPPF	200	He I & He II	30-90	1 to 7	On SS	1997	5
Gravity Probe B	1500	He II	730	14	600-650	1995	TBD
SIRTF	4000	He II	730	3 to 14	700	1997	6 to 12
Astromag	3100	TBD	730	TBD	On SS	1996	10
Far IR/Subm Space Telescope	2000	He II	700	TBD	500	1997	6 to 10
LDR	TBD*	He II	730	TBD	700	2000	10 to 15
Subm Telescope	250	TBD	180	7	400	1998	TBD
Superconducting Magnet Fac.	500	He I or He II	90	TBD	On SS	1998	5
Planetary IR Telescope	500	He II	180	TBD	500	1999	6 to 10

* Depends on degree of mechanical refrigeration;
quantity could be ~2700 kg without mechanical refrigerator
**Launch Dates are Approximate

4.1.1 Advanced X-Ray Astrophysics Facility (AXAF)

AXAF is one of the four great observatories planned by NASA. The program, recently awarded to TRW as prime contractor, is currently awaiting a final decision on a new start funding request for fiscal year 1989. The current study contracts for AXAF are under the direction of NASA-MSFC and have been classified as A109 sensitive; therefore, detailed information on configuration, helium quantity, and interfaces were not available for distribution. However, only one instrument, the X-ray Spectrometer (XRS), requires superfluid helium in the range of 200-400 liters. Two AXAF Dewar definition studies being contracted by NASA-GSFC are underway to define the overall concept and fluid system configuration; however, these studies are also A109 sensitive. A recent paper by Dr. Steve Castles (Reference 4.4) presents data suggesting the superfluid helium capacity of the XRS Dewar may be as high as 1300 liters.

Discussions with NASA-GSFC personnel have indicated that the structural and fluid interfaces will be located on the aft end of the AXAF, which will have an overall configuration similar to that of the Hubble Space Telescope.

4.1.2 Space Infra-red Telescope Facility (SIRTF)

SIRTF is a 1-meter class, long duration, superfluid helium-cooled telescope planned for launch in the mid 1990's (References 4.5-4.7). Current plans are for SIRTF to be launched on the Shuttle into a 300 km orbit inclined at 28.5 degrees. It will then be transported to its final operating altitude of 900 km by the OMV. The SIRTF fluid management system, shown schematically in Figure 4.1, consists of a toroidal shaped Dewar with a capacity of 4000 liters of superfluid helium. This fluid system provides enough helium for an orbital lifetime of 2 years plus margin. The total operating life of SIRTF is planned for 6 to 12 years meaning that up to 5 resupplies of superfluid helium could be required. The previously mentioned STICCR contracts studied methods of on-orbit instrument changeout for SIRTF. These operations would result in the SIRTF being near ambient conditions at the start of the helium replenishment operations. Recent discussions with ARC personnel have indicated that on-orbit instrument changeout is no longer being planned. Therefore, SIRTF should always be at superfluid helium temperatures unless a contingency situation has occurred and it can not be retrieved by the OMV in time to be resupplied in a "cold" condition. The baseline servicing location is the Orbiter cargo bay pending placement of the Servicing Facility at the Space Station.

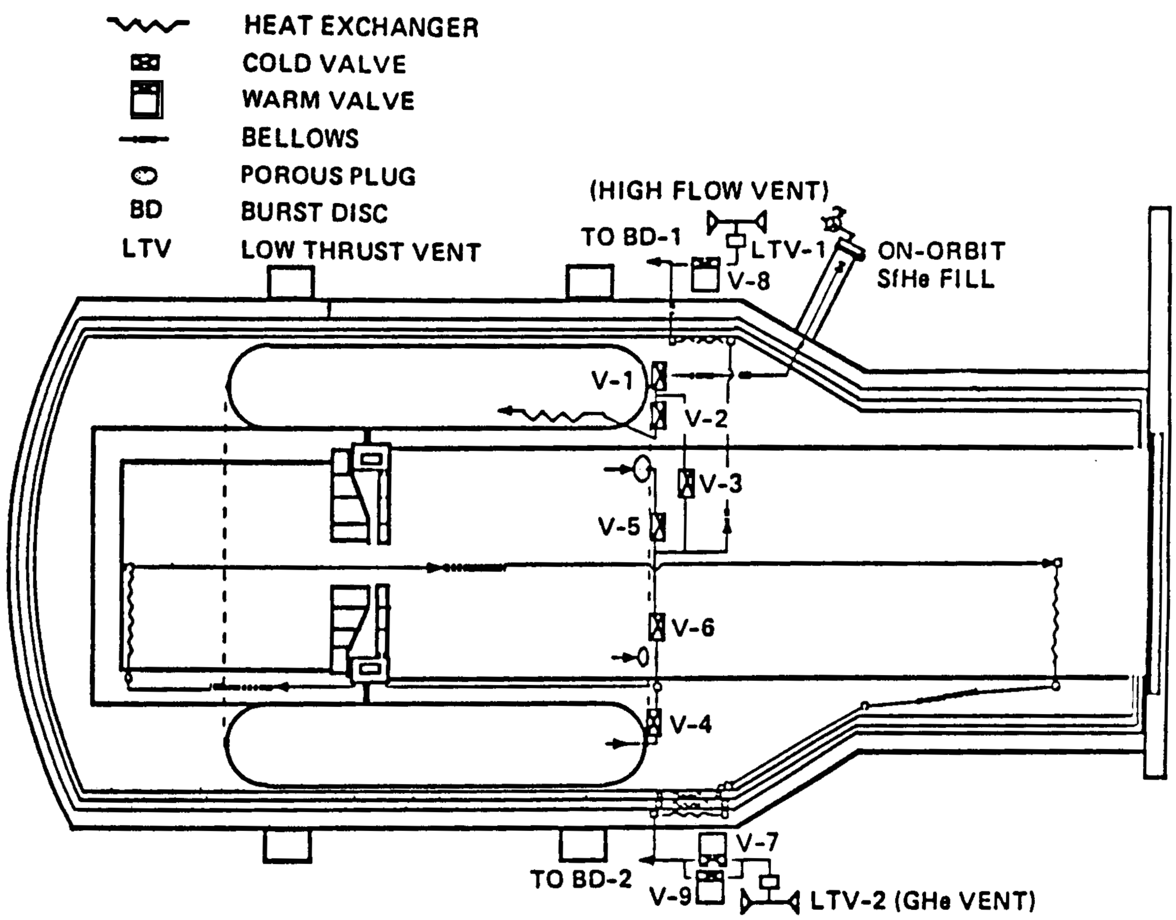

Figure 4.1 SIRTF Fluid Management System (Reference 4.5)

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Based on this information, a user summary table was prepared for SIRTF as shown in Table 4.2. A similar table has been prepared with as complete information as possible for each of the identified users (Reference 4.3). These tables were used in all subsequent tasks to establish tanker/user interface requirements.

Table 4.2 Superfluid Helium Tanker User Data Sheet (Example for SIRTF)

SUPERFLUID HELIUM TANKER USER DATA SHEET	
GENERAL	
Progam:	SIRTF
Orbit Altitude (km):	900, 28.5°
Year Launched:	1997
Year of First Servicing:	1999
Launch Site:	ETR
Spacecraft Type:	Free Flyer Observatory
Spacecraft Lifetime (yrs)	6 to 12
SPACECRAFT ENVELOPE	
Length (ft):	29 (overall)
Diameter (ft):	6.77
CG Location (ft aft):	TBD
Mass (lb):	15985
Appendages:	2 Solar Arrays, 2 Antennas
INTERFACES	
Preferred S/C Orientation for Refueling:	TBD
Initial S/C Deployment Mode:	STS RMS/OMV
Grapple Fixture Provided?	Yes
Type:	Standard RMS Type
Berthing Requirements for Refueling:	TBD
Berthing Mechanism Type:	FSS Latches
Helium Coupling Type:	Moog Helium II Coupler
Electrical Coupling Type:	TBD
GROUND SERVICING EQUIPMENT	
Supply Dewar Capacity (liters):	New Design
Ground Hold Capability (hrs):	TBD
Loading Location/Procedure:	TBD
Ground Vent Rate (g/sec):	TBD
AVIONICS DURING BERTHING TO SFHT	
Total Spacecraft Power (Watts):	250 Watts
Max. Heater Power Required:	120 Watts
Max. Avionics Power Required:	130 Watts
Valve Control Required for SFHT:	11 (7 Cold, 4 Warm)
Measurements Required:	Temp(8), Press(5), Flow (2)
Monitors Required:	Valve Position, Liq. Level, Heater Voltage, T,P, Power
EMERGENCY SEPARATION CONSTRAINTS:	
HELIUM RESERVICING	
Helium State Required:	Superfluid
Initial Helium State Before Servicing:	Superfluid, Normal, Empty
Quantity Required (liters):	4000
Service Time (days)	3 to 14
Service Margin (days)	300
Resupply Interval (days):	730
Number of Tanks:	1
Quantity per Tank (liters):	4000
Type of Vent System:	Porous Plug
Transfer Rate Desired (liters/hr):	1000 l/hr
Total Transfer Time Constraints:	TBD
Instrumentation	TBD
No. of Temperature Transducers:	8
Temp. Transducer Type:	GRT and Platinum Resistance
No. of Pressure Transducers:	5
Press. Transducer Type:	Validyne AP10
Instrumentation Accuracy:	TBD
Mass Gaging Accuracy (%):	±1%
Flowrate Accuracy (%):	±5%
Valve Control Requirements:	9 Valves

4.1.3 Astromag

Astromag is planned as a Space Station attached payload. It consists of a superconducting magnet in the 1 meter diameter range that is cooled using stored superfluid helium (Reference 4.8). The magnet will be used to study the energy and momentum of charged particles from deep space. The superfluid helium storage system consists of a Dewar with a volume of approximately 3100 liters. The Dewar is spherical in shape and is located between the magnetic coils to which it is thermally tied. The helium servicing interval is estimated at 2 years.

4.1.4 Other Users

Other users of the SFHT include several Space Station based experiments and both NASA and foreign free-flying spacecraft. The following is a brief summary of the primary mission of each. The Critical Point Phenomena Facility (CPPF), a U.S. Laboratory-based experiment, is a facility that will be used in the study of critical point and phase transition phenomena. The Lambda Point Experiment, designed to study the transition between Helium I and Helium II will utilize the CPPF. The Superconducting Magnet Facility will be an attached payload at Station and will be used as a materials processing facility. Several of the users are free-flying payloads whose primary mission is astronomical observation. Gravity Probe B will be placed in polar orbit to measure effects predicted by the general theory of relativity. It is the only user identified in polar orbit. The Large Deployable Reflector (LDR) is a facility designed to conduct infrared astronomical observations. It is a large spacecraft that would require several Shuttle launches and on-orbit assembly. Several of the users are foreign observation spacecraft. The Infrared Telescope in Space and the Submillimeter Telescope are both Japanese payloads designed for astronomical viewing. The Far Infrared/Submillimeter Space Telescope is a European Space Agency spacecraft also designed for astronomical viewing.

4.2 RESUPPLY REQUIREMENTS SUMMARY

Based on the results of the SFHT user literature search, time-phased helium requirements were compiled. The total helium requirements versus time for all identified users is shown in Figure 4.2. Based on current requirements, SIRTF requires the largest amount of superfluid helium (4000 liters). However, some of the smaller users, such as the Critical Point Phenomena Facility (CPPF) require helium resupply every 90 days, which also results in significant yearly quantities. If all the identified users become funded programs in the currently planned time span, the helium requirement will peak at approximately 12000 liters in the 1999 to 2001 time frame. It should be noted that the capacity of the Large Deployable Reflector (LDR) is currently being evaluated and could be greater than 10000 liters which would add significantly to the requirements.

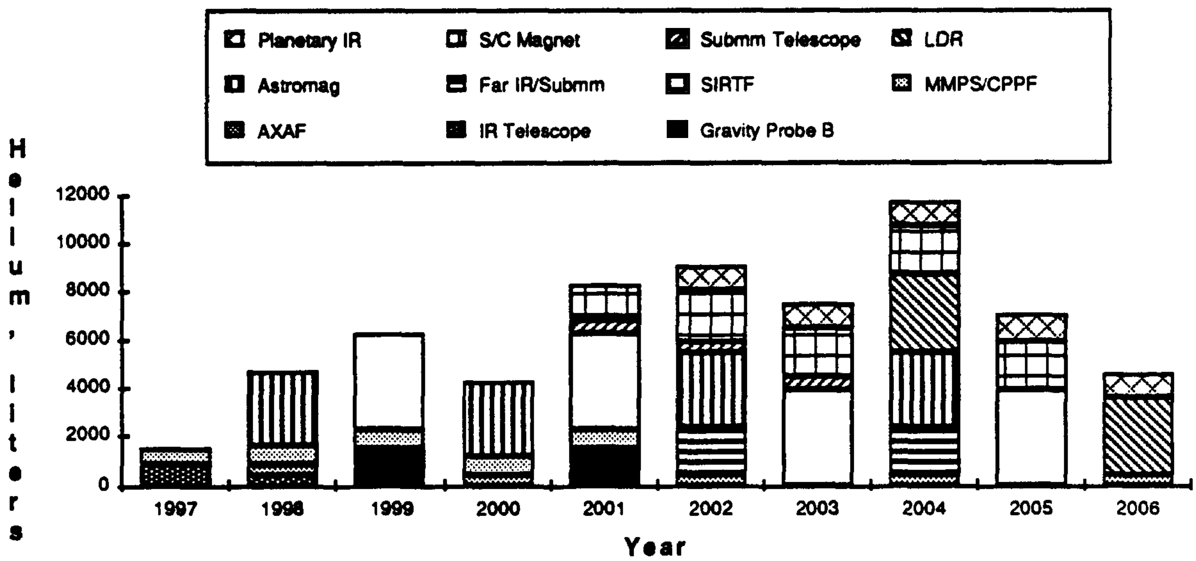

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Figure 4.2 Time-Phased Helium Requirements for All Identified Users

Because of the uncertainty involved with many of the users, particularly on their likelihood of being funded in the time schedule currently planned, a reduced user complement was defined to determine the sensitivity of the helium resupply requirements. This was done by considering those users that are the best defined and furthest along in their development phase. These users were AXAF, SIRTF, Astromag, CPPF, and Gravity Probe B. CPPF was considered since it is representative of a payload designed to be placed inside the U.S. Laboratory Module on the Space Station. Gravity Probe B is a special case, however, since it is the only user to be operated in a polar orbit. Therefore, it was not considered as a driver for the SFHT. The helium required for the reduced user complement is shown in Figure 4.3 for comparison. The requirements are significantly reduced; however, SIRTF remains the design driver due to its large capacity. These representative helium resupply requirements were used in the SFHT fluid subsystem sizing trades conducted during Task 2.

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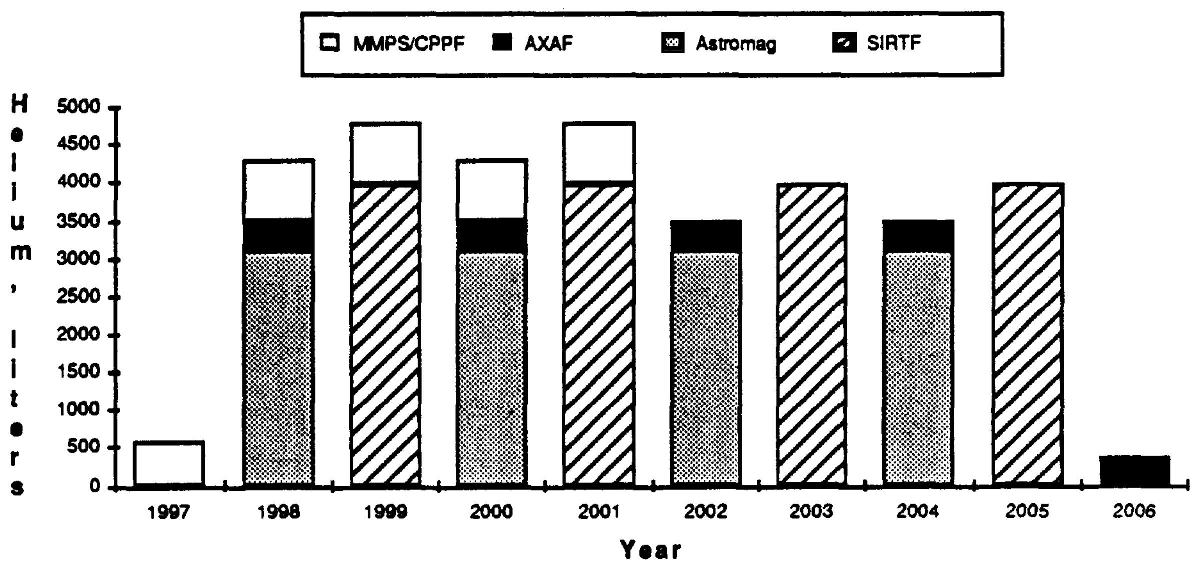

Figure 4.3 Time-Phased Helium Requirements for Reduced User Complement

4.3 ON-ORBIT RESUPPLY OPTIONS

Three orbital SFHT resupply options were evaluated for impacts to the SFHT design. These were resupply from the Orbiter cargo bay, resupply in-situ while attached to the OMV, and resupply at the Space Station. The following sections discuss the preliminary requirements for each resupply option and their effects on the design of the SFHT subsystems. These requirements were used to define the interfaces and operations for each option as discussed in subsequent sections.

4.3.1 Resupply from Orbiter

Resupply from the Orbiter cargo bay will be required for those payloads requiring helium replenishment prior to the Space Station IOC or those that are not planned to be serviced at the Space Station. Payloads such as SIRTF and AXAF will require retrieval by the OMV and subsequent transportation to the Shuttle orbit.

Resupply from the Orbiter bay could initially involve EVA operations similar to those developed under the OSCRS program and those that will be demonstrated on the SHOOT program. These operations will include the attachment of EVA support equipment, and manual mating and demating of the Helium II couplers. EVA will not be required during the lengthy cooldown and refill operations. The trade-off between EVA manual hookup and automatic mating/demating was investigated during Task 3 (see Section 6.1.2.2) to select the preferred SFHT initial operational capability. Either the Flight Telerobotic Servicer (FTS) or the Integrated Orbital Servicing System (IOSS) could also be part of this capability if specified by the user.

Two key issues associated with helium replenishment operations while in the Orbiter bay include the location of the SFHT and payload in the bay and venting during all phases of the mission. Location of the SFHT in the cargo bay influences the location of the SFHT/satellite interfaces, such as the fluid couplers and associated flex lines, since it is highly desirable to minimize the length of the transfer lines. Location within the bay also affects the packaging of SFHT elements such as the avionics. If the SFHT is in the front or back of the bay or is sandwiched between two payloads, then the avionics must be packaged such that they can radiate excess heat to space as was done in the OSCRS design. Another important design impact influenced by the SFHT bay location is an emergency overboard vent interface with the Orbiter. An Orbiter interface such as at the T-0 umbilical location or a "generic" Orbiter vent location we believe is required for SFHT emergency venting, and a line must be run from the SFHT bay location to the aft end of the Orbiter. Heat leak limitations dictate that this vent line be as short as possible which may limit the locations that the SFHT can be placed in the bay.

Normal venting during all on-orbit mission phases will also impact the design of the SFHT. Normal venting operations must be non-propulsive and directed such that it will not create a hazard to either the Orbiter, EVA crewmembers, or other payloads within the bay. Emergency venting can be propulsive but must also be in a non-hazardous direction. These restrictions will impact the location of the vent interfaces; options such as a vent mast similar to that considered as part of the OSCRS program were evaluated during Task 3.

4.3.2 Resupply from Space Station

Operations at Space Station will involve the transfer of the SFHT from the launch vehicle (either the Shuttle or ELV) to the Station storage location. In the case of Shuttle launch, the SFHT/Shuttle interfaces will have to be demated to allow transfer from the cargo bay via the Station Mobile Remote Manipulator System (MRMS). Once at the Station storage location, the SFHT/Station/Servicing Facility interfaces need to be mated. This may require multiple utility umbilicals on the SFHT to accommodate the hand-off procedure since the Station requires that new interfaces be mated and verified before disconnecting from the old interfaces.

Resupply of helium to users at the Space Station will take place in the Customer Service Facility (CSF) or from a tanker mated on the Station truss structure. Resupply at the Space Station is preferred for such payloads as AXAF and SIRTF, provided that the Servicing Facility is in place, since it can be combined with other maintenance operations. As with servicing from the Orbiter bay, it is assumed that the user will be transported to the Space Station by the OMV. In addition to the large astronomical payloads, there will be several small capacity users at the Space Station, either in the United States Laboratory (USL) or on the truss as attached payloads, as was discussed in Section 4.1. These smaller users will require frequent resupplies from the SFHT at 30 to 90 day intervals.

Servicing the users inside the laboratory module requires an interface somewhere on the module shell or on the nearby truss with a Helium II coupler and a transfer line running to an interface inside the pressurized area. Structural attachment hardware for handling the SFHT may also be required at this interface location, although it may be possible to leave the SFHT attached to the MRMS during the replenishment operations. Since is is difficult to run a vacuum- jacketed helium line a great distance in the module utility runs due to limited space, a centralized refueling interface somewhere in the module would likely be required. The individual experiments would be transported by the crew to this interface for helium replenishment. This centralized refueling port would ideally be located as close to the external SFHT interface as possible to minimize the transfer line length.

There are some significant requirements that are unique to resupply operations at the Space Station that impact the design of the SFHT. One of the most important is the contamination limits that the Station imposes. These requirements are described in Reference 4.9, "Space Station External Contamination Control Requirements." Currently, venting of liquids or solids is prohibited and gases can only be vented at 14 day intervals. While helium is one of the more benign substances that will be vented at the Space Station, large quantities will be generated during SFHT operations, particularly during chilldown of an initially warm user, and it appears that venting during helium replenishment operations will exceed the limits imposed by the Station. To control the waste gas venting problems, an Integrated Waste Fluid Management System (IWFMS) (Reference 4.10) has been proposed that would store all waste gases produced by Station elements for subsequent venting at 14 day intervals through a resistojet propulsion system. However, the IWFMS capacity could need to be large to store the helium vented during SFHT operations. Additionally, the IWFMS will store waste gases at pressures between 100 and 200 psi. Tying the SFHT Dewar (which will be at approximately 0.5 psi) into such a system will create pressure control problems for the SFHT. Therefore, preliminary assessments indicate the SFHT should be allowed to vent freely and not be tied in to the IWFMS.

Regardless of the storage and transfer location, venting from the SFHT must be done in a direction that will minimize contamination to the Station elements and attached payloads. This may necessitate interfacing the SFHT with a long vent line that will discharge the helium in a preferred location away from other Station elements, particularly during resupply operations. Normal venting during storage may be low enough to allow venting within the vicinity of the SFHT. Both of these issues were addressed in detail in Task 3, and are discussed in section 6.1.2.1. (Note: This vent gas disposal issue may be a driver for locating the SFHT at a platform some short distance away from the Station for storage and resupply.)

Another key Space Station requirement is that all hazardous fluid resupply operations be performed automatically with manual backup (Reference 4.11). This requires the incorporation of an automatic umbilical mating mechanism on the SFHT that is compatible with the Helium II coupling currently under development, or use of the Flight Telerobotic Servicer (FTS) for mating and demating of the couplings. The FTS Requirements Document for Phase B Study, Reference 4.12, lists several reference mission capabilities. One of the missions that the FTS must perform is to support propellant resupply for the Gamma Ray Observatory (GRO). This involves mating and demating of the propellant couplings, an operation very similar to what will be required for the SFHT. Therefore, the baseline SFHT design should be compatible with operations with the FTS.

Storage location of the SFHT at the Space Station is another design driver. The Customer Servicing Facility is not currently part of the Space Station program. If helium replenishment operations take place prior to the Servicing Facility being operational, then the SFHT must be stored somewhere on the truss element. Meteoroid and debris protection must be provided for the SFHT, possibly integral with some type of thermal control. This protection could be permanently located on the Station and would not have to be part of the SFHT, thus saving weight. This weight savings occurs each time the SFHT must go through the launch environment. An interface with the Station is required for power and monitoring of the SFHT during storage operations. If the SFHT is stored within a future-planned Servicing Facility, separate meteoroid and debris protection may not be required at that time.

4.4 SFHT TRANSPORT/LAUNCH OPTIONS AND CONSTRAINTS

4.4.1 Orbiter Launch

Launch of the SFHT on the Orbiter requires structural/mechanical, electrical, and fluid interfaces. If the SFHT is being transported by the Shuttle to the Space Station, these interfaces need to be mateable and demateable to allow the SFHT to be removed and replaced in the cargo bay on-orbit.

Structural interfaces required for SFHT support in the bay are the standard STS trunnion and keel fittings. If it is required to remove the SFHT from the bay while on-orbit, an active attach/release structural interface such as the payload retention latch assembly or the active keel actuator is required. An electrical interface between the SFHT and the Orbiter is required for power and data management for monitoring and control of the SFHT systems via an Aft Flight Deck (AFD) control interface when resupply operations are to occur from the cargo bay. If the SFHT is being transported to the Space Station, only a monitoring interface is required since the SFHT is essentially a passive payload.

A fluid interface between the SFHT and the Orbiter is required to handle an emergency vent from the SFHT due to a loss of guard vacuum while on the ground. Since the venting rates in this case are substantial, the vent must discharge outside the Orbiter, and an interface such as that available at the T-0 umbilical is required. This interface limits the location that the SFHT can occupy in the cargo bay due to conflicts with other payloads arising from routing a vent line through their bay allocation. Additionally, it has to incorporate a quick disconnect in order to allow removal of the SFHT from the bay if it is being transported to the Space Station. In addition to the above interfaces, the SFHT must accommodate the Shuttle launch environments. Applicable criteria have been defined for the SFHT design effort and are documented in References 4.13 and 4.14.

4.4.2 Expendable Launch Vehicle (ELV) Launch

Designing the SFHT to accommodate launch by an ELV as well as by the Shuttle adds to its manifesting flexibility, particularly if ELV's are used in the future for Space Station logistics resupply missions. Existing ELV's were examined to evaluate their capabilities in payload weight to orbit, payload shroud geometry, and cost (References 4.15-4.19). These are summarized in Table 4.3. Each of the launch vehicles has sufficient payload capability to place the SFHT in a useful orbit. The limiting factor in using an ELV to launch the SFHT is payload shroud diameter. Designing the SFHT to accommodate both a Shuttle and ELV launch requires the SFHT structure to be reconfigurable unless the SFHT is launched on the Titan IV vehicle. Reconfiguration is also required to be performed on-orbit if the SFHT is to be returned to the ground by the Shuttle following launch on any expendable ELV but Titan IV. The Delta launch vehicle has the smallest payload fairing while the Titan IV can accommodate Shuttle-sized payloads with little or no structural reconfiguration.

Other issues involving an ELV launch of the SFHT are stabilization of the SFHT once it is delivered to orbit, and telemetry and power interfaces between the SFHT and the ELV. If the SFHT is not launched attached to an OMV, then either the SFHT or the ELV must provide a means of stabilization to allow subsequent pick-up by the OMV or Shuttle for transport to the user spacecraft or the Space Station. The Delta II, Atlas/Centaur, and Titan III provide a reaction control propulsion system to provide payloads with three axis stabilization prior to deployment (Reference 4.17). The Titan IV currently has no such capability. Telemetry and power interfaces between the ELV and the SFHT during launch and on-orbit deployment are expected to be minimal since the SFHT is a passive payload (this was addressed in greater detail during Task 3).

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Table 4.3 ELV Payload Capability

PARAMETER	DELTA II	ATLAS/CENTAUR	TITAN III	TITAN IV	STS
LAUNCH COST	$45M*	$59M*	$110M*	$160M**	$140-$245M
PAYLOAD TO 250 NM ORBIT, LBS	8000 (6920) 10000 (7920)	10500	29500	~39000	48000***
DOLLARS PER POUND (TO ABOVE ORBIT)	5625	5619	3729	4103	2917-5104
PAYLOAD FAIRING I.D., IN.	110	115,143.7 *	143.7	180.0	180.0
PAYLOAD ADAPTER INTERFACE DIAMETER, IN.	32.5,60	32.5	32.8-70.0	111.77	N/A

*FROM DATA SUPPLIED BY NASA LeRC FOR COLD-SAT PROGRAM
** HARDWARE COSTS ONLY, NO MISSION SUPPORT/INTEGRATION INCLUDED
***WITH PERFORMANCE UPGRADES

Accommodation for the SFHT at the ELV launch sites is also an important interface issue. Currently, there are two 6000 gallon liquid helium Dewars at KSC which normally are used to support Atlas Centaur launches. Therefore, there will be a large supply of helium in the vicinity of the launch site for servicing of the SFHT. The SFHT will, however, require dedicated penetrations in the payload shroud for the vent line, fill and drain lines, and power/monitoring hook-ups. The capability of each of the ELV shrouds must be examined to determine the impacts of these penetrations. In addition, the launch processing sequences of the ELV's need to be examined to determine if there are any items that might impact the SFHT ground processing flow, including ELV launch pad operations and close out times (these issues were addressed in detail during Task 3).

4.4.3 Resupply Using OMV

Resupply of helium from a SFHT that is mounted to and transported by the OMV requires that the SFHT interface simultaneously with the OMV and the spacecraft to be resupplied. Appropriate interfaces must be provided on both ends of the SFHT to accommodate the OMV and user spacecraft attach mechanisms respectively. This will impact both the design of the structural support system of the SFHT as well as the utility routing and the number of interfaces required at each end. The types of structural interfaces between the OMV and the SFHT are shown in Figure 4.4 (Reference 4.20). Currently, the OMV can interface with a payload using either a standard grapple fixture or FSS type latches, both of which can be mated or demated automatically on-orbit. For missions where the OMV and SFHT will be launched as an assembled package, the 135 inch bolt interface can be mated and demated on orbit. In addition, power and data management interfaces between the SFHT and the OMV are required.

4.5 REVIEW OF DESIGN GOALS

A review of the SFHT design goals (presented in the Program Statement of Work, Table 2) was performed after the user and vehicle interface requirements were collected. It was determined that each of the goals, summarized in Table 4.4, appeared to adequately address all requirements with the exception of the ground hold time requirement. It was determined from a technical interchange meeting held at KSC between KSC personnel and Martin Marietta SFHT personnel, that the maximum ground hold time would be four days instead of 21 days specified in the SOW Table 2. The cargo bay doors are closed at T-48 hours prior to launch. A total of 24 hours of hold time is built into the count and an additional 24 hours is provided to accommodate one

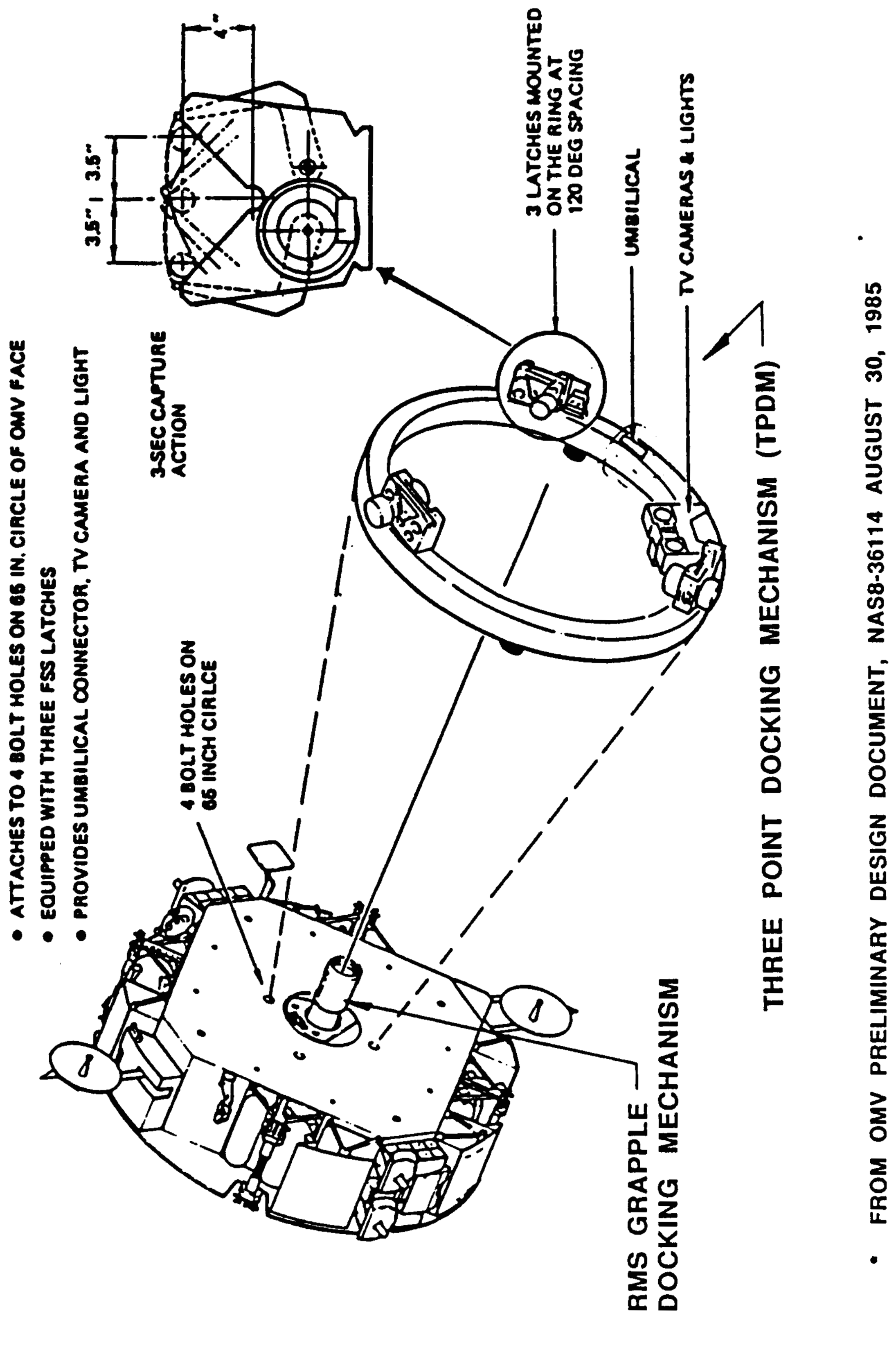

Figure 4.4 OMV Structural/Mechanical Interfaces Payload Accommodations

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Table 4.4 Summary of SFHT Design Goals

ITEM	REQUIREMENT
Resupply Flow Rate	0 l/hr to 1000 l/hr
Gauging Accuracy	Flow: ± 5% Mass: ± 1%
Hold Time	Ground: 10 Days On-Orbit: 90 Days
Resupply Quantity	Final Quantity of 4000 l

launch scrub. This results in a total hold time of 4 days. With this exception, we concurred with the design goals specified in Table 2. Subsequent discussions with both NASA-JSC and NASA-KSC resulted in the conclusion that four days would require a waiver to be processed. A 10 day hold time following Orbiter cargo bay door closure was thus established. An additional 24 hours was added to accommodate one launch scrub, resulting in an eleven day total hold period prior to cargo bay doors being reopened for launch reprocessing.

5.0 TASK 2 - CONCEPTUAL SFHT FLUID SUBSYSTEM DESIGN

The requirements compiled during Task 1 were used as the criteria around which fluid subsystem trade studies were conducted. We used a systems approach to assess the relative influence of all parameters impacting the fluid subsystem. We arrived at a preferred fluid subsystem concept. A summary of the trade studies and resultant conceptual fluid subsystem design are discussed in this section.

5.1 FLUID SUBSYSTEM TRADE STUDIES

Our approach to identifying and conducting the appropriate trade studies was to start with the SHOOT and SIRTF (STICCR) baselines. We then determined which elements were viable options when scaled to the size range for the SFHT (based upon the user requirements assessment of Task 1). Once optimum SFHT Dewar size and shape were selected, the fluid subsystem trades fell into three general categories, ground servicing techniques, fluid storage and maintenance techniques, and fluid transfer techniques. We evaluated the options basically in this same order; this allowed us to resolve the ground servicing approach early, and then using these results, conduct the transfer technique analysis. By this point in the trade study process, sufficient resolution of tankage design parameters was obtained to permit the more detailed look at the storage Dewar design. The SHOOT/STICCR fluid subsystem baselines are now discussed, followed by a summary of the trade studies.

5.1.1 <u>SHOOT/STICCR Fluid Subsystem Baselines</u>

The following elements of the SHOOT test bed form the basis for the large-scale tanker scaling considerations (Reference 5.1):

- o Dewar - Cylindrical 210 liter vessel with 2 vapor-cooled shields supported in a vacuum shell with glass-reinforced epoxy support straps.
- o Pump - Thermomechanical pump designed for 500 l/hr flow (design goal of of 800 l/hr)
- o Acquisition System - Screen channel system to handle 500 l/hr flow (design goal of 800 l/hr)
- o Phase Separators - Venting
  - Normal helium phase separator - thermodynamic vent (TVS)
  - Superfluid helium porous plug
- o Emergency Vent Line - Burst disks serve as hazard control.
- o Instrumentation
  - Mass Gauge - heat pulse (alternate - superconducting level detectors)
  - Flow Meter - Venturi or heat flow meters
  - Thermometers - Germanium resistance thermometers (1.3 to 40 K)
    Platinum resistance thermometers (above 40 K)
  - Pressure Transducers - Validyne

The one aspect of the SHOOT experiment not amenable to a direct scaling assessment is its operational scenario. Normal fluid is to be loaded on the ground and then converted to superfluid beginning during ascent when the external pressure has dropped sufficiently to permit pump down. The result is an approximate 30 to 35 percent loss of fluid once desired superfluid conditions are obtained in the Dewar. We have groundruled launching the SFHT with superfluid helium; concepts and ground operational scenarios were thus an open issue with no initial baseline for trade study comparison. Since ground loading concepts and operational performance has not been addressed for SIRTF or its resupply (e.g., STICCR studies), there was no baseline point of departure here either for handling such large quantities required by the SFHT. A key feature of our trade study activity was to define fluid ground handling concepts and approaches that would minimize ground facility impacts and permit the desired quantity of superfluid to reach orbit for subsequent resupply.

One area not addressed by the STICCR studies that received considerable attention in our study was tanker transport to orbit by ELVs. This is a major design driver on Dewar shape, and its resultant structural and thermal impacts. Many of the tanker design results presented in the STICCR studies were thus re-evaluated in light of these broadened requirements envelopes.

5.1.2 SFHT Fluid Subsystem Trade Studies

A summary of the fluid subsystem trade study options investigated is presented in Table 5.1. The tankage trades were conducted first, followed by the storage concepts and then the transfer techniques. These evaluations resulted in derived requirements for the elements making up the Dewar (e.g., pumps, liquid acquisition devices, venting components, etc.).

Table 5.1 SFHT Fluid Subsystem Trade Studies

Tankage - Tank Size (single vs multiple) - Tank Shape - Tank Construction Liquid Acquisition - Screen Channels - Vanes/Baffles - Integrated Channel/FEP Venting - Conventional Porous Plugs - Thermodynamic Vents - Hybrid Plug/Active Phase Separators - Burst Discs/Relief Valves (Emergency)	Storage Concepts (Ground Processing) - Normal Boiling Point Superfluid - Pressurized (subcooled) Superfluid Transfer Techniques - "Open" Cycle - "Closed" Cycle Pumps - Thermomechanical (TM) - Centrifugal - Hybrid TM/Centrifugal - Centrifugal/Jet Liquid Gauging - Mass Gauge - Heat Pulse - Integrated Flow - Mass Inventory

5.1.2.1 SFHT Fluid Storage Sizing Trades - Trade studies were performed to optimize the capacity of the SFHT fluid system based on the user requirements presented in Section 4.1. While SIRTF is the chief design driver for the SFHT, the trade studies were performed to ensure that users with capacities different from SIRTF (particularly smaller users) could be efficiently resupplied without encurring unreasonable cost and weight penalties. Key variables that were examined included the number and type of users, SFHT launch costs, SFHT boiloff losses, and SFHT weight.

The time-phased helium requirements for all identified users were compiled based on their projected launch dates and service intervals, as was presented in Table 4.1 and Figure 4.2. The first step in evaluating tanker capacities was to determine the number of times a given tanker size would have to be flown to satisfy the time-phased resupply requirements. A spreadsheet was developed to parametrically evaluate different SFHT capacities versus the user requirements. The user requirements were laid out quarterly beginning in 1997. Each user could be individually specified as being either cold or warm at the initiation of resupply. If the user was specified as warm, then the user capacity was multiplied by 2.5 to account for chilldown losses. If the user was specified as being cold, it was conservatively estimated that the user contained no residual helium and would require its full resupply quantity. One or two different SFHT capacities could be specified to evaluate the benefit of two different size tankers, one for smaller users and one for the larger users. Alternatively, one tanker size could be specified which is sufficient to accommodate all users. The numbers in these two columns indicated the quantity of tankers of each capacity flown during a quarter.

The quantity of helium in the tanker or tankers versus time was estimated by subtracting a representative boiloff rate of 1.5% per month along with the user requirements for that quarter. When the helium in the tanker reached a level that was insufficient to meet the user requirements for the next quarter, another tanker was flown. In this way, the number of tankers required to satisfy the total user requirements could be determined and key variables such as the number of users, their initial state, and the tanker capacity could be examined.

Results typical of the parametric analyses are summarized in Table 5.2. Reference 5.2 contains all of the cases that were examined. In evaluating the user requirements, it became obvious that if all of the potential users specified previously in Table 4.1 were flown, the helium resupply quantities would become substantial; Table 5.2 shows the flight frequency of a 15000 liter capacity SFHT versus these requirements. This is a worst case where every user is initially

Table 5.2 SFHT Resupply Frequency to Match Mission Model (All Users, Each Initially Warm)

	Capacity of Tanker 1 (l):	1260		Capacity of Tanker 2 (l):	15000
Quarter	Helium Required, liters	# of Tanker 1 Flown	# of Tanker 2 Flown	Helium in Tanker (l)	
1997	0			0	
	1625		1	12810	
	500			11745	
	1625			9554	
1998	500			8489	
	10375		1	12549	
	500			11484	
	500			10419	
1999	4250			5603	
	500			4538	
	500			3473	
	10500		1	7408	
2000	500			6342	
	9250		1	11527	
	500			10462	
	500			9397	
2001	500			8332	
	2375			5391	
	1750			3076	
	12375		1	5136	
2002	1250		1	18321	
	26875		1	5881	
	9250		1	11065	
	3012.5			7488	
2003	2500			4422	
	2500			1357	
	1250		1	14542	
	12500			1477	
2004	1250		1	14662	
	26250		1	2846	
	9250		1	8031	
	2500			4966	
2005	1250			3151	
	2500			85	
	1250		1	13270	
	12500			205	
2006	0		1	14640	
	17250		1	11825	
	8000			3259	
	1250			1444	
TOTALS	201512.5		15		

warm and results in 15 tanker flights in the ten year time period. It is recognized that none of the potential users of the SFHT are funded programs at this time and that to use the complete user complement might result in an unrealistically large SFHT.

Therefore, a reduced user complement was derived by selecting those users that are the best defined and farthest along in the definition phase in order to present a more probable manifesting scenario for the tanker. These users were SIRTF, AXAF, Astromag, and the CPPF. These users represent a range of requirements and were thus used as an appropriate "mix" of representative programs to perform a trade study to optimize the SFHT capacity.

The launch costs for SFHTs ranging in size from 4000 liters to 15000 liters were determined by first computing the number of flights required to resupply the reduced user complement. The weight of the SFHT was estimated and then multiplied by the number of flights and \$3600 per pound for a Shuttle launch. The results are shown graphically in Figure 5.1. As shown, the general trend is for increased total launch costs with increased capacity. The up/down trends in the launch costs occur due to changes in the number of flights. SFHT sizes in the 6000 liter range present a good compromise between size and total launch costs and are large enough to accommodate a cold SIRTF resupply.

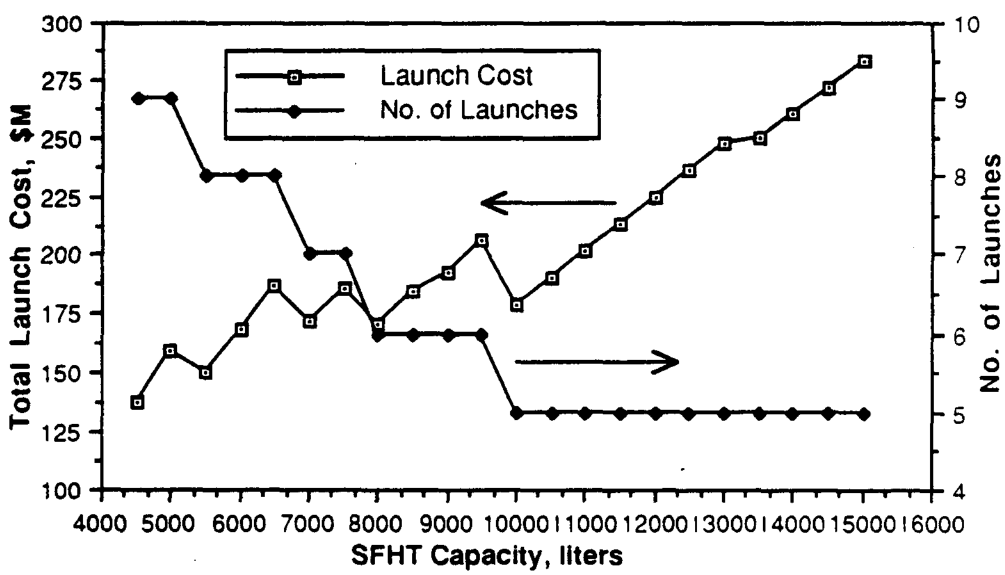

Figure 5.1 Total Launch Costs as a Function of Number of Launches of a Specified SFHT Capacity

Another key factor examined was the penalty associated with on-orbit boiloff. As mentioned earlier in this section, boiloff was estimated assuming a loss rate of 1.5% per month. Cummulative boiloff losses were compared with the cummulative resupply requirements for the various tanker sizes. Figure 5.2 shows the results for both a 15000 liter capacity tanker and a 6000 liter capacity tanker, assuming the same user requirements. The boiloff losses for the 15000 liter capacity tanker can exceed the user requirements, depending on the type of users. Ideally, the amount of transported helium should be as close to the user requirements as possible for the most efficient resupply system. The boiloff penalty illustrated here is also summarized in a slightly different manner in Figure 5.3, which gives a resupply efficiency, defined as dollars per usable pound of helium delivered to orbit, for each of the tanker sizes. The dollars per usable

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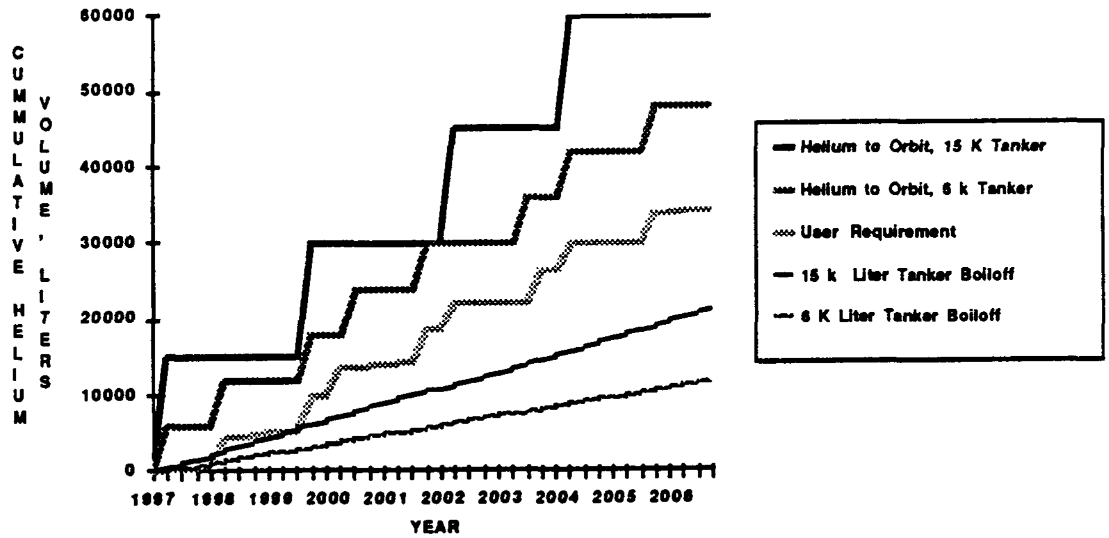

Figure 5.2 Tanker Capacity Sensitivity to Boiloff Losses in Meeting a Specified User Resupply Scenario

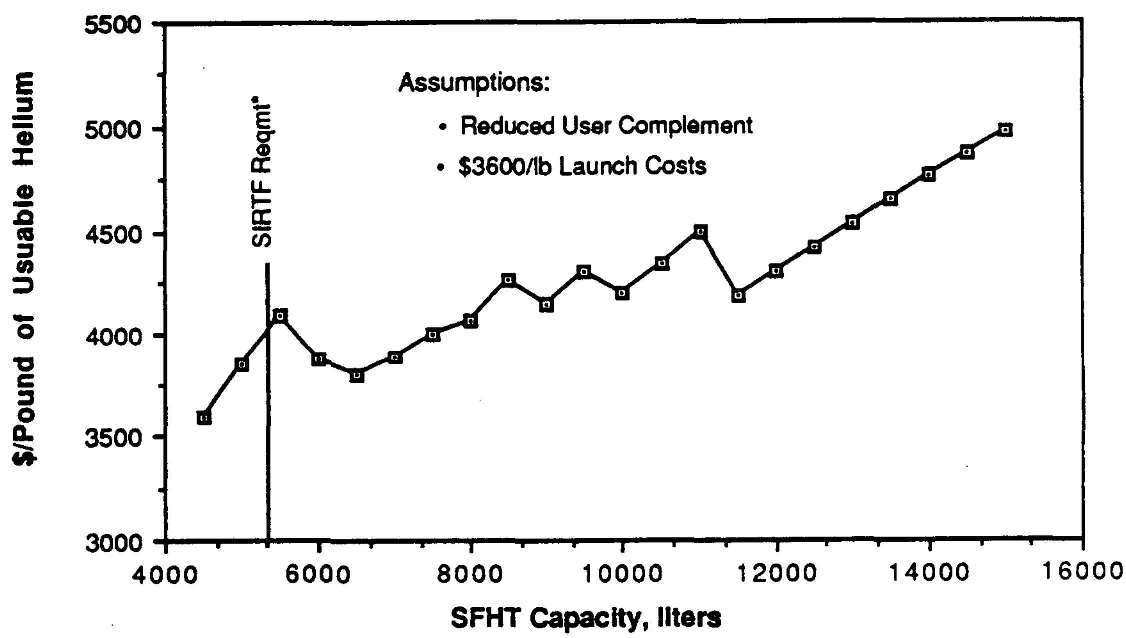

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Figure 5.3 Cost of Usable Superfluid Helium Delivered to Orbit as a Function of SFHT Capacity

pound of helium were derived by subtacting the cummulative boiloff losses from the cumulative amount delivered to orbit and dividing this into the launch costs. Again, the general trend is for costs to increase as tanker size increases since boiloff losses are greater for the larger SFHT capacities.

Tanker packaging studies were conducted to examine all of the issues associated with the SFHT Dewar design. These issues included geometrical constraints from both Shuttle and ELV launch, location in the Shuttle bay and the limitations of the venting interface and cg location constraints, and the effect of Dewar geometry on heat leak. Many of the design requirements for the SFHT are conflicting when assessing tank packaging and the final design must necessarily be a compromise.

The first issue examined was the geometrical constraints imposed by the Shuttle cargo bay and the ELV payload fairings. NASA's future plans have considered a mixed fleet manifesting approach where ELV's are used in conjunction with the Shuttle, particularly for Space Station logistics missions. Therefore, it would be desirable to configure the SFHT to be compatible with as many launch vehicles as possible to provide flexibility. When launching the SFHT on the Shuttle, it is desirable to have a compact Dewar design in order to minimize the overall length of the tanker, since launch costs are calculated either by weight or length depending on which is the more significant. This dictates using the entire 15 foot payload width and configuring the SFHT with a compact Dewar. However, this is in conflict with the requirement to be ELV compatible, unless the Titan IV vehicle is used exclusively. Current and planned ELV's such as the Delta, Atlas, and Titan, have payload fairings ranging from 8.3 foot diameter to 15.4 foot diameter. Packaging the SFHT to be launched on vehicles such as the Delta or Atlas necessitates decreasing the overall tanker diameter and increasing the length.

Preliminary estimates of the SFHT configuration show that for a Shuttle launch, length, not weight, will be the determining factor in launch costs. However, optimizing the SFHT for a Shuttle launch would preclude the use of any ELV except Titan IV. This approach would limit the manifesting flexibility of the SFHT, particularly since launch on a Titan IV would require flying with other payloads due to the Titan IV payload capacity far exceeding the weight of the SFHT. Therefore, a compromise design is indicated to accommodate both Shuttle and ELV launches.

Location of the SFHT within the bay is another factor that affects the Dewar geometry and the overall packaging. A vent interface with the Orbiter at the T-0 umbilical or similar "generic" vent location will likely be required to accommodate an emergency vent. Since this line must accommodate a high flowrate, it will likely be of a large diameter and therefore it is desirable to minimize this line length. Ideally, the SFHT should be located in the farthest aft location permitted by Orbiter/payload cg constraints. The Space Shuttle Systems Payload Accommodations Handbook, Reference 5.3, presents the methods for estimating the allowable locations for a payload cg in the bay in each of the three axes. In the X axis, which runs parallel to the long axis of the cargo bay, allowable payload weight decreases rapidly the farther aft the location. Therefore, a SFHT designed for minimum length may be penalized by a longer vent line since it cannot be placed as far aft. If the SFHT is the farthest aft payload, there will also be unused space between it and the aft bulkhead. A SFHT that is designed for both Shuttle and ELV launch, and consequently longer in length, may be able to be located farther aft since more of the tanker will extend both in front and in back of the cg. This should result in a shorter vent line. SFHT CG locations in the cargo bay for various capacity tankers are shown in Figure 5.4.

Dewar surface area also is important in selecting the Dewar geometry, in addition to the length/diameter issue. Spheres offer the lowest surface area-to-volume ratio and therefore are the ideal shape from a heat leak standpoint. They have the additional advantage of being symmetrical and therefore can be designed to take launch loads in various directions, a condition that results from using multiple launch vehicles. However, it becomes difficult to package a sphere within the restricted payload fairing of an ELV and still satisfy the capacity requirements for the SFHT. For example, a spherical Dewar of 6000 liters has a diameter of 7.4 feet. With the addition of a vacuum jacket and support structure, this tank could not be packaged within the Delta's 9.2 foot payload fairing. Therefore, consideration must be given to other tank shapes, resulting in a compromise on heat leak.

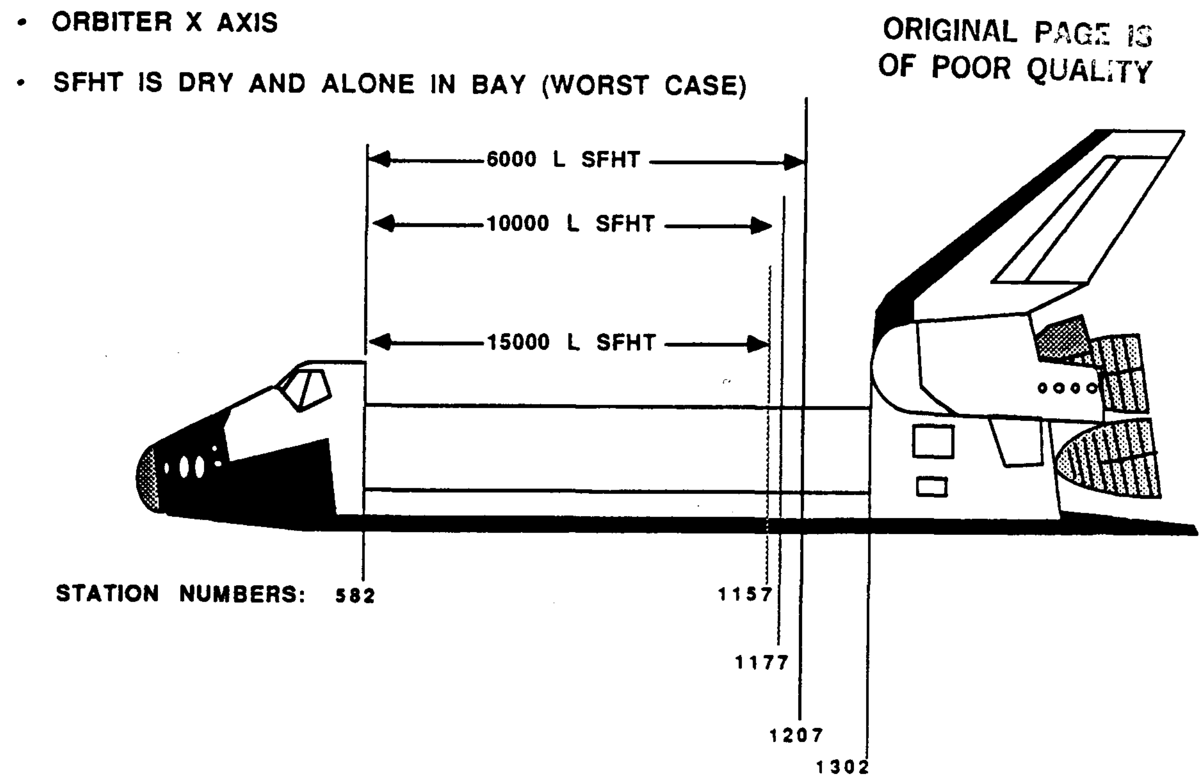

Figure 5.4 SFHT CG Location Requirements in Shuttle Bay

With the above considerations in mind, preliminary groundrules and design goals were established to aid in the SFHT packaging studies. As a preliminary design goal, it was established that the SFHT should be compatible with ELV's other than the Titan IV, with a 9.2 foot diameter fairing for the Delta being the limiting case. Therefore, the Dewar should be configured to package within the Delta fairing while allowing sufficient clearance for support structure, lines, etc. This groundrule adversely affects the heat leak and increases the overall SFHT length. However, it does provide the most flexibility in manifesting and also allows a tanker design that can be placed farther aft in the bay. These considerations were assessed further under Task 3.

5.1.2.2 <u>Ground Servicing Techniques</u> - Ground servicing of the SFHT will be a lengthy process dictated by the thermal conditioning and fill procedures involved with superfluid helium. Since these operations and the limitations of the KSC facilities involved are critical to the design of the SFHT, ground servicing issues must be considered early in the design process. While superfluid helium payloads have flown on the Shuttle before, they were relatively small in capacity compared to the SFHT. In order to make use of the procedures developed for these payloads and to better understand the facility capabilities and ground processing flow for the SFHT, a technical interchange meeting was held at KSC.

A discussion with KSC personnel on the current capabilities of the processing and launch facilities revealed that no equipment (e.g., vacuum pumps, supply Dewars, etc.) exists for the servicing of a superfluid helium payload. Previous hardware used to service the Spacelab superfluid helium payloads is no longer at KSC. Therefore the SFHT project would need to supply the necessary GSE hardware. Review of the capabilities of the Payload Changeout Room (PCR) shows that there are significant physical limitations for the SFHT GSE. KSC stated that a 750 liter capacity supply Dewar is probably as big as could be handled in the PCR. This size limit is dictated by the limited volume in the PCR work areas and the weight capabilities of the Payload Ground Handling Mechanism (PGHM) platforms which are limited to 1500 lbs maximum.

Possible scenarios for ground processing flows for the SFHT were also discussed. KSC has no preference on servicing/deservicing the SFHT in either the horizontal or vertical orientation. Servicing the SFHT vertically would require the SFHT to supply its own handling and storage fixture since equipment to handle payloads vertically at the various offline facilities is limited. For example, in the Payload Hazardous Servicing Facility (PHSF), there is no equipment for handling payloads except with an overhead crane. A horizontal payload could be supported using standard payload strongback fixtures such as those used in the O&C building. If the SFHT is processed vertically, a unique handling fixture would be required. KSC recommends that the SFHT be processed vertically to avoid going through the Orbiter Processing Facility (OPF). For the first flight of the SFHT, however, it might be preferrable to process the tanker through the O&C building for Cargo Integration Test Equipment (CITE) testing, as opposed to CITE testing in the Vertical Processing Facility (VPF).

On missions where the SFHT is being launched with a mixed payload complement (such as a Logistics resupply mission to Space Station), it would be preferrable to have the SFHT be the last payload loaded into the Orbiter at the PCR. The vertical transport cannister could be taken to whichever facility is used to process the SFHT; the SFHT is loaded into the cannister and then taken directly to the pad. This would minimize the amount of time the SFHT spends in transit or at the pad. If the SFHT were loaded into the transport cannister with other payloads, it might have to spend time in another facility such as the Vertical Processing Facility, which would require transporting the GSE to the various facilities to continue ground conditioning of the helium.

An important groundrule relative to ground servicing is the period that the SFHT will be required to maintain superfluid helium at a satisfactory state for launch without benefit of ground servicing. A lockup period of ten days has been established as the maximum time from removal of ground connections and closure of the Shuttle payload bay doors until launch. During this period, the liquid helium must remain sufficiently below the lambda point temperature so that on reaching orbit, control of the fluid condition can be maintained by the space vent system without transition to the normal state. In addition, 24 hours must be allowed for a launch scrub turnaround. At that time, the cargo bay doors can be reopened and the SFHT reconnected to ground support equipment (GSE) and recooled to the launch ready state.

A fixed requirement for the SFHT is the ability to deliver helium to the receiver tank being serviced in orbit as superfluid. Options exist, however, for the state of the fluid at the time of launch, and these options permit alternatives in the ground servicing procedures. Three fluid states have been identified as possible alternatives, and trade studies have been conducted to identify the most promising of these in view of ground servicing requirements. These are 1) normal helium, to be converted to superfluid in space, 2) saturated superfluid helium, and 3) pressurized superfluid helium.

The simplest option from the ground servicing point of view is to load and launch the tank with normal helium at or near its normal boiling point and convert it to superfluid on orbit. Liquid can be transferred to the tank under approximately ambient pressure with direct tank venting, as shown in Figure 5.5. Topping is simple, and it will be possible to achieve a relatively small ullage volume. Once on orbit, however, it will be necessary to condition the liquid to the desired superfluid state. This must be done by the thermodynamic vent process (based on an open loop refrigeration process rather than direct venting of vapor in low gravity), using the porous plug phase separator (discussed in a later section) to accomplish the vent/refrigeration process. Because more than a third of the fluid will be consumed in conditioning the remaining liquid to superfluid, the tank will need to be grossly oversized. This concept could be practical in the case where a large quantity of liquid would need to be dedicated to cooling down a warm receiver tank. The cooldown would be accomplished using vapor generated in conditioning the fluid in the tanker. Such a requirement will occur infrequently if at all, however, and the normal helium launch option is not viable.

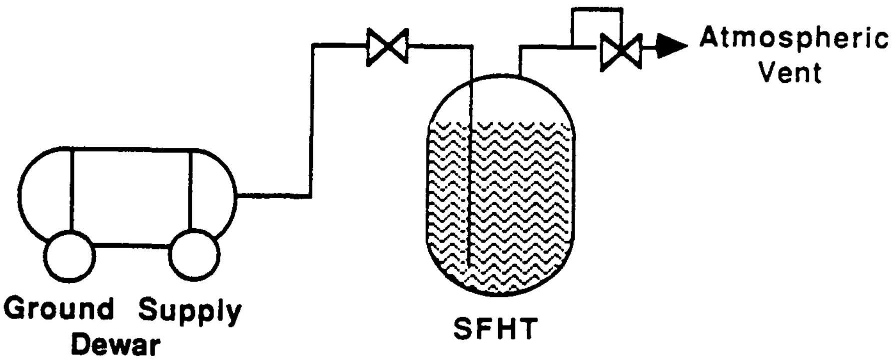

Figure 5.5 Normal Helium Load and Launch

The required state for the fluid at the time of space transfer to a user spacecraft is superfluid at a temperature somewhat below the lambda point, probably 1.8K or lower, and the tank pressure will correspond to the vapor pressure at this temperature (approx. 12.3 torr) since a tank partly filled with superfluid helium cannot be pressurized. Therefore the saturated superfluid state at the time of launch is a logical option. Two approaches could be considered for loading. First, liquid helium can be converted to superfluid in a facility supply tank and transferred to the tanker. This approach would be difficult to achieve because of the heat leak that will be inherent in the transfer line and fittings, and it may be difficult to achieve the desired loaded condition. Second, normal liquid can be loaded into the tank, and then cooled to transform it to superfluid. Cooling can be accomplished by a process illustrated in Figure 5.6. After the tank is initially loaded to a near full condition, say 97%, the loading is stopped and a vacuum pump connected to the tank. As the tank pressure is reduced, the helium boils, converting sensible heat to the heat of vaporization and reducing the temperature of the remaining liquid. Conversion from normal boiling point fluid to 1.8K superfluid requires boiling away about 38% of the initial fluid (neglecting cooldown losses and parasitic heat leak, etc.), and therefore the tank would be about 62% full. Normal helium would then be transferred to again fill the tank to about 97% full and this process would be repeated. Table 5.3 illustrates the multiple fill - pumpdown process and shows that at least 5 fills would be required to achieve a 95% filled tank with 1.8K superfluid. An alternative approach is to repeat this process several times and then finally top the tank with superfluid from a small tank. This alternative may be less desirable than directly filling the tank with superfluid, since the heat leak inherent in the transfer line will be more significant for the small quantity of fluid transferred.

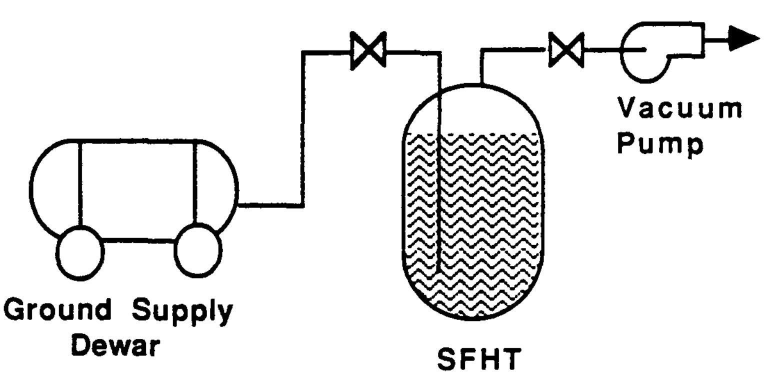

Figure 5.6 Conversion of Normal Helium to Superfluid by Repeated Pump/Refill Procedure

Table 5.3 Fill-Evacuate-Repeat Process for Conditioning Helium to Superfluid

Example 6000 L Tank - Parasitic Heat Leak Neglected		
Operation	Qty Normal He Added	Qty Remaining When 1.8K Reached
Initial Fill to 97%	1609 LBM	1001 LBM
Top to 97%	745	1475
Top to 97%	336	1692
Top to 97%	150	1787
Top to 97%	67	1831 (95.2%)

Another approach for converting the normal helium loaded into the tanker to superfluid at the desired launch temperature is illustrated in Figure 5.7. Normal helium is loaded into the vented tanker at about one atmosphere until the desired fill condition is reached. All valves are then closed. An independent cooling system is then placed into operation to cool the fluid to the superfluid state and reduce its temperature to the desired launch condition. The independent cooling system is an open loop refrigeration cycle. Normal helium is admitted from an external supply tank, through a flow restrictor to reduce the pressure, into a heat exchanger mounted in the tank. This heat exchanger exhausts into a vacuum pump that operates to reduce the pressure to a low value (that varies with time), finally reaching a pressure somewhat lower than the vapor pressure of the superfluid at its final temperature. The liquid flowing through the restrictor partially flashes, its temperature is reduced corresponding to the saturation temperature at the reduced pressure, and a temperature difference is created such that this two phase mixture is at a temperature lower than the liquid being cooled. Heat is removed from the contained liquid, causing the coolant fluid to fully vaporize, and the tank temperature is reduced as long as the temperature difference is maintained.

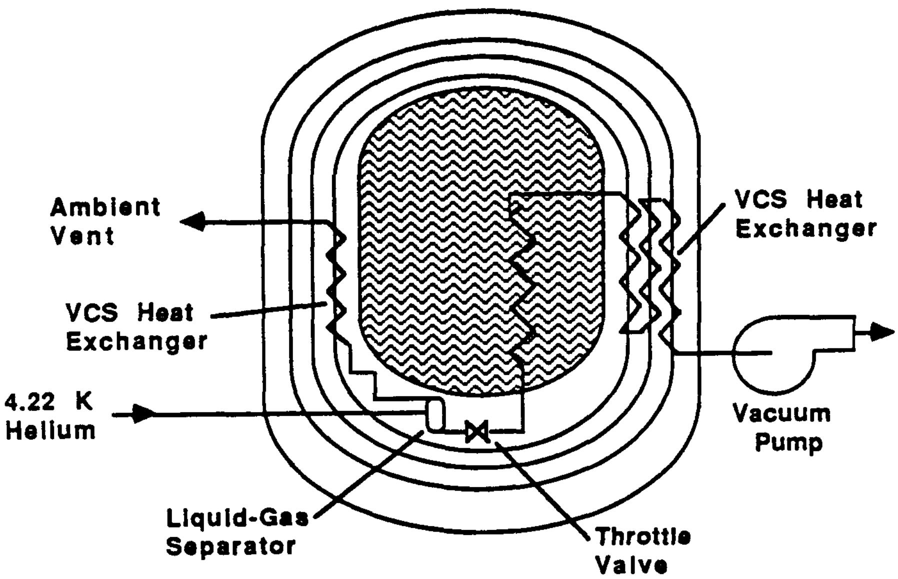

Figure 5.7 Conversion of Normal Helium to Superfluid Using Isolated/Independent Open Loop Cooling System

The independent cooling system described above permits a further option in the state of the superfluid helium at the time of launch. In the process described above, a small ullage would be left in the tank. The tank pressure will remain at the vapor pressure corresponding to the helium temperature at all times, and is therefore saturated. The tank could be totally filled with liquid, however. As the fluid is cooled toward the lambda point, tank pressure is reduced. Therefore, opening the transfer line from the supply Dewar at near atmospheric pressure while the cooling system remains in operation would cause liquid to flow into the tank until all of the ullage vapor is condensed. If the tank is then allowed to equilibrate with the supply Dewar just as the lambda point (2.172K) is reached and locked up, so that the pressure is about one atmosphere at that point, then the tank will remain pressurized as it is cooled further. In fact, the pressure will increase because of the inversion in the density versus temperature coefficient at the lambda point as illustrated in Figure 5.8, reaching a maximum pressure of about two atmospheres when the temperature reaches about 1.5K. (The actual pressure will be less because the tank will expand slightly with increasing pressure.) This load condition appears easier to achieve when compared with a saturated load with a very small ullage volume. In the latter case, it is necessary to have an accurate level sensing or total quantity measurement capability to adjust the loaded quantity, and a means for offloading from the tank (that is at a very low pressure) may also be required. A slight gain in quantity of liquid launched is achieved, and in the case of a capillary liquid acquisition device in the tank, total initial fill of the device is assured. The independent cooldown and pressurized fluid approaches were suggested by our consultant, Dr. Glen McIntosh, early in our trade study (Reference 5.4), and these appear to offer significant advantages. Pressurized superfluid helium is being used in the work being done on superconducting magnet power storage at the University of Wisconsin. There the advantages are to optimize cooling of the magnets with minimum system complexity.

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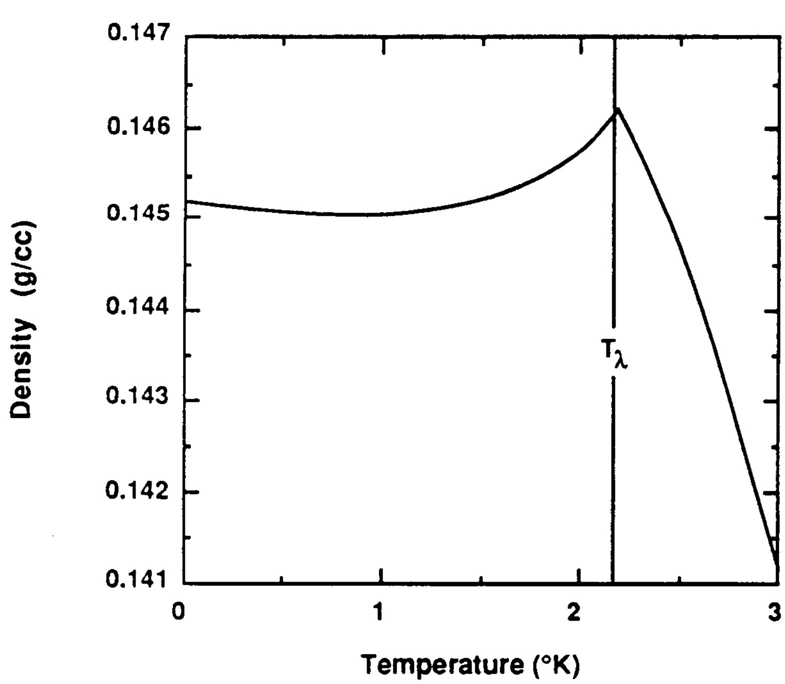

Figure 5.8 Density vs Temperature of Saturated Liquid Helium

Several approaches were considered to achieve the required eleven day lockup time while the independent superfluid helium conditioning system is deactivated. One promising approach is to use an internal guard tank, constructed integrally with the inner vapor cooled shield surrounding the helium vessel, as illustrated in Figure 5.9. This approach is being used by Lockheed in the design of the Gravity Probe B Spacecraft (Ref. 5.5). The guard reservoir can be fabricated as a slim toroid that also is the cylindrical section of the vapor cooled shield. It provides a quantity of helium to serve as a heat sink during the lockup period. It also serves to greatly reduce the heat leak to the helium tank during ground operations by maintaining the inner vapor cooled shield at about 4.3K. This concept has considerable merit, although it involves some increase in complexity. A variation of this concept is to provide a small reservoir supplying normal helium to the independent conditioning system. This reservoir would be located within the insulation and vapor cooled shields, and would normally serve as a supply to the conditioning system that could be filled intermittently. At the time of lockup, it could be completely filled, and would provide a heat sink capacity as it vented at one atmosphere through a heat exchanger on the inner vapor cooled shield. In addition, the use of external cooling of the outer vapor cooled shield as a means for reducing heat leak and increasing ground lockup time was investigated. This could be accomplished using an external mechanical refrigerator, or by piping liquid nitrogen to the shield.

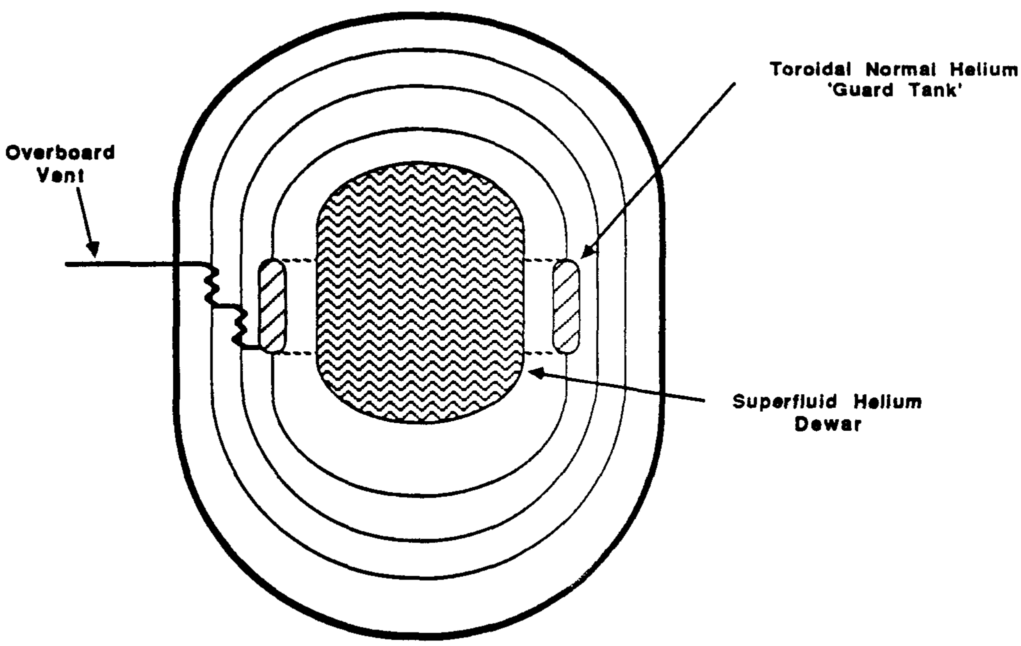

Figure 5.9 Internal Guard Tank Approach for Extending SFHT Lockup Time

None of these methods of increasing lockup hold time will be required if heat sink capacity can be achieved by overcooling the fluid, insulation, and vapor cooled shields, while at the same time the insulation system is made adequate to limit the heat input to that which can be absorbed by the heat sink capacity. Preliminary analyses of our SFHT thermal protection system and the independent conditioning system indicated that the vent rate could be increased significantly above that required to achieve the required launch condition. This additional cooling will reduce the temperature of the liquid, the shields, and the insulation sufficiently to permit more than an eleven day lockup period without reversion of the fluid to the normal state. The final system configuration and predicted performance during lockup is presented in Section 6.1.4.1.

5.1.2.3 Fluid Storage and Maintenance Techniques - The development of the technology for helium storage systems has been remarkably successful, and the performance of the IRAS stands out as an example of extremely effective thermal protection and management in a helium cryostat under much less than optimum conditions. The SFHT is a much larger system, and a more efficient tank design is possible, increasing the probable success in achieving long term helium storage with very low boiloff losses. Storage of superfluid helium in space with minimum losses requires a Dewar design that incorporates efficient multilayer insulation, a low heat leak support system, and design and placement of pipes and other penetrations to minimize their heat leak contribution. The requirement for loading and maintaining the helium in the ground environment necessitates a vacuum jacketed system to achieve the thermal insulation capability of multilayer insulation.

In addition to providing extremely effective thermal isolation of the helium vessel from the environment, it is necessary to utilize the boiloff vapor as a heat sink to intercept a large portion of the heat leaking through the various conductive paths. Furthermore, in the weightless environment of space, vapor generated by heat leak cannot be vented directly. Rather, it is necessary to utilize a scheme wherein liquid (or vapor) can be admitted to a vent system, and heat required for vaporization of the liquid is used in an open loop refrigeration cycle to remove the heat leak reaching the storage tank, thereby preventing the increase of tank pressure. The open loop refrigeration approach to control of tank pressure and the techniques for intercepting heat leak through the various thermal paths, taken together, are usually referred to as the "thermodynamic vent system" (TVS).

An optimum cryogenic storage vessel would be spherical since this shape results in a minimum external surface area for any required storage volume. It would also be designed with a minimum initial ullage to achieve the minimum tank size, reducing heat leak and weight. An efficient system for supporting the inner vessel from the outer vacuum jacket will minimize the number of supports and their cross sectional area, while maintaining a significant length of each support member to increase the thermal resistance. The support members should be fabricated of material combining high strength and stiffness with low thermal conductivity. Several vapor cooled shields (VCS) will separate the multilayer insulation into blankets so as to intercept a large portion of the heat leak, and this intercepted heat is carried away by the vented vapor as it passes through heat exchangers on the VCSs. Thermal shorting straps tie the other major heat leaks, namely supports, pipes and wires, to the VCS to further intercept inflowing heat.

Tank supports are typically made of a nonmetalic composite such as fiberglass-epoxy that has high strength and low weight and thermal conductivity. Alumina-epoxy is a composite material that has received attention as a candidate for cryogenic tank supports in recent years (Reference 5.6). This material has a thermal conductivity somewhat higher than glass-epoxy, but has strength and stiffness properties that lead to an improved overall support design. This stems primarily from the requirement to maintain stiffness in a tank support system to maintain the high natural frequencies needed to survive the launch environment. Compared with glass supports, the design for alumina can use longer support members and/or smaller cross sections with a resulting reduction in heat leak.

There are two basic options in the geometric design of a support system to provide load paths for the inner vessel. Tension members can be designed without concern for bending or buckling loads. Sufficient tension straps can be used to provide a load path in all directions. Because the straps support only in one direction, however, more are required than would be the case if they could be loaded in both tension and compression. Ternsion-compression members, however, must be designed with buckling in mind, and therefore become less efficient when added length is also a goal. Tension strap systems have been used extensively in design of Dewars for both ground and space applications, and have proven to be a practical approach. NASA Ames Research Center has sponsored work by Lockheed Missiles & Space Company (Reference 5.7) in development of the passive orbital disconnect strut (PODS). The PODS is a tension-compression member that carries ground and launch loads. On reaching orbit, however, the linkage relaxes to a minimum load path configuration that has a high thermal resistance, thereby minimizing onorbit heat leak. The PODS concept is promising and warrants careful consideration for all applications where very long term cryogenic storage on orbit (years) is required. This concept adds complexity to the Dewar design, and in particular requires very careful attention to the thermal contraction that will occur on cooldown to operating temperature. It is necessary to precisely adjust the coupling of each strut during assembly so that all struts will be simultaneously unloaded when cold and in the weightless environment.

For all support concepts, it is necessary to consider the thermal contraction that will occur on cooldown. Adequate support must be provided for a warm, empty tank for handling. When the tank is loaded and cooled down, the supports must not become excessively loaded, or relaxed, because of the dimensional changes due to thermal contraction. Changes in dimension due to differences in pressure loading, if any, must also be considered. If tension-compression members are used, a single plane design can be used that will inherently adjust to all changes in dimension. In this concept, a number of struts tie from a single plane on the inner vessel to an offset, parallel plane on the vacuum jacket (Figure 5.10). Shrinkage of the tank will result in a vertical movement of the tank relative to the vacuum shell, but not in loading of the struts.

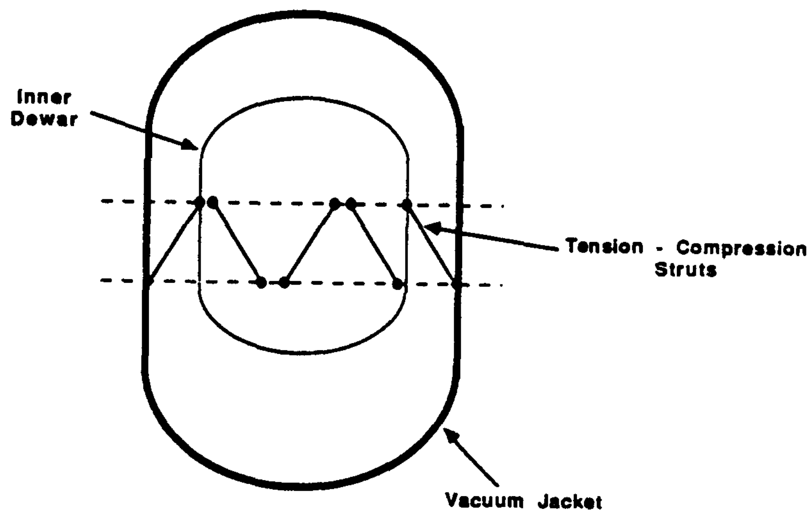

Figure 5.10 Tank Support Geometry Not Loaded By Tank Shrinkage

In the design of an all-tension support system, one set of "up" supports is opposed by a set of "down" supports. It is possible to design the geometry of these members such that they rotate in an arc as the tank dimensions decrease, without change of length (Figure 5-11). This is a classical method for design of tension support systems, and is also applicable to multiple plane systems using tension-compression members. It has the disadvantage, however, of severely limiting the placement of the support straps, and is not equally suited for all tank shapes. An alternative approach is to spring load the tension members so that they will provide the minimum required support for the warm, unloaded case. On cooldown, the tank shrinks, compressing the springs fully so that they do not influence the stiffness of the tank support. A series of Belleville spring washers under the adjustment nut for each tension element provides this feature (see Figure 5-12), although the result is an increase in tension of all of the straps and corresponding increase in cross sectional area and heat transfer. This arrangement can be used, however, to provide flexibility in the geometry, permiting longer length of the straps which more than compensates for the area increase and reduces heat leak. The support system that we have selected is described in Section 6.1.4.2. It uses 8 tension straps of alumina epoxy, with Belleville washers to compensate for cooldown shrinkage of the tank. Length of the supports is

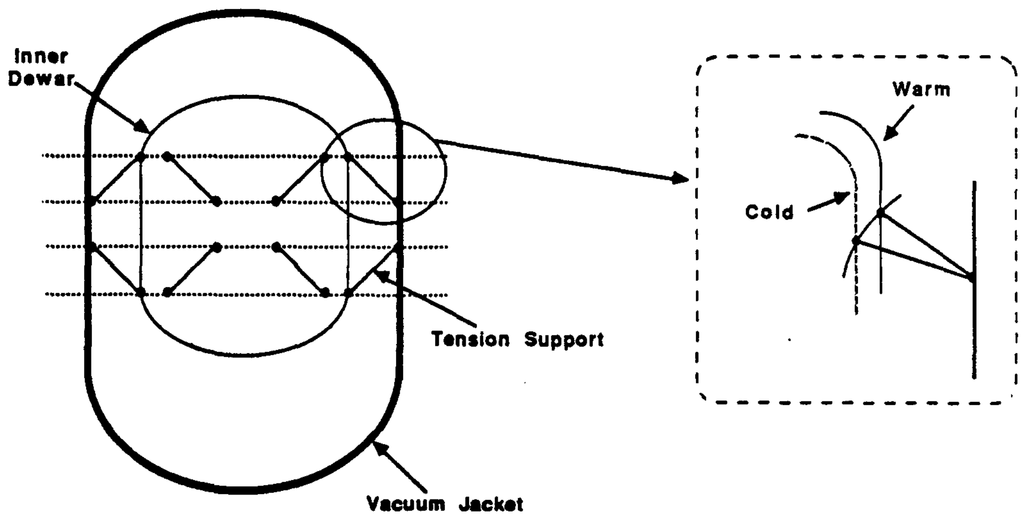

Figure 5.11 Arrangement of Tension Supports To Compensate For Thermal Contraction Of Tank

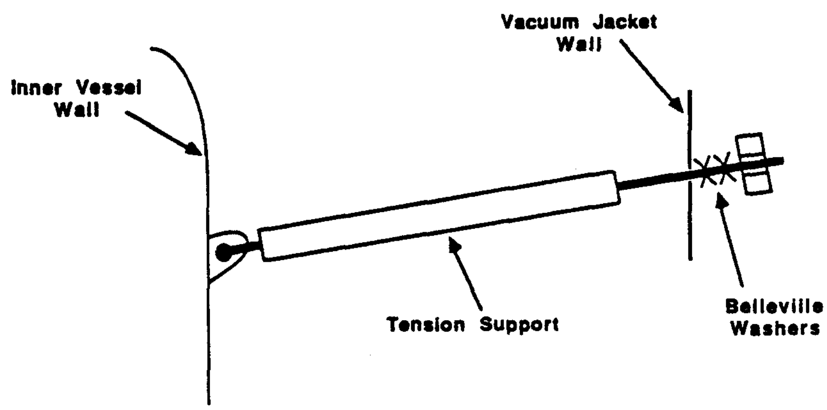

Figure 5.12 Spring Relieved Tension Nut Support Using Belleville Spring Washers

increased by allowing the supports to penetrate into the inner tank. Additional thermal length is achieved by telescoping a portion of the tension straps into glass-epoxy compression tubes.

The primary heat path for a large cryogenic vessel is through the tank wall. High performance multilayer insulation (MLI) is required to provide the needed thermal resistance. Since MLI depends on a high vacuum to reduce heat transport to the primary mode of radiation between reflectors (plus unavoidable solid conduction), a vacuum jacket is required to maintain the vacuum for ground operations. The performance of MLI is dependent on its design and careful attention to fabrication and installation. Conduction through the solid materials is increased by compression, bunching, attachments, and other factors that cause deviation from the ideal blanket design. Increased radiation heat transfer will occur wherever gaps are left, and through breaks in continutiy of individual reflective layers at joints between blankets. While the thermal performance (effective thermal conductivity) of MLI is theoretically independent on its thickness, it is generally accepted that performance deteriorates as blankets become thicker. Fortuitously, in a liquid helium storage system, there is a need to break the MLI into several blankets because of the need for vapor cooled shields to help intercept a large part of the heat leak and carry this heat away in the vented vapor. Insulation is normally installed on separate blankets on each shield (and in some instances on the tank), resulting in several blankets of moderate thickness.

We have evaluated the design options for a SFHe storage system to meet SFHT requirements using a computer program that performs iterative steady state analyses to determine optimum placement of vapor cooled shields and heat intercept points for the other major heat leaks, the supports, pipes, and wires. This program also permits evaluating the effects of a number of parameters, such as the total thickness of MLI, the number of vapor cooled shelds, the effects of including or omitting MLI on the tank, the effect of emissivity of the tank and VCS surfaces, and external (vacuum jacket) temperature. Other factors that were evaluated are the effectiveness of the heat exchangers on the VCS (as evidenced by difference between VCS temperature and the temperature of the vapor exiting the heat exchanger), and the thermal conduction required for straps that connect the heat intercept points for supports, pipes, and wires, to the respective VCS. Results of these studies in terms of sensitivities of the various parameters are presented in Figures 5-13 through 5-17.

Figure 5-13 shows that the external temperature is a strong driver, as would be expected. Our analyses have assumed an external vacuum jacket temperature of 300K for purposes of comparison and worst case evaluations. The actual temperature will depend on the external surface coating, mission characteristics, and vehicle attitude. The predicted average surface temperature for a white-painted vacuum jacket in low Earth orbit is 235 K (discussed later in Section 6.1.5.2). Therefore, the likely heat leak is about 60% of that predicted for the reference temperature. Other approaches for reducing vacuum jacket temperature would include more effective surface coatings such as silverized teflon and optical solar reflectors. Heat leak could also be greatly reduced by cooling the outer boundary using a space radiator or mechanical refrigerator, and Figure 5-13 gives an indication of the possible benefit of further reduction of temperature. The more effective approach for use of refrigeration would be to cool the outer shield within the vacuum jacket, with possible addition of one or more shields. The heat load on the cooling or refrigeration system would be reduced by the MLI blanket outside the cooled shield, improving its effectiveness. Evaluation of a refrigerator or space radiator augmented thermal protection system requires an optimization analysis tailored to the specific configuration and heat removal characteristics.

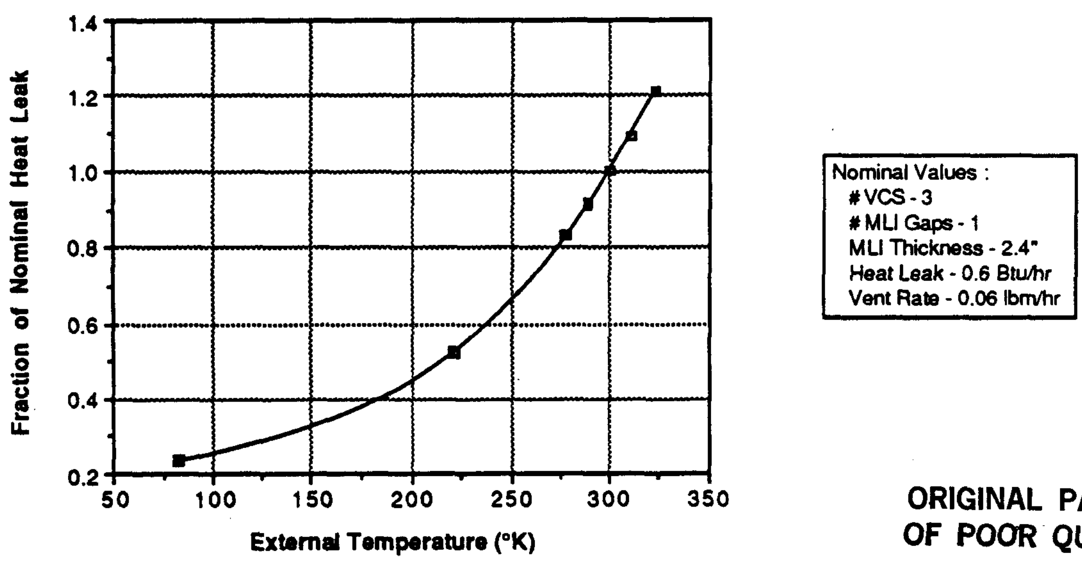

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Figure 5.13 Effect of External Temperature on Dewar Heat Leak

Figure 5-14 shows the effect of total insulation thickness (with 3 vapor cooled shields), number of vapor cooled shields, and the number of spaces starting at the tank wall from which MLI is omitted. Of these, the MLI thickness has the greatest effect. It is noted that no effect of degradation due to blanket thickness is included in this analysis. However, in general the cases analyzed do not require excessively thick blankets. The number of VCS is shown to be a strong

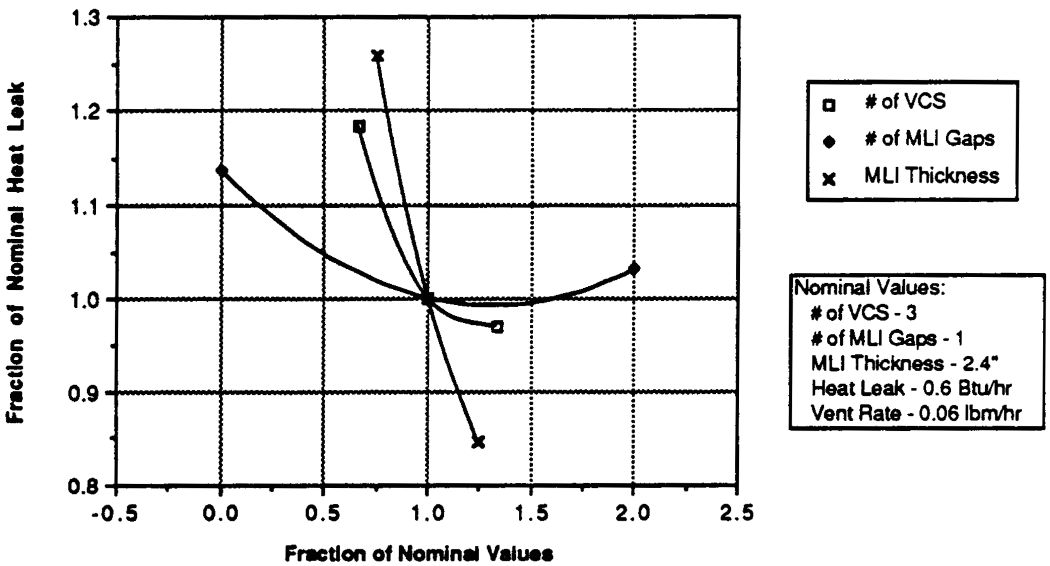

Figure 5.14 Parametric Analysis of MLI Thickness, Number of Vapor Cooled Shields, and Number of Uninsulated Gaps

driver between 2 and 3 shields, with diminishing benefits for more shields. This figure also shows that an improvement is achieved by omitting MLI on the tank wall. This is not because the MLI installed in this area is ineffective or detrimental. Rather, placement of the same MLI in the outer positions is far more effective. The results presented in Figure 5-15 show that only a minor increase in heat leak results from reduction of the length of tubing in the heat exchangers

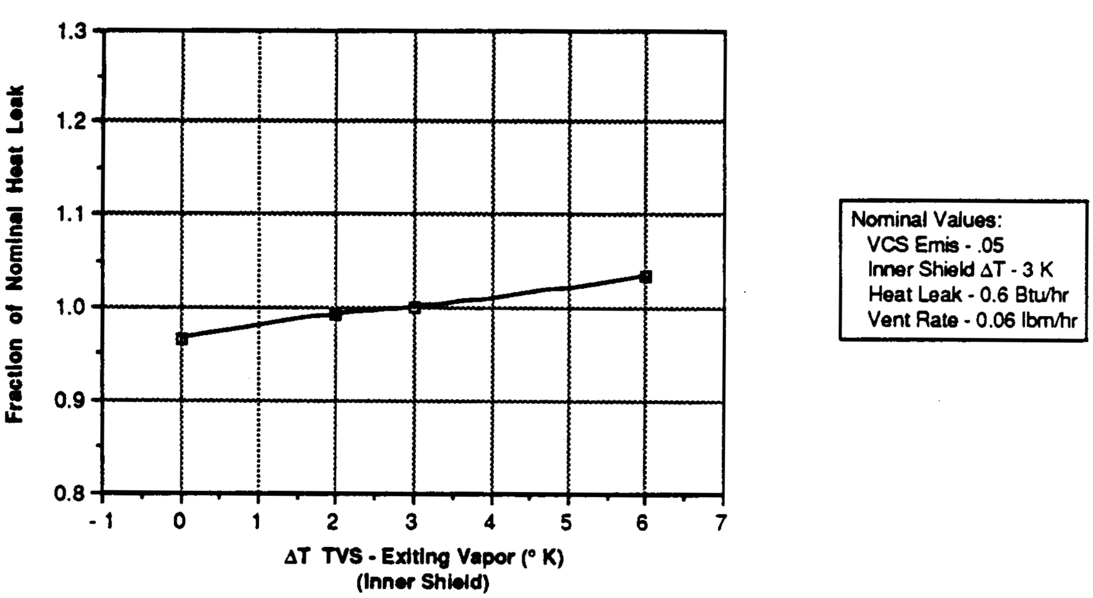

Figure 5.15 TVS Heat Exchanger Trade Study

on the VCS, based on the parameter of difference in temperature between the exiting fluid and the VCS. Figures 5-16 and 5-17 show that there is a very small sensitivity of TVS performance to the emissivity of the tank and shield, and to the size of the straps used to conduct heat from the heat intercept points on the supports. The same conclusion applies for thermal shorting straps from pipes, and wires to the VCS.

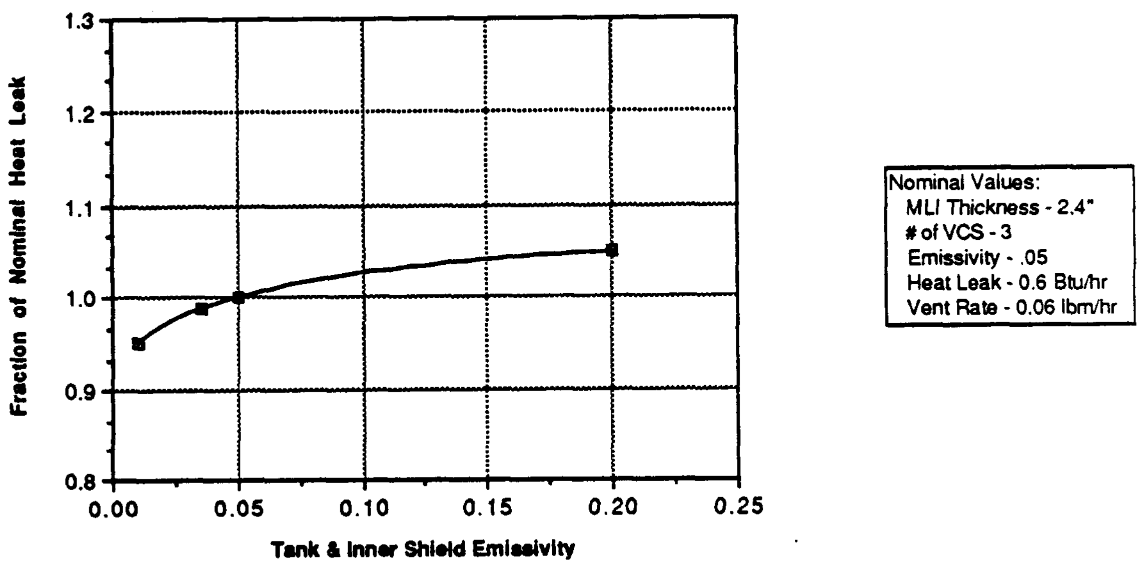

Figure 5.16 Effect of Tank and Shield Emissivity

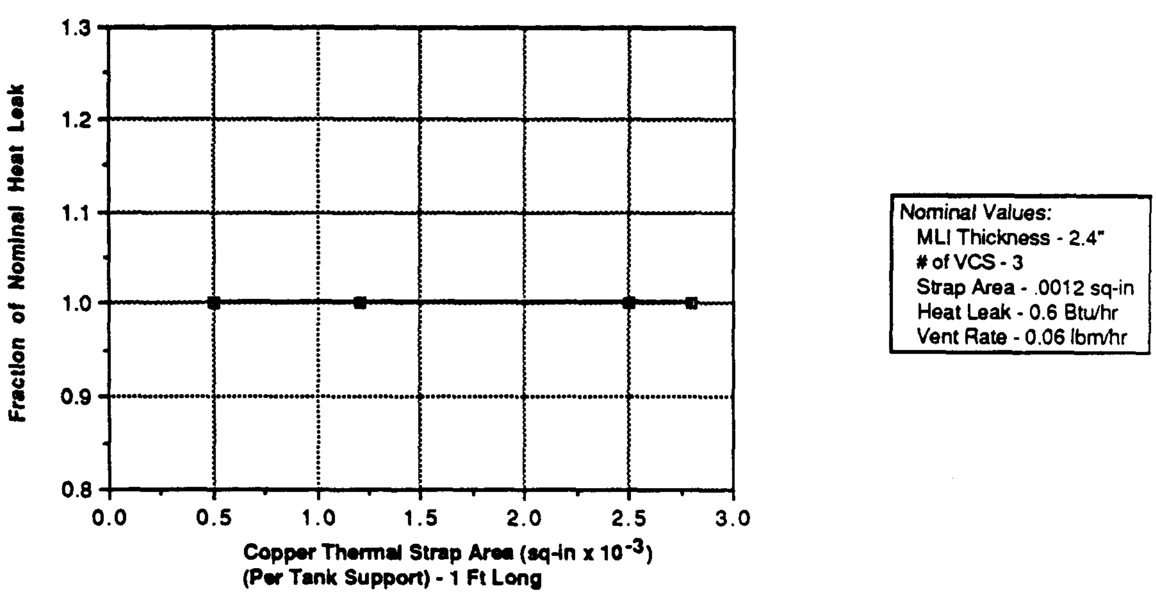

Figure 5.17 Effect of Strap Thermal Conduction

In studies of space storage of other cryogenic fluids, the TVS is implemented by a heat exchanger mounted in or on the tank so as to remove heat from the tank and its contents. Liquid is usually collected using a capillary liquid acquisition device, and admitted to the tank heat exchanger through a restrictor or throttling valve frequently referred to as a "Joule Thomson" expander. Pressure is reduced through the restrictor, and the tank heat exchanger operates at a lower pressure than the tank. Entering liquid partially flashes on reduction of pressure, and the temperature of the resulting two phase mixture corresponds to the saturation condition in the heat exchanger, lower than the temperature of the fluid in the tank. The temperature difference results in a heat flow from liquid in the tank to the vent fluid, and the vent fluid fully vaporizes, absorbing the heat of vaporization and possibly a small amount of sensible heat. The vent fluid exiting the tank heat exchanger is vapor at near the temperature of the fluid in the tank. It is next routed to points in the thermal protection system. Generally, one or more vapor cooled shields (VCS) are mounted concentric to the tank, separating blankets of multilayer insulation, and heat exchangers are coupled to these shields to divert entering heat to the vent fluid. Other heat leaks such as supports and pipes can also be intercepted. Since these are more concentrated, it is frequently more effective to tie these members at strategic points to the vapor cooled shields using thermal shorting straps such as copper wire.

The unusual characteristics of superfluid helium permit a different approach to the TVS. A porous medium, such a a sintered metal plug or compressed powder will restrict or prevent flow of the normal component of superfluid helium that exhibits normal viscous characteristics. The superfluid, or entropyless, component of the SFHe tends to flow freely (within limits) through such a plug. If a plug is fabricated that presents a significant resistance to the flow of the normal component, but not complete blockage, then it can be used as a porous plug phase separator (PPPS). The PPPS can perform the function of the flow restrictor and the tank heat exchanger in a TVS. The PPPS is exposed to liquid on its entrance side, and is connected to the vent piping leading to the VCS on the other. In operation (see Figure 5-18), a small flow of helium (both components) flows through the plug to the low pressure side. Because of the reduced pressure, vaporization occurs at the face of the plug, or perhaps slightly within it, reducing the temperature. The reduction of temperature increases the concentration of the superfluid component of the helium on the downstream side of the plug. Now there is a concentration gradient across the plug, and the viscousless super component of the fluid flows back through the plug into the tank to eliminate the gradient. In this manner, the energy carrying normal component of the fluid is withdrawn from the tank, but the component at the minimum energy or entropyless state tends to be retained, with the result that the heat content of the stored fluid is reduced. Heat transfer also occurs by conventional conduction through the plug due to the

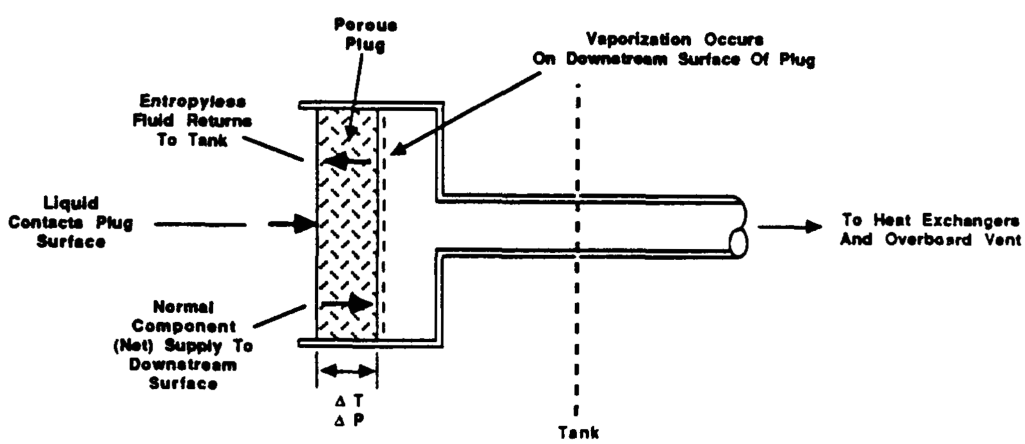

Figure 5.18 Porous Plug Phase Separator

temperature difference. When a PPPS is properly designed, it tends to be self regulating, limiting the net flow to that required to remove the heat that enters the tank and keep the fluid temperature and pressure constant. The PPPS concept has been well proven in ground testing and has been used successfully in the IRAS spacecraft and the Spacelab IRT experiment. This approach offers minimum complexity and space qualification. Its disadvantage is that performance is dependent on a properly designed plug to match the heat leak and the desired storage temperature/pressure.

In addition to the requirement for heat removal to control the fluid condition during long term storage, there is a large cooling requirement on the supply tank during transfer when pumping for transfer is accomplished using a fountain effect or thermomechanical (TM) pump. This pump is also a porous plug, with near total blockage of flow of the normal component of SFHe. Pumping action results from the application of heat downstream of the plug, decreasing the concentration of the entropyless component. Pumping occurs as this component flows without viscous losses through the plug in an effort to equalize the concentration across the plug. The result is that only the minimum energy component of the fluid is removed from the supply tank, and the energy-containing normal component remains behind. Temperature in the supply tank increases. This phenomenon is called the mechanocaloric effect. It is necessary for efficient operation of the TM pump to maintain the supply fluid at a constant (low) temperature. Therefore, venting must be accomplished during transfer, and this vent demand is very much greater than the steady vent requirement during long term storage. If the PPPS concept is employed to meet this vent requirement, a separate plug of larger size, or a number of parallel plugs, will be required.

Our proposed ground servicing concept utilizes a tank heat exchanger to condition and maintain the helium during ground operations. It is therefore possible to consider the use of a conventional Joule Thomson (JT) type expansion and heat exchanger without the penalty of adding a heat exchanger specifically included in the design for on-orbit usage. The JT approach offers the advantage of greater controllability, using a throttling valve to regulate the flow based on feedback logic, and is not necessarily dependent on advance knowledge of the heat leak or transfer rate for its correct operation. It is more complex, however, and requires active operation throughout the mission of valves that are embedded within the cold region. Futher, no cryogenic storage system is known to have operated in space using such components, in contrast to the successfull experience with the PPPS in space. It is also noted that the PPPS will be demonstrated on the upcoming SHOOT experiment for both the storage hold and the high cooling demand during transfer.

The SFHT is currently expected to deliver SFHe to a user spacecraft within 90 days, but may be required to hold the fluid for up to a year in an alternative scenario. A number of concepts are available to increase the storage efficiency of the SFHT. Reduction of the external temperature will reduce the boiloff rate, as illustrated in Figure 5.13, and increase storage life. Therefore, all means, such as thermal coatings that will reduce the temperature of the thermal environment will improve storage efficiency. Active cooling to reduce the heat leak is another approach. If a refrigerator or space radiator is used to reduce the temperature of the outer VCS, significant improvement can be made. The outer shield would be cooled, rather than the vacuum jacket enclosure, to increase the effectiveness of the available cooling capacity. An additional shield may be added in such case, with MLI, to optimize the result.

The availability of a space refrigeration system capable of extracting the total heat leak to the SFHT (without benefit of heat interception by vent gas) at the temperature of superfluid helium, could of course eliminate all venting and extend storage life indefinitely. In such a case, the final refrigerating element (such as expander) could be located in or on the inner helium vessel, and all of the heat entering would be removed. An alternative use of this type of refrigeration capability would be to design the system as if no refrigeration is available, and then to reliquefy the vent gas and inject it back into the tank. This approach may simplify the refrigerator. It also has the advantage of providing a backup storage system of reasonable efficiency in the event of failure of the refrigerator. It would also be possible to configure a system along these lines where the refrigeration capability is not adequate to totally eliminate venting, and could reliquefy only part of the vented vapor.

5.1.2.4 Liquid Acquisition Techniques - A study was conducted to determine which liquid acquisition techniques would be most practical for use in the SFHe tanker. There are only two acquisition system concepts that appear feasible, open sheet metal systems or channel systems fabricated from fine mesh screen. Both of these are capillary systems in which the surface tension of the fluid is used to orient the liquid and provide a barrier to vapor flow.

The main environmental factor affecting surface tension liquid acquisition system design and performance is the acceleration environment in which the acquisition system must operate. In general, the open sheet metal systems are limited to acceleration environments of 10^{-4} g or less. If the acceleration environment exceeds 10^{-4} g, the hydrostatic force produced exceeds the surface tension force of the liquid and displacement of the liquid occurs. This displacement can be such that liquid outflow from the tank during transfer is interrupted. Re-establishment of flow requires reorientation by the surface tension forces which could require a lengthy time period. Channel systems provide a continuous path between the bulk liquid and the tank outlet regardless of liquid orientation or displacement. Several channels are typically employed so that continuous communication between the bulk liquid and tank outlet is provided even if liquid moves in the tank. If the helium transfer process from the SFHT to the using space system is always accomplished at the Space Station, where the acceleration typically will be less than 10^{-4} g, then the open system would be preferred. However, since some of the transfer may be from the Shuttle to the using system, some Shuttle transient accelerations as high as 10^{-3} or 10^{-2} g may be imposed on the SFHT. Therefore, the recommended system considering all orbital locations and environments is a channel system fabricated from fine mesh screens. A similar conclusion was reached in the fluid management study conducted by Lockheed in support of the STICCR study (Reference 5.8). Martin Marietta, in studying requirements for the SHOOT program for NASA-GSFC, also has recommended a channel system for fluid acquisition.

A capillary system pressure loss assessment was conducted to establish a preliminary conceptual design for the SFHT. The SFHT tank was assumed to be cylindrical with hemispherical domes. The tank diameter was 84 inches with a barrel section 12 inches long. The temperature of the fluid was assumed to be at the lambda point because at this condition the fluid surface tension is lowest and the viscosity is highest. Both of these factors contribute to a conservative analysis. A pressure drop analysis was conducted on the channel system assuming all the flow is carried to the outlet through one channel. When the total pressure loss across the channel equals or exceeds the screen bubble point, vapor is ingested into the channel and the liquid flow from the tank terminates. The total pressure loss consists of hydrostatic, channel internal friction, fluid acceleration, and screen flow pressure loss terms.

A parametric study was conducted assuming various channel cross-sectional dimensions. A flow rate of 1000 liters/hour and accelerations of 10^{-2} g and 10^{-3} g were assumed. The results of the analysis are shown in Table 5.4. The analysis indicated for a channel cross section of 3.0 x 0.5 inches that liquid could be drained from the tank until 10.86 in^2 of screen area was in contact with the bulk liquid. The effect of an acceleration of 10^{-2} g is also shown in the table. The hydrostatic pressure loss is increased by a factor of 10, reducing the allowable screen pressure loss so that approximately 90 square inches of wetted screen is required at breakdown. The increased wetted screen area implies a significant increase in residual liquids. A similar analysis has been performed for the SHOOT fluid acquisition system for a Shuttle acceleration of 10^{-2} g and 800 liter/hour flow rate. Results of this analysis are also shown in Table 5.4.

Table 5.4 Liquid Acquisition Device Pressure Loss Analysis

PROGRAM	SFHT		SHOOT
Flow Rate, Liters/Hr	1000		800
Channel Dimensions, In.	3 x 0.5		2.25 x 0.5
Acceleration, g	10^{-3}	10^{-2}*	10^{-2}*
Hydrostatic Head, psi	0.00051	0.00510	0.00174
Channel Friction, psi	0.00176	0.00176	0.00066
Acceleration Loss, psi	0.00088	0.00088	0.00100
Screen Loss, psi	0.00485	0.00026	0.00460
Total (Bubble Point**), psi	0.00800	0.00800	0.00800
Wetted Screen Area, in^2	10.86	89.29	9.21

* Maximum Shuttle Acceleration
**Bubble Point = 0.012/1.5 S.F.

A study was made to evaluate the residuals that would be left in the helium tank at the end of the transfer process. It was assumed that the acceleration environment was directed so as to locate the bulk liquid residual between the channels. For an acceleration of 10^{-5} g, the Bond number for the fluid in the tank was calculated to be approximately 70. SFHe tank Bond number variation is shown in Figure 5.19. This large a Bond number indicates a very flat liquid interface

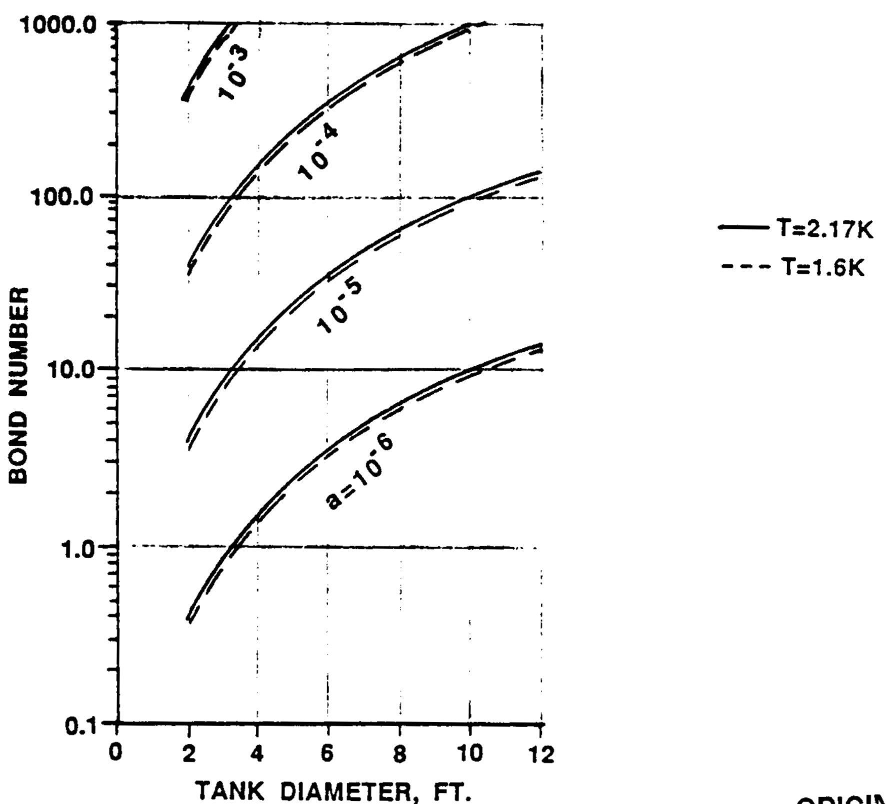

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Figure 5.19 SFHE Tank Bond Number Variation that could result in a maximum quantity of liquid located between the channels. This quantity was estimated to be 360 liters or 5.8% of the total tank volume. This volume does not include the liquid contained within the liquid acquisition system channels which is also considered to be an unusable quantity, as well as any liquid between the channel and tank wall which is unavailable for flow into the channels under the settled fluid condition.

In order to reduce the residual, a horizontal channel was located at the equator of the tank linking the four vertical channels. The general arrangement is shown in Figure 5.20. With this channel design, the maximum liquid residual external to the channels would be located in one quadrant of the tank between the two vertical channels and the horizontal channel. The estimated residual volume in this external quantity was estimated to be 140 liters. The horizontal channel volume does add to the acquisition system volume; however, the total residual including 20 liters for the acquisition device is only 160 liters, resulting in a 97.4% expulsion efficiency.

5.1.2.5 Fluid Gauging Techniques - To properly load superfluid helium on the ground and efficiently transfer it on-orbit, the SFHT must have the capability to accurately "know" the mass of helium within the storage Dewar during the entire operational scenario. For SFHT we have selected the types of gauges and meters baselined for SHOOT.

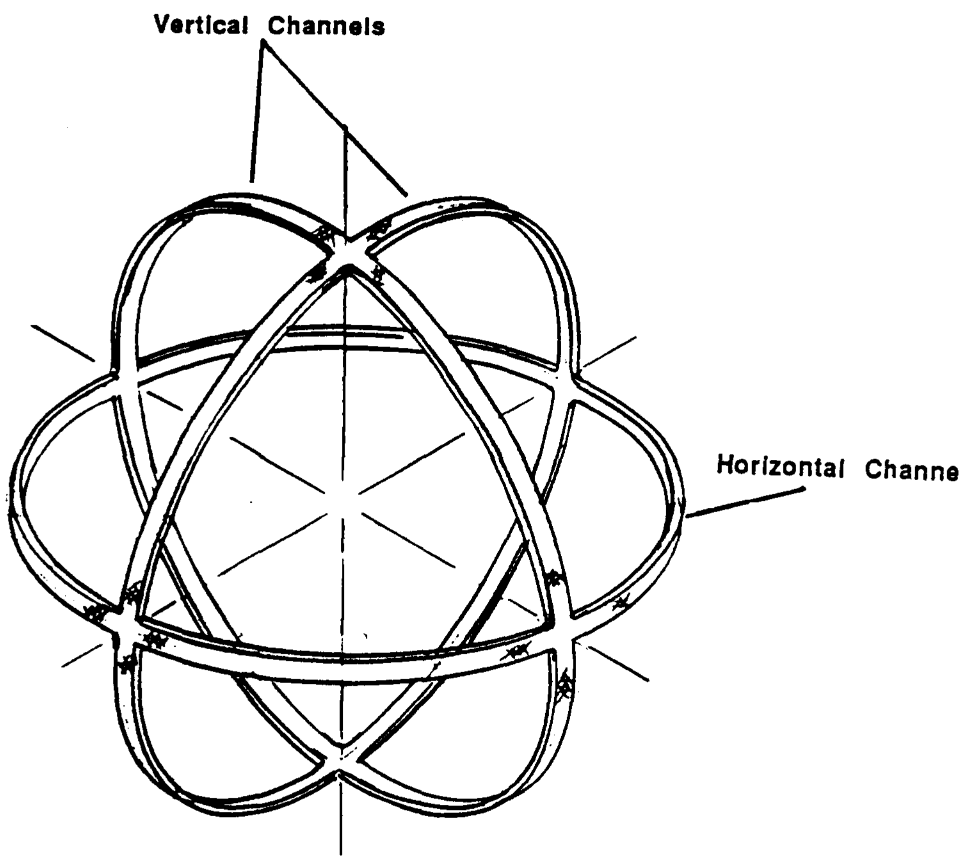

Figure 5.20 Liquid Acquisition System with Horizontal Ring Channel

The heat pulse gauge determines the mass of helium by inputting a heat pulse, from heaters, into the fluid and monitoring Germanium Resistive Thermometers (GRT) for a temperature rise. The rise in temperature correlates to the liquid mass through the liquid helium specific heat characteristics. Units developed for the SHOOT will be used by SFHT to control the power to the heaters and monitor the temperature sensors. Power to the heaters will be variable, 0-56 watts with a variable pulse time of .25 to 25.0 seconds. SHOOT has tested this technique and has obtained accuracies of 3% in the temperature range of 1.3K to 1.9K with no more than 1% loss of liquid helium. At present this technique does not meet a one percent accuracy requirement as desired by the SFHT but the goal of SHOOT personnel is to improve the technique, if possible, to obtain the 1% accuracy. The ideal concept would require only one heater and one temperature sensor. We propose multiple heaters and sensors considering maintainability and reliability of elements embedded within the all-welded inner storage vessel.

We are also identifying the use of small silicon chips for determining the liquid/vapor boundary of the liquid in the dewar. The chips are being developed by the NASA/GSFC Cryogenic, Propulsion, and Fluid Systems group for use in the SHOOT experiment. SFHT plans on utilizing the chips by incorporating the chips in one channel of the Liquid Acquisition Device (LAD) and in the bulk of the liquid. Units being developed for the SHOOT experiment will provide excitation and monitoring for the chips. Due to the characteristics of the chips a discrete signal is obtained when power is applied indicating a liquid zone or a vapor zone. In a low-g environment helium will leave a film on the sensors. Power will be applied for a brief time to burn off the film; then a reading will be taken. The level of power is small (0.024 Watts) compared to the power for the heaters in the mass gauging technique (40 Watts) and the on-time is very brief (50 milliseconds); thus the effects on the liquid are negligible.

Redundant venturi flowmeters are also recommended for the SFHT. The meters are being built by the Ames Research Center for the SHOOT experiment. The rate of flow through the meters is determined by the pressure drop in the meter. For the SHOOT experiment two differential pressure sensors for each flow meter will measure the pressure difference between the inlet and the throat, a 0.125 psid pressure sensor for low flow (25 L/hr - 200 L/hr) and a 1.25 psid pressure sensor for high flow (200 L/hr - 800 L/hr). In testing, Ames has obtained accuracies of 16% to 1% for flow rates of 25 L/hr to 200 L/hr and 3% to 1% for flow rates greater than 200 L/hr. For SFHT the flow rates will be 250 L/hr to 1000 L/hr. This increase in the upper end of the flow range will require a change in the differential pressure sensor to a higher range, perhaps to 2.0 psid. The flow meter and pressure sensor will require testing at the higher flow rates to 1000 L/hr to determine the effects on accuracy.

5.1.3 Fluid Transfer Techniques

Various techniques for transferring liquid helium from a supply tanker to a receiving tank were evaluated and a preferred approach for accomplishing the transfer process was selected. The fluid flow and thermal characteristics of the various elements of the transfer system (i.e., pump and transfer line) were evaluated, including cooldown of the system. This lead to an end-to-end parametric transfer simulation from supply Dewar to user receiver Dewar. The results are presented below.

5.1.3.1 Transfer Pumps - One of the major design drivers in the transfer system is the pumping technique to be employed. Because of the unique characteristics of superfluid helium, autogenous pressurized transfer of the cryogen in a manner similar to the method used in cryogenic propellant feed systems is not possible. The extremely high thermal conductivity of the SFHe transfers heat away from the ullage region so that a positive pressure above saturation cannot be maintained. Therefore, pressurized transfer is not an option to be considered in the transfer system.

An alternative method for transferring the SFHe is by means of pumps. Two pumping options currently available are conventional mechanical pumps and the thermomechanical (TM) or fountain effect pump (FEP). Testing of a conventional centrifugal pump in superfluid helium has been conducted at the National Bureau of Standards Cryogenic Laboratory in Boulder, Colorado, under the sponsorship of NASA-ARC. Results thus far indicate that the centrifugal pump tends to cavitate easier or sooner with superfluid helium than with normal helium. Additional development work is required if this type of pump is to be used.

The thermomechanical (TM) or fountain effect pump (FEP) has no moving parts and appears to be a viable solution to the superfluid helium pumping problem. The TM pump is presently being developed by NASA-GSFC for use in the SHOOT demonstration program. This pump concept employs a porous plug with an electrical heater element on the downstream side. Application of heat produces a temperature difference across the plug. Assuming the plug is a perfect superleak, the static pressure developed by this temperature difference can be calculated from the following:

$$P = \rho S \ T$$

For large temperature differences, using temperature dependent fluid properties, a convenient formula is

$$\Delta P = 3.0515 \ (T_H{}^{6.7} - T_C{}^{6.7}) \qquad (1)$$

where ΔP is the pressure rise in Torr and T_H and T_C are the temperatures on the hot and cold sides of the fountain pump. The valid temperature range is

$$1.55 \text{ K} \leq T \leq 2.17 \text{ K}.$$

Where a net mass flow is present, the FEP heater must operate at higher powers, due to the entropy transport of the fluid. The required heater power is

$$Q = \rho VAST_H \qquad (2)$$

where ρ is the fluid density, S is entropy, T_H is temperature on the hot side of the pump, V is the net fluid velocity and A is the cross-sectional area of the flow tube.

A parametric plot of ideal thermomechanical pump performance is presented in Figure 5.21, covering the operating regimes of the SFHT, assuming the storage Dewar is at 1.8 K. This type of TM performance map was originally generated by Dr. Peter Kittel (Reference 5.9). Actual fountain pump operating data are shown in Figures 5.22 and 5.23 (Reference 5.10). At low heater powers, the predicted mass flow rates agree quite well with theoretical pump performance curves, as illustrated in Figure 5.22. At higher FEP heater powers, a saturation effect is seen. Figure 5.23 plots the temperature profile along the flow tube. Note the temperature gradient upstream of the pump. Heat is being generated in the FEP inlet, presumably through the mechanocaloric effect. Fountain pumps for the SFHT will have to be empirically characterized in order to obtain operational performance maps similar to the results shown in Figures 5.22 and 5.23.

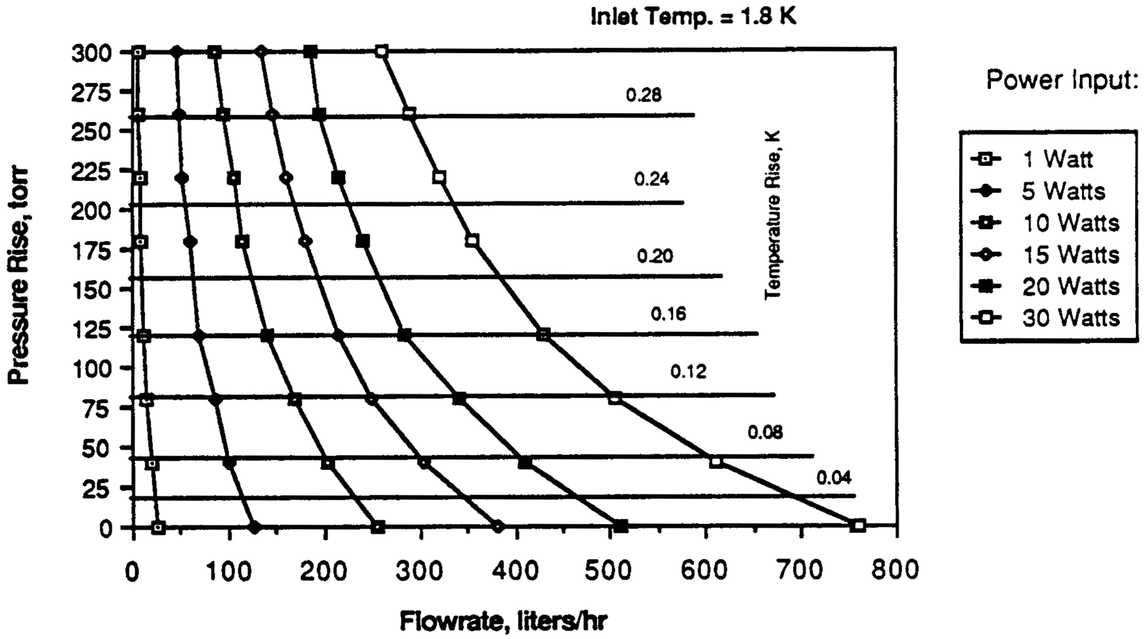

Figure 5.21 Ideal Thermomechanical Pump Performance

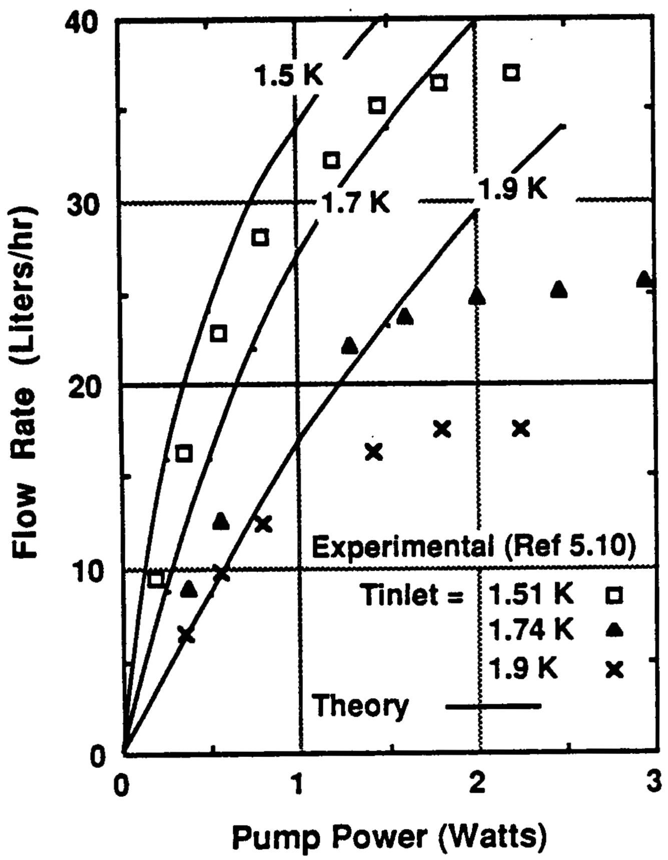

Figure 5.22 He II Flow Rate as a Function of FEP Heater Power Compared with Theory

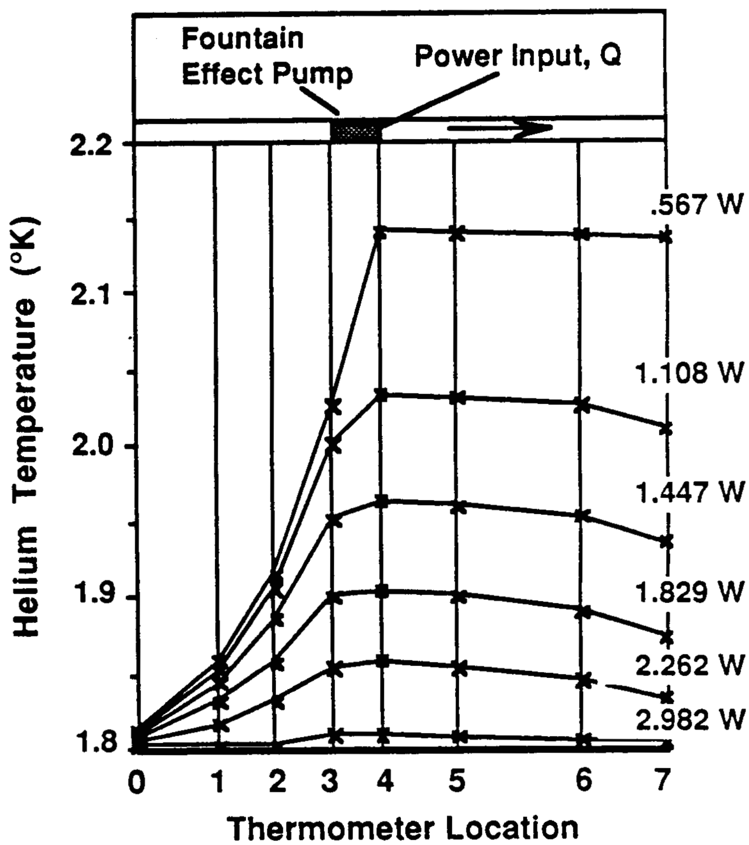

Figure 5.23 Temperature Distribution in the FEP at Different Heater Powers

5.1.3.2 Transfer Line - Another design aspect that influences the transfer of superfluid helium between the supply and receiver tanks is the thermodynamic and hydraulic characteristics of the transfer line. The flow state of liquid helium in the transfer line can be described using the two fluid model. Gorter-Mellink conduction has been shown to affect the heat transfer of forced convection He II. A zeroth-order estimate of the temperature profile can ignore counterflow, especially at higher flow velocities, but the complete two-fluid model should be used.

When the temperature profile along the transfer line is determined, the heat flux conducted upstream to the supply dewar can be found from

$$\dot{q} = \left[\rho_s \quad \frac{S^4 T^3 \nabla T}{A \rho_n} \right]^{1/3}$$

where ρ_s is the superfluid density, ρ_n is the normal fluid density and A is the Gorter-Mellink parameter. This heat flux results from parasitic heat leaks into the transfer line, from line couplings and from thermal radiation along the length of the line. A unique aspect of this counterflow conduction is that the parasitic heat leaks can provide an additional fountain pressure contribution, either by lessening the FEP heater power for a given pressure head or by increasing the pressure head for a constant heater power. Alabama Cryogenic Engineering, Inc. has developed a numerical model of forced convection He II, the results of which agree with existing experimental data (Reference 5.11). A typical transfer line temperature profile is presented in Figure 5.24.

The transfer line diameter can be sized in order to lower the line pressure drop. Existing friction factor data for He II indicates that it behaves very similarly to normal cryogens. A modified Blasius law can account for He II friction factor data. The friction factor does not depend very sensitively on temperature. An increased line diameter also influences the temperature rise of the existing liquid, since the enthalpy increase per unit volume is proportional to $1/d^2$.

5.1.3.3 Transfer System Concepts - Four fluid transfer system concepts were identified as potential candidates for evaluation. The first of these, shown schematically in Figure 5.25, is called an "open" transfer system and is designated as a baseline concept. The heat generated by the pump splits into two components. Q_R travels down to the receiver dewar and Q_S goes into the supply Dewar. The pump essentially isolates the supply and receiver Dewars; the transfer line heat leak raises the temperature of the fluid entering the receiver Dewar. Note that most of the FEP heater power goes into converting the zero entropy fluid exiting the pump into fluid at this temperature. Subsequently, this Dewar must be pumped down to the operating temperature, resulting in venting of some of the transferred liquid mass.

The second configuration, Figure 5.26, couples the supply and receiver Dewars through a heat exchanger. Any excess heat can be absorbed into the supply Dewar. A larger diameter transfer line, which enables counterflow to work more effectively, will drive more of the transfer line heat leak back to the supply Dewar through the heat exchanger. When the transfer is complete, the supply Dewar can cool down the receiver Dewar to the desired temperature, the transfer line acting like a counterflow heat pipe. Thus, the entire transfer process can be completely regulated by the supply Dewar.

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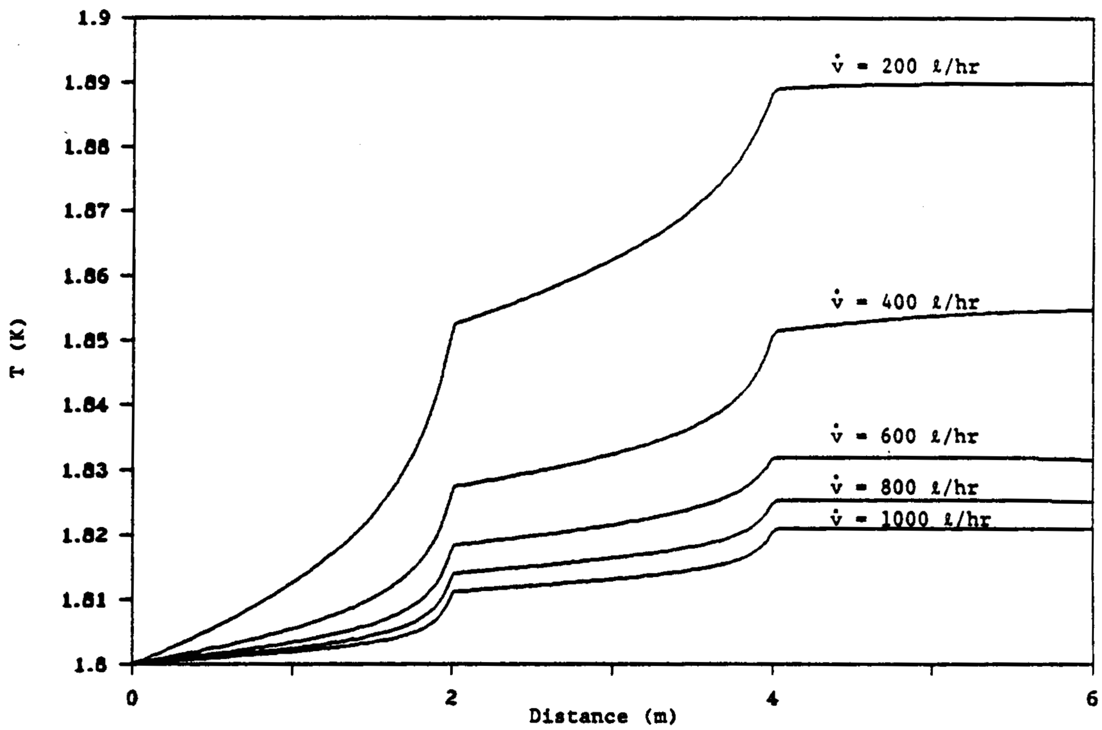
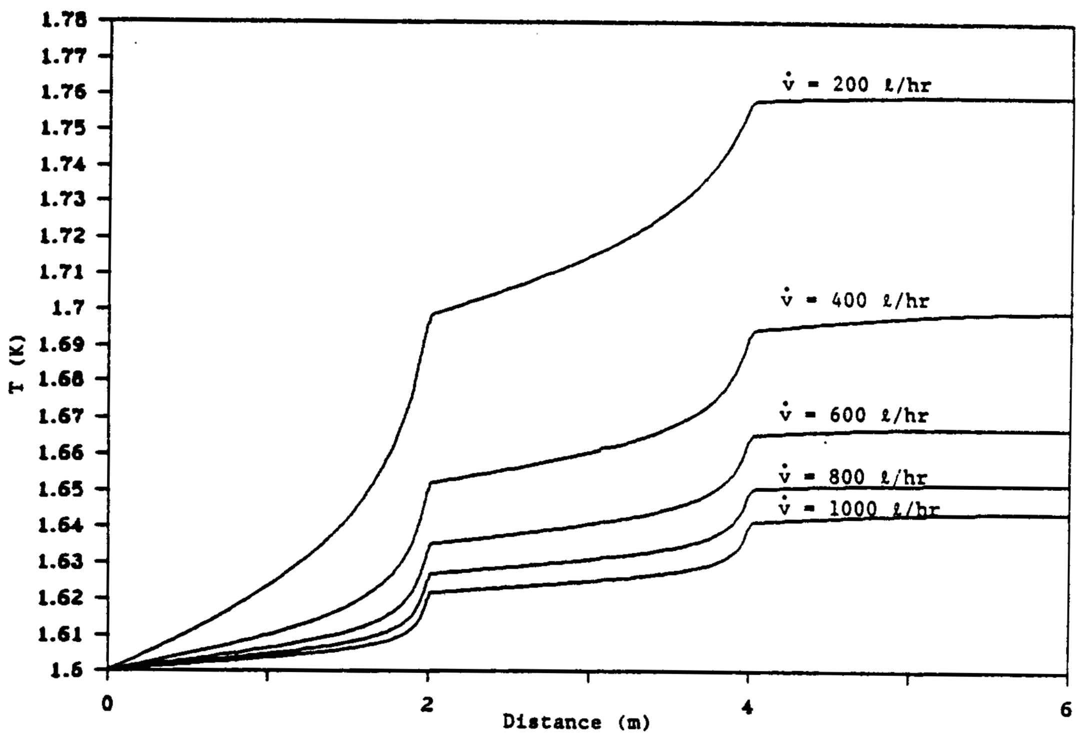


Transfer line temperature profile at differing transfer rate. Supply dewar at T=1.8 K, dT/dX = 0 at receiver dewar. Line diameter = 1.27 cm.



Transfer line temperature profile at differing transfer rate. Supply dewar at T = 1.6 K, dT/dX = 0 at receiver dewar. Line diameter = 1.27 cm.

Figure 5.24 Transfer Line Temperature Profiles at Differing Transfer Rates

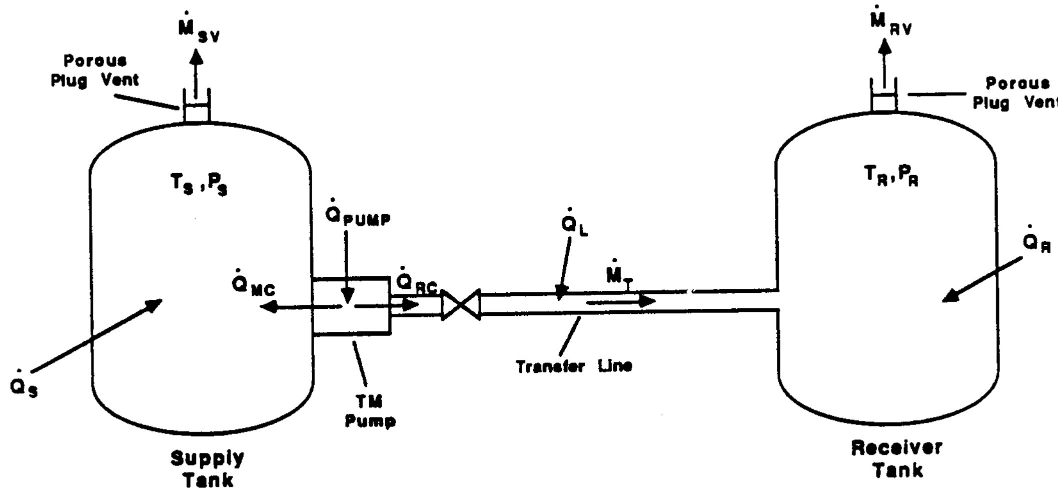


Figure 5.25 "Open" Transfer System Schematic

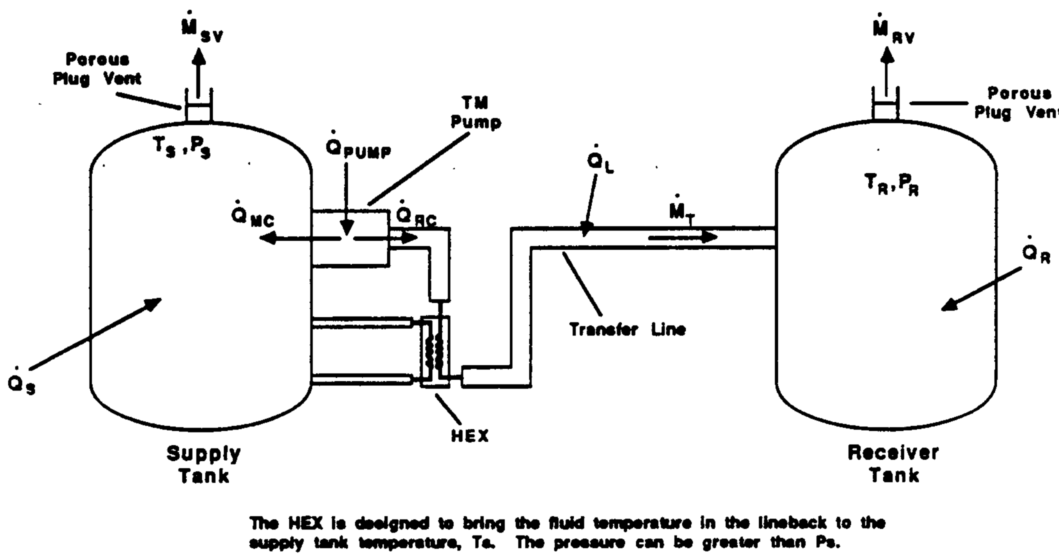


Figure 5.26 "Closed" Transfer System Schematic

A third concept considered does not utilize a pump in the transfer line. The fluid transfer from the supply to the receiver tank through the transfer line is driven by maintaining different temperature conditions in each tank through differential venting, as shown in Figure 5.27. The resulting saturation pressure difference drives flow through the transfer line.

The three concepts presented thus far deliver superfluid helium from the supply to the receiver. A fourth concept considered supplies normal helium slightly above the lambda point to the receiver tank through a throttle valve in the transfer line, as shown in Figure 5.28. Use of normal helium allows pressurization of the supply tank to provide a higher driving pressure.

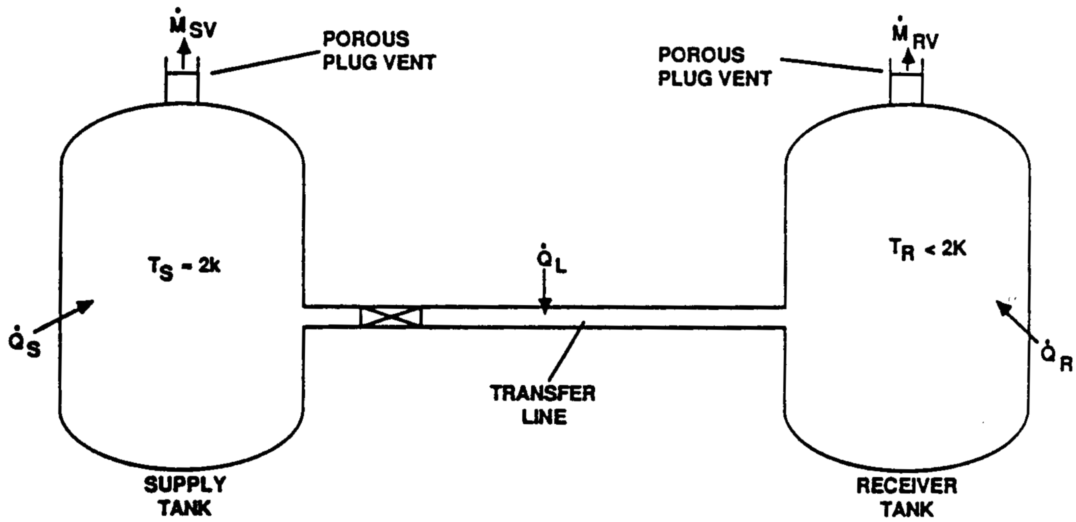


Figure 5.27 Differential Venting Transfer System

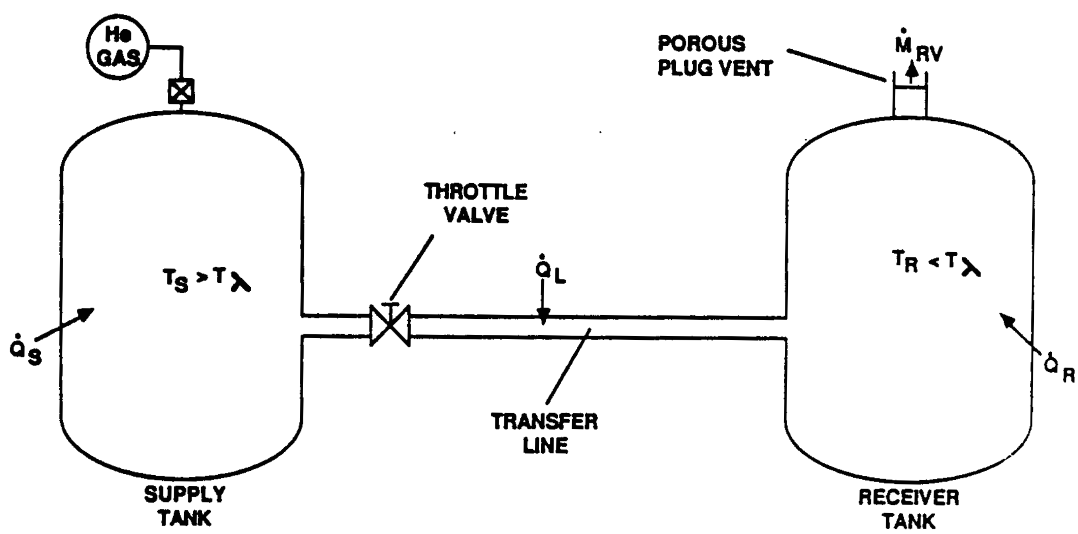


Figure 5.28 Liquid Throttling Transfer System

Expansion of the normal helium through the throttle valve and the resulting liquid flashing lowers the liquid temperature below the lambda point producing superfluid liquid helium and vapor.

5.1.3.4 Transfer System Analysis - In order to evaluate and compare steady state operation of the open (baseline) and closed transfer methods, a simplified analytical model, was assembled and used for parametric analysis. For specified storage tank and transfer line geometry, required temperature conditions in both storage and receiver tank, and parasitic heat leaks in both tanks and the transfer line, the model determines total transfer time, actual mass transferred to the receive tank, thermomechanical pump requirements, and the required vent rates in both tanks to maintain the required storage temperature. An ideal thermomechanical pump is assumed in the model. However, the influence of the mechanocaloric effect upon the storage thermal condition is included in the analysis. The transfer line model assumes turbulent flow so that the Fanning friction model is used to calculate pressure loss and determine TM pump requirements. Both the open and closed transfer techniques were analyzed. Operating conditions assumed in this analysis are presented in Table 5.5. The results of the analysis indicated that the total mass lost from both the supply and receiver tanks during the transfer process was slightly less for the closed system than for the open system. However, the maximum difference was less than 0.6 kg. This slight performance gain was not considered significant enough to offset the increased design complexity of the closed system. Therefore, the closed system was not considered further as a candidate system concept.

Table 5.5 Transfer System Analysis Operating Conditions

Storage and Receiver Tank Temperature, K	1.5, 1.8, 2.0
Storage and Receiver Tank Heat Leak, Watts	1.0
Transfer Line Heat Leak, Watts	4.0
Supply Tank Volume, Liters	6000
Tranfer Rate, Liters/Hour	250, 500, 750, 1000
Transfer Line Length, M	10
Transfer Line Diameter, cm	1.27

Figure 5.29 presents the transfer time required for the open system as a function of transfer rate and storage tank temperature for a 6000 liter storage tank. The transfer line length and diameter were 32.8 feet (10 meters) and 0.5 inch (1.27 centimeters), respectively. Figure 5.30 presents the transfer efficiency for this tank configuration also as a function of transfer rate and storage temperature. An assumption made in this case is that the storage and receiver tank temperatures are equal.

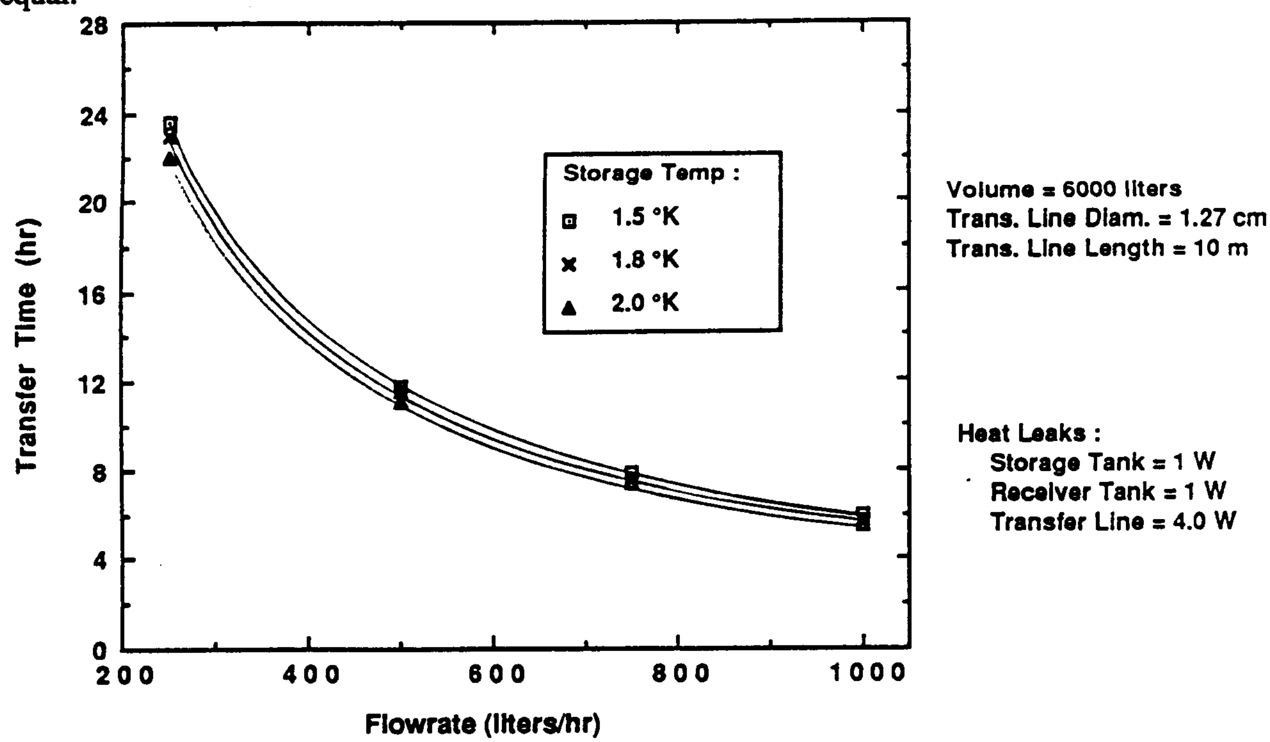


Figure 5.29 Transfer Time as a Function of Flowrate for Different Initial Storage Temperatures

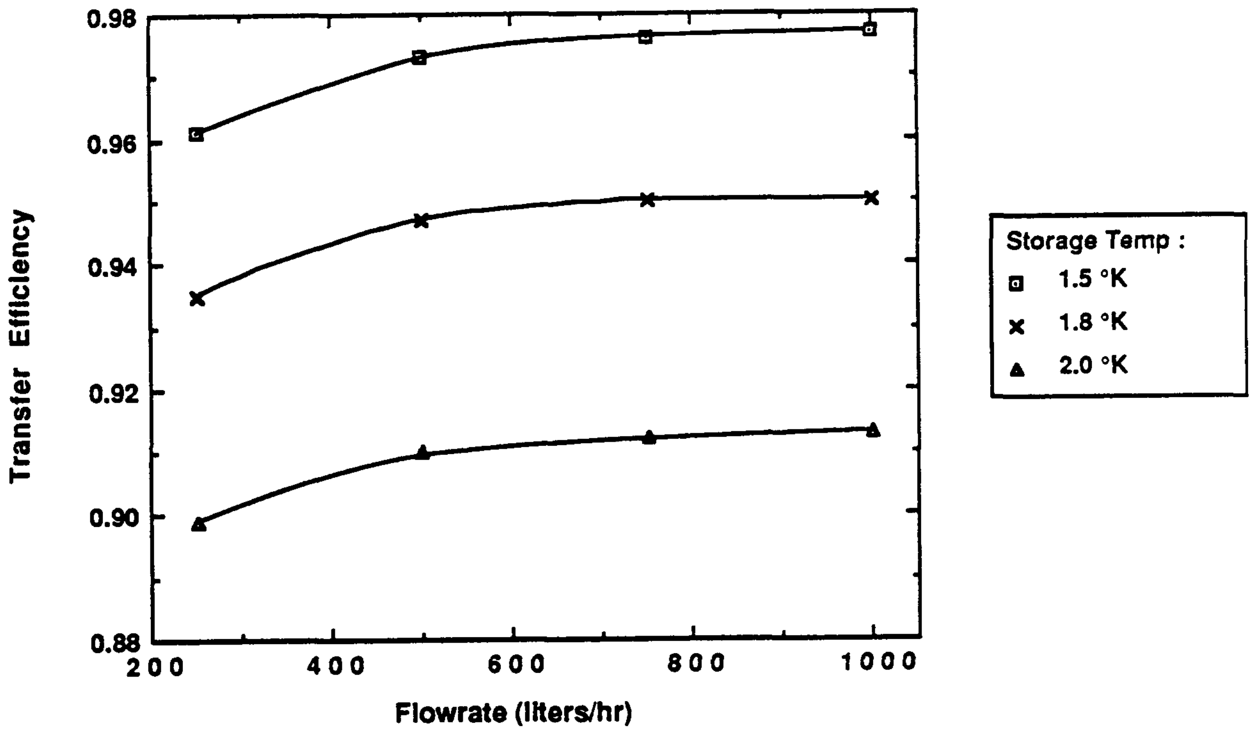


Figure 5.30 Effects of Transfer Flowrate and Storage Temperature on Transfer System Efficiency

An evaluation of the differential venting transfer system was conducted based upon the assumed conditions listed in Table 5.6. The calculated line friction loss during a transfer rate of 1000 l/hr was 0.0143 atm. This pressure drop is 60% of that available if the storage and receiver tank temperatures are maintained at 2.0 and 1.6 K, respectively. If the receiver tank temperature rises to 1.8 K, the line friction loss just equals the tank pressure difference, allowing no margin for other component losses. This transfer technique requires accurate control of liquid temperatures which may be difficult to achieve. Therefore, this transfer concept was also eliminated from further consideration.

Table 5.6 Differential Venting System Operating Conditions

Tank		Storage	Receiver
Temperature, K		2.0	1.6
Pressure, ATM		0.03128	0.00749
Volume		6000	6000
Flow Rate, Liters/Hour		1000	1000
Heat Leaks, Watts		1.0	1.0
Transfer Line			
Length	4.5 M		
Diameter	1.2 CM		
Heat Leak	2.5 Watts		

The fourth transfer system concept considered utilizing a liquid throttling process in the transfer line between the storage and receiver tanks. The helium in the supply tank was assumed to be slightly above the Lambda point temperature of 2.2 K. The receiver tank temperature was maintained at 1.6 K. The flow rate from the supply tank was 1000 l/hr. Of this flow rate, 127 l/hr (12.7%) was vaporized to produce superfluid helium and cool it to the receiver temperature of 1.6 K. The accumulation rate of superfluid helium in the receiver tank was 873 l/hr. If the supply tank was pressurized to 3.0 atm, the required vaporization would be 25% of the total flow to produce superfluid helium at 1.6 K. Because of the large fluid losses, this concept was also not given further consideration.

The conclusion reached from the transfer system analysis was that the most promising transfer technique was the open transfer system employing a thermomechanical pump. This transfer concept provided the least complexity and minimum transfer losses.

6.0 TASK 3 - CONCEPTUAL SFHT SYSTEM DESIGN

This task involved the conceptual design of all SFHT subsystems (fluid, structural/mechanical, thermal and avionics). Facility requirements and GSE conceptual design were addressed, and both ground and on-orbit operations were defined, including operational timelines.

6.1 SFHT SYSTEM DESIGN

A starting point in the SFHT conceptual design effort was to revisit the tanker optimization conducted as part of Task 2. Additional trade studies were conducted, and a reference tanker capacity was selected to permit operations trades to be conducted around a tanker configuration point design. Each of the various tanker subsystems was then evaluated and conceptually designed to produce an integrated SFHT conceptual design.

6.1.1 Tanker Optimization

SFHT configuration sizing trades were reevaluated and expanded, particularly with respect to launch vehicle options, to produce a recommended SFHT size and shape. We particularly emphasized the practicality and feasibility of the mixed-fleet launch approach to SFHT transportation to orbit.

6.1.1.1 Fluid Storage Sizing Trades - Trade studies were performed previously as part of Task 2 to optimize the capacity of the SFHT fluid system based on the user requirements. This section presents a summary of an update of these trades performed during Task 3. The reduced user complement that we identified during Task 2 was again used as the reference set with updated program start and launch dates, as presented in Table 4.1. The SFHT manifest model, also developed as part of Task 2, was redone using these requirements and is shown in Figure 6.1. As shown, eight flights of the 6000 liter capacity SFHT are required to satisfy the users if all are resupplied from the Space Station. If SIRTF is resupplied from the STS (currently the baseline), then nine total flights are required: four in the STS for SIRTF and five to Space Station for the remaining users.

Currently, both SIRTF and Astromag prefer to be serviced while helium is still on-board. In the case of SIRTF, it is preferred not to allow the instruments to warm-up once they have reached helium temperatures. For Astromag, it is also desired to service with helium remaining to avoid having to cool the large magnets back down to operating temperatures thereby minimizing helium usage (Reference 6.1). Experiments mounted in the U. S. Laboratory, (MMPF/CPPF and Lambda Point Facility) are easily accessible and it should be possible to schedule refilling of these experiments while cold. A sensitivity analysis was previously performed as part of Task 1 to determine the impact on the flight frequency if some or all of the users required chilldown as well as resupply. The general trend was that as the resupply frequency and the amount of helium required increased, a larger capacity SFHT would be more efficient provided that all servicing was done at one location (i.e. Space Station) where the SFHT could serve as a general supply depot for all users. For example, if all of the users were resupplied warm, thirteen flights of the 6000 liter SFHT would be required during a ten year period compared to eight flights of a 15000 liter tanker. Offloading of a large capacity tanker for a cold SIRTF resupply from the STS, however, would eliminate the advantage in mass fraction possible with the larger tanker. Using the 11750 liter tanker design from the BASD STICCR Study (Reference 6.2), the fully loaded tanker has a mass fraction of 0.36. When offloaded to 5500 liters for a cold SIRTF resupply, the mass fraction is lowered to 0.21. Therefore, an intermediate size tanker appears to offer the best compromise to perform all of the planned resupplies from different locations.

Based on the above results, we feel that a 6000 liter capacity SFHT, derived from the Task 1 trades, satisfies the mission requirements in the most efficient manner. It is sufficient in size to resupply SIRTF under normal conditions without an undue penalty for the smaller users. Also, this capacity makes the option of packaging into smaller ELV payload fairings a practical option, as discussed in the next section. However, an important conclusion reached during the sizing studies was that the optimum SFHT size is heavily dependent on the user requirements in terms of both user capacity and resupply frequency. Therefore, it is recommended that the sizing issue continue to be readdressed as the user requirements mature.

6.1.1.2 Launch Vehicle Options - An objective of this study was to determine design impacts to the SFHT of launch both on an ELV and the Shuttle. A mixed manifesting approach, using both ELV's and the Shuttle, is being considered for Space Station logistics resupply (Reference 6.3). Early in Task 2, we established the requirement to examine all ELV's, not just the Titan IV. This was done to ensure that compatibility with a maximum number of ELV's was examined.

	Capacity of Tanker 1 (l):	1260		Capacity of Tanker 2 (l):	6000
Quarter	Helium Required, liters	# ofTanker 1 Flown	# of Tanker 2 Flown	Helium in Tanker (l)	
1997	0			0	
	200		1	5493	
	200			4986	
	200			4479	
1998	200			3972	
	3700		1	5965	
	200			5458	
	200			4951	
1999	200			4444	
	200			3937	
	200			3430	
	4200		1	4923	
2000	200			4416	
	3700			409	
	200		1	5902	
	200			5395	
2001	200			4887	
	200			4380	
	200			3873	
	4200		1	5366	
2002	0			5059	
	3500			1252	
	0			945	
	0			638	
2003	0			331	
	0			24	
	0		1	5717	
	4000			1410	
2004	0			1103	
	3500		1	3296	
	0			2989	
	0			2682	
2005	0			2375	
	0			2068	
	0			1761	
	4000		1	3454	
2006	0			3147	
	400			2440	
	0			2133	
	0			1826	
TOTALS	34200		8		

Figure 6.1 SFHT Manifest to Meet Reference User Complement Requirements

Designing payloads such as the SFHT to accommodate both ELV and Shuttle launch must necessarily impose some compromise in the design. Specifically, the dual launch requirement involves compromising the SFHT's length since most ELV payload fairings are smaller than the 15 foot diameter of the Shuttle cargo bay.

A benefit of the selection of the smaller capacity 6000 liter SFHT is that it provides easier packaging within the smaller payload fairings. Designing the SFHT to a nine foot diameter to package within the Delta II payload fairing dynamic envelope results in a slightly longer length tanker which penalizes it somewhat for a Shuttle launch. This penalty is minimized, however, by the smaller capacity tanker. Therefore, due to the selection of the 6000 liter SFHT, we chose to maximize compatibility and design the SFHT to fit within the Delta II fairing. The length penalty associated with this design diameter for a Shuttle launch is 2-3 feet. The packaging of the nine foot diameter, 6000 liter SFHT in the various ELV fairings is shown in Figure 6.2 for comparison. The SFHT uses most of the payload fairing volumes for the Delta II and Atlas/Centaur vehicles. For the Titan vehicles however, significant payload weight and volume margins remain, indicating that the SFHT would be part of a multiple payload launch for these vehicles.

A study was initiated to determine if any launch cost benefits are provided by designing for compatibility with all of the existing ELV's rather than just the Titan IV and Shuttle. The manifesting model developed during Task 2 determined that 9 flights of the SFHT would be required if resupply missions were performed from both the Shuttle cargo bay and the Space Station. It was assumed that all SIRTF resupply missions would be performed from the Shuttle and that AXAF, Astromag, and MMPF/CPPF servicing be done from the Station, resulting in five flights to the Station. Launch costs for this scenario were calculated for each of the ELV's. Costs were computed by calculating the percentage of payload capacity used by the SFHT (assuming an SFHT wet weight of 6000 lbs) to a 250 nautical mile orbit and multiplying the launch cost presented in Table 4.3 by this percent. The results are presented in Figure 6.3 which shows the launch costs for all combinations of ELV and Shuttle launches. As shown, the mixed manifesting approach results in launch costs that are comparable to those of the Shuttle. Other benefits such as manifesting flexibility and the simplifications of ground operations of an ELV launch (discussed in Section 6.3.1.2) are not included.

6.1.2 Operations

An early assessment of on-orbit operational scenarios was made to ascertain SFHT design drivers impacting system conceptual designs. Interface requirements for the various servicing scenarios were defined, including automated versus crew operations.

6.1.2.1 Interface Requirements - Interface requirements for SFHT operation with the STS, Space Station, OMV, and ELVs are addressed in the following subparagraphs.

SFHT/STS Interfaces - The STS can be both the launch vehicle and the base of resupply operations for the SFHT. Interfaces required between the SFHT and the STS are structural, electrical, and fluid. The SFHT can be launched in the STS, removed on-orbit, and then replaced in the cargo bay for return to the ground. Therefore, these interfaces must be mateable and demateable on-orbit.

The interfaces between the SFHT and the STS are depicted in Figure 6.4. Structural interfaces will consist of the standard trunnion and keel fittings located on the SFHT cradle. An active keel mechanism is required to permit berthing and unberthing of the SFHT while on-orbit. Also, a minimum of two standard RMS grapple fixtures will be required to permit the Shuttle RMS to perform the berthing/unberthing and to pass the SFHT to the Space Station MRMS. The electrical interface between the SFHT and the Shuttle will be used to provide power, monitoring, and control to the tanker. Details of the function of the interface can be found in Section 6.1.6. This interface will also require a mateable/demateable electrical coupler for those missions where the Shuttle is serving only as the launch vehicle and not the base of operations of the SFHT.

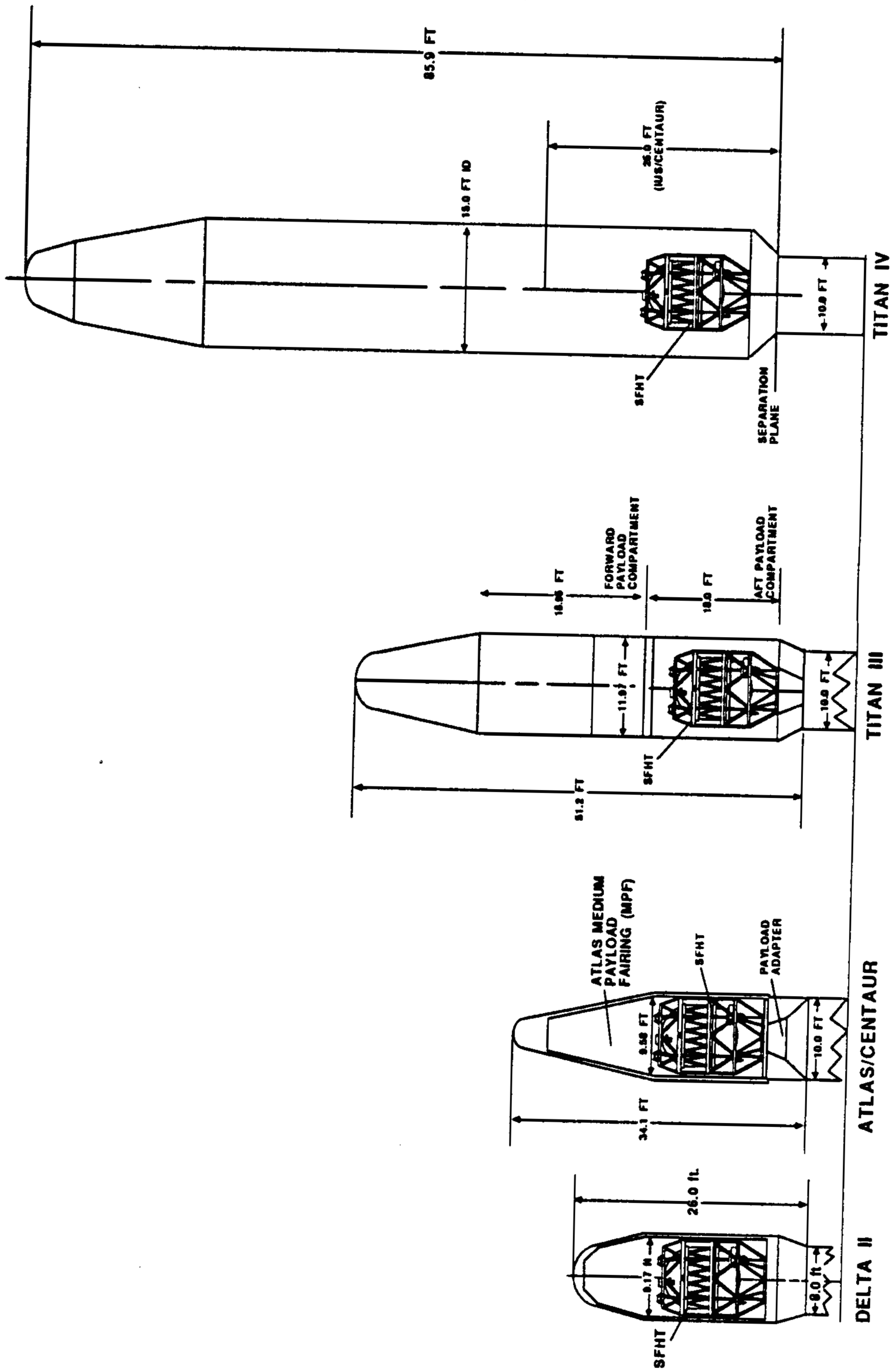


Figure 6.2 ELV Payload Fairing Comparison - SFHT

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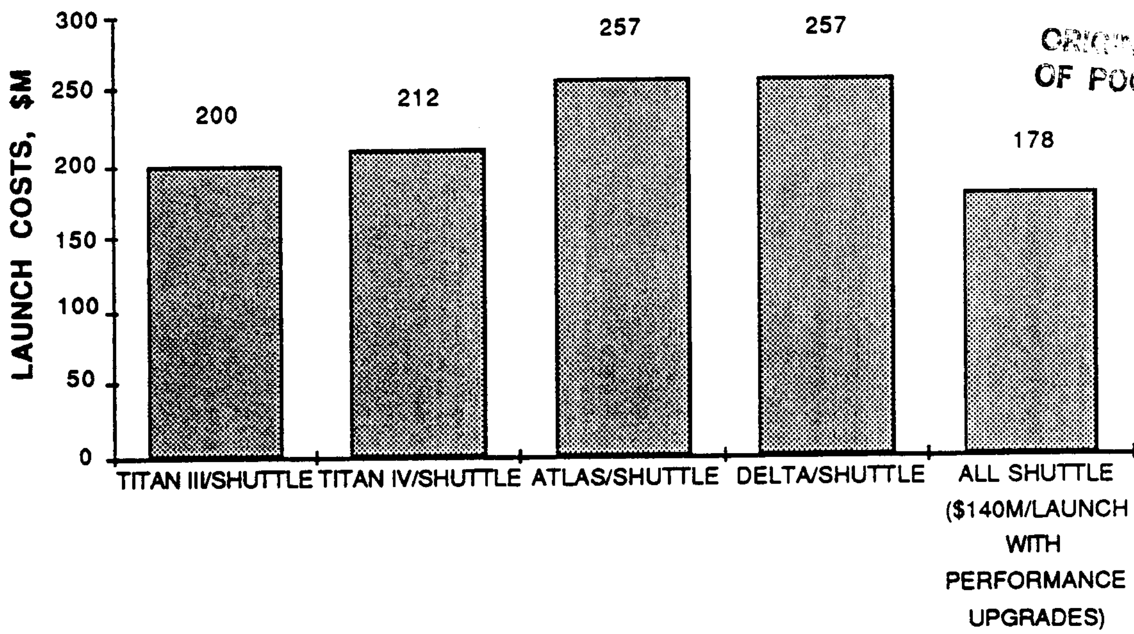

Figure 6.3 SFHT Launch Cost Comparison for Mixed Fleet Manifesting

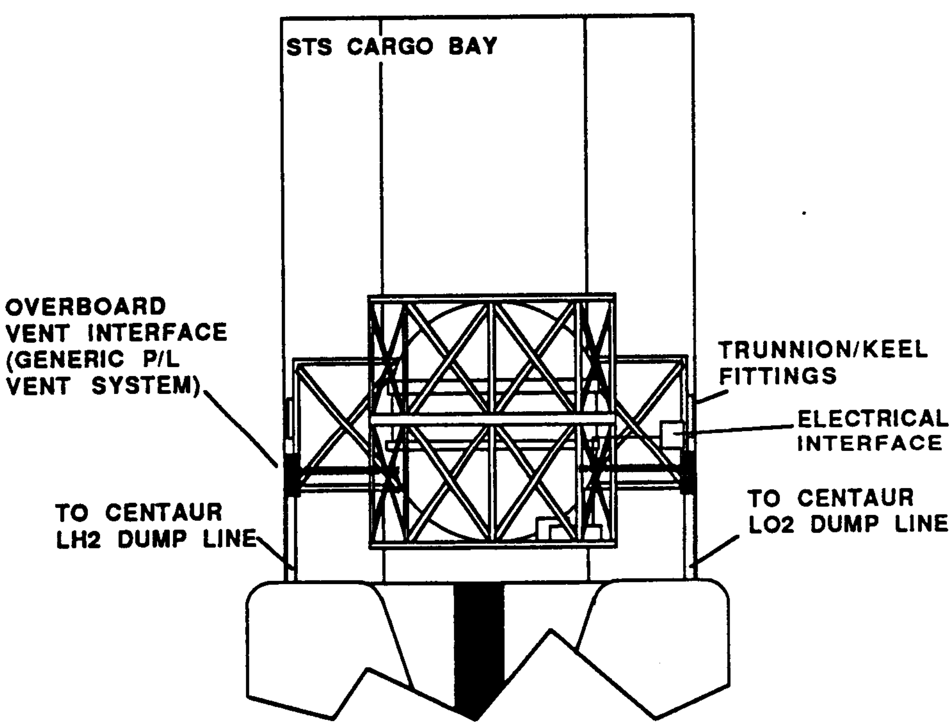

Figure 6.4 SFHT Mounted in the STS Cargo Bay

Early in Task 2, the need for an emergency overboard vent interface between the SFHT and the Shuttle was identified to handle a catastrophic loss of vacuum in the Dewar. The large mass flow rates resulting from such a failure mode (~2 to 3 lbs/second) coupled with the cold temperature of the vent gas require an overboard dump at all times when the SFHT is in the payload bay. The generic payload vent system being installed in all the Orbiters consists of a two inch diameter line running the length of the payload bay on either side (Reference 6.4). The two lines discharge overboard through the Centaur liquid hydrogen and liquid oxygen dump interfaces. The lines will be insulated to prevent the formation of liquid air during dumping of cryogenic fluids such as helium. In addition, the lines can be pressurized on the ground with nitrogen or helium gas and capped off to provide a positive pressure to prevent leakage of air. The SFHT would have two interfaces with this system, one on either side of the tanker to provide two independent paths for the emergency vent system. The interfaces would be located at the payload bay sill and mated in the Payload Changeout Room as the SFHT is placed in the cargo bay. These interfaces need to be demateable on-orbit, and mateable if the SFHT is returned to the bay with helium still on-board. If the SFHT is dry, then the interface need not be mated for return to the ground.

SFHT/Space Station Interfaces - The SFHT can be stored at the Space Station to perform periodic resupply of a variety of users. As discussed in Section 4.0, users at the Space Station will consist of experiments in the U.S. Laboratory, free flying payloads brought to the Station, and semi-permanent payloads attached to the truss assembly. Since the Servicing Facility, discussed in Section 6.1.2.3, is not currently part of the Space Station baseline configuration, interfaces were defined assuming the SFHT is attached to the truss assembly only. These interfaces, shown in Figure 6.5, consist of structural, electrical, and fluid interface.

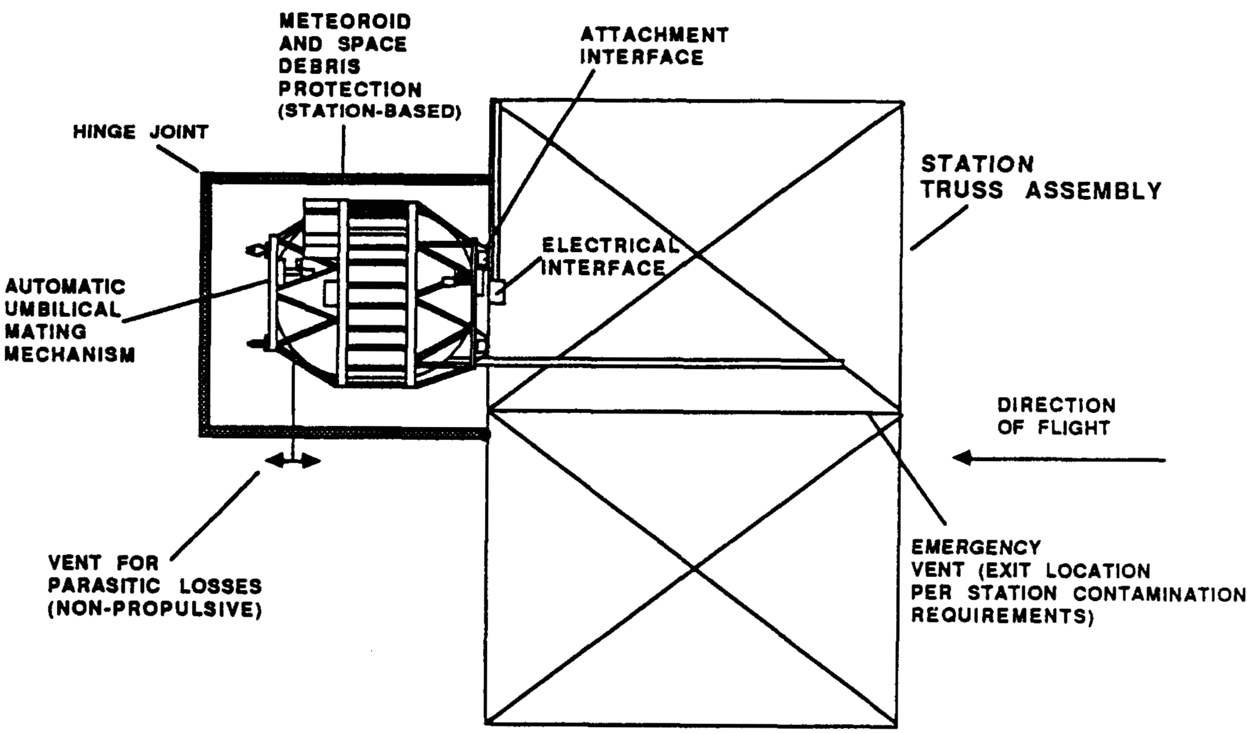

Figure 6.5 SFHT Attached to Space Station Truss Assembly

The SFHT would be attached to the truss assembly using a standard docking mechanism such as the FSS latches. If the SFHT is left in its transport cradle (see Section 6.1.5.1), then the SFHT could be attached to the truss via the trunnion and keel fittings. An additional structural interface requirement, although not directly a part of the SFHT structure, is for meteoroid and space debris protection. This protection is required since the SFHT may spend up to 12 months attached to the Station. The amount and configuration of this protection depends on the location of the SFHT on the Station and how much it is shielded by other elements of the Station. Regardless of the SFHT location, the debris protection would be left on the Station and not incorporated in the SFHT structure to save weight. The meteoroid and space debris protection would consist of an aluminum panel 0.03 inches to 0.075 inches thick configured with hinges to allow it to be folded away for SFHT removal or replacement.

Another SFHT/Station interface requirement is to provide shielding of potentially explosive containers to prevent their failure from propagating to other nearby structures or containers, or from endangering other Station elements such as the pressurized modules (Reference 6.5). This requirement could imply that shielding must be provided around the SFHT to contain fragments caused by a catastrophic failure of the Dewar. This requirement, however, would impose a substantial weight penalty. In order to satisfy this requirement, the possible failure modes of the SFHT Dewar were evaluated. Assuming that adequate meteoroid and debris protection is provided, then the SFHT Dewar could only explode if the Dewar guard vacuum was compromised by an internal leak. In this case, two-fault tolerant mechanical pressure relief is provided. In addition, the Dewar would be designed to leak-before-burst criteria. Therefore, it is felt that the requirement for shielding could be satisfied by debris protection and mechanical pressure relief devices. However this hazard should be further addressed as the possible locations of the SFHT at the Space Station are better defined.

An electrical interface, described in Section 6.1.6.3, provides power, command, and data handling from the Space Station avionics. The Space Station avionics replaces the Shuttle Aft Flight Deck control system for controlling and monitoring the SFHT during all phases of its mission. This interface must also be mateable and demateable. An electrical interface between the SFHT and the Station MRMS would not be required unless it was desired to perform helium replenishment operations while attached to the MRMS. In this case, one fault tolerant command, data, and power would be provided to the SFHT by the MRMS.

As with the Shuttle, an emergency overboard vent interface is required to handle the loss of Dewar vacuum. This line must run from the SFHT storage location to a point where the discharge will not produce a hazard to either the crew or a Station element. Currently, waste gases from the Station will be discharged at the end of a stinger to reduce the contamination potential and to provide for reboost thrust. If it is determined that the emergency vent must discharge in this same area, the line length required would be approximately 100 feet. This long length would necessitate a line diameter of 2 inches or more in order to obtain a manageable pressure drop during the emergency vent. A preferred approach would be to configure the emergency vent system with the minimum amount of line length required to direct discharge away from primary Station elements.

SFHT/OMV Interfaces - Coupling the SFHT and the OMV for transport in-orbit will require both structural and electrical interfaces. The OMV can provide payloads with three types of structural interfaces (Reference 6.6). The Three Point Docking Mechanism (TPDM) interfaces with standard FSS type latches and consists of three coordinated latches mounted on a structural ring, with redundant TV cameras, lights, and electrical umbilicals. The RMS Grapple Docking Mechanism interfaces with a standard RMS grapple fixture and incorporates three snare wires with a retracting mechanism, cameras and lights, and an integral electrical connector. Both of these interfaces are intended for orbital operations and are therefore limited in the amount of loads they can withstand. Payloads can be bolted to the front face of the OMV using a 135 inch diameter circular interface capable of a 10000 ft-lb cantilevered moment for a Shuttle launch. This bolted interface can be mated or demated by an EVA astronaut on-orbit. Capability to use this interface for an ELV launch, however, has not been examined and appears to be limited (Reference 6.7). Therefore, it appears that the SFHT cannot be physically mated to the OMV during an ELV launch.

In addition to a structural interface, an electrical interface for power and telemetry will be required. The OMV provides total power of 5 kwh to a payload with a 1 kw peak. A Fairchild data system is also available for payload use. The SFHT will also have to provide the necessary hardware to provide pass-through of OMV utilities to a user spacecraft such as SIRTF. The SFHT/OMV electrical interface would be a part of the TPDM or RGDM mechanisms.

The SFHT/OMV interfaces are summarized in Figure 6.6. Additional equipment will be required by the SFHT to operate while attached to the OMV even though this equipment is not a direct physical interface with the OMV. A docking target visible to the camera package on the OMV's TPDM will be required to ease mating of the SFHT and OMV on-orbit. Once attached, a camera and light package attached to the front face of the SFHT would allow additional viewing for mating to a user spacecraft. An automatic coupler mating mechanism on the front face of the SFHT would also be required to mate fluid and electrical couplers to the user along with an FSS or similar interface to mate with the user spacecraft.

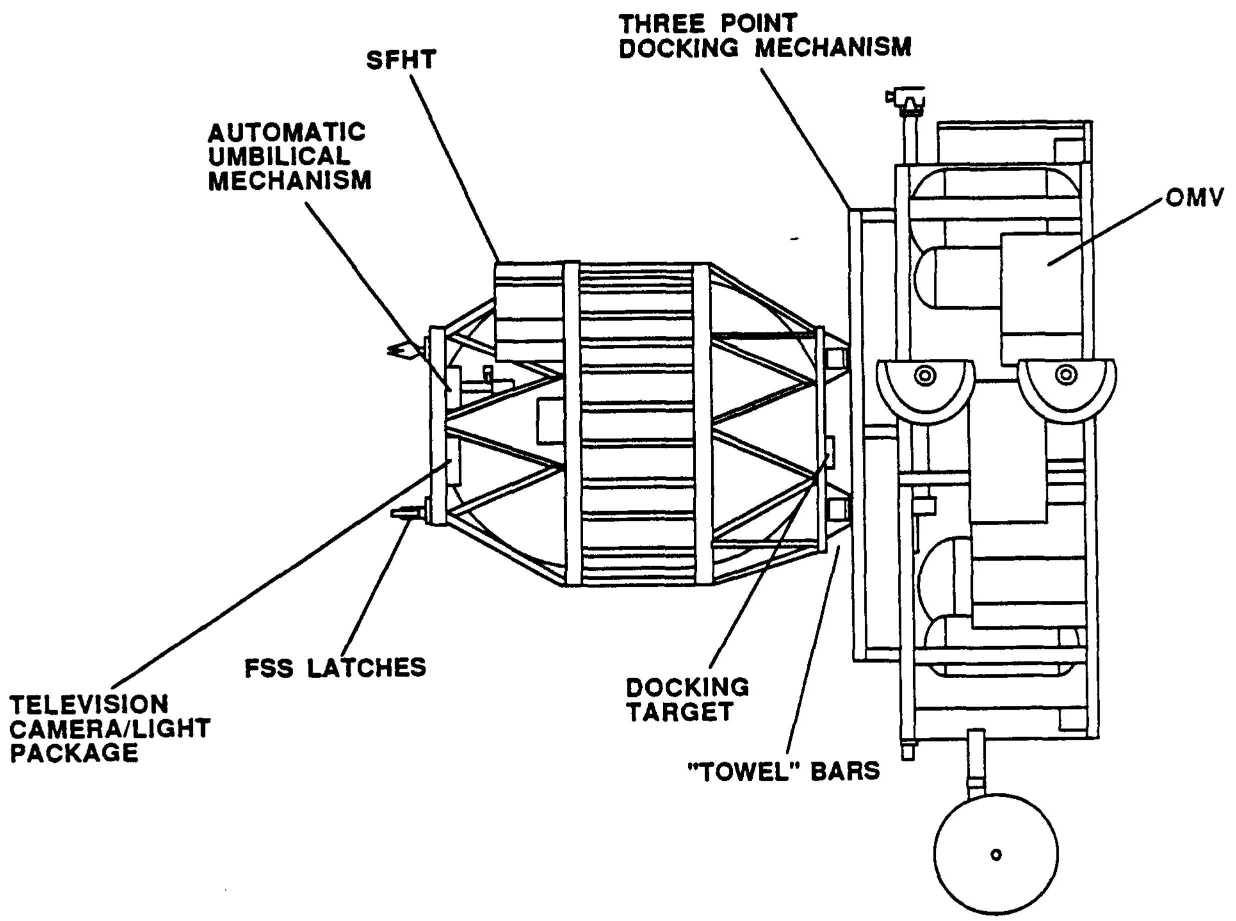

Figure 6.6 SFHT Mated to OMV for Transport to User Spacecraft for In-Situ Resupply

SFHT/ELV Interfaces - Launch of the SFHT on an ELV requires launch vehicle interfaces similar to those required for a Shuttle launch. Figure 6.7 shows the SFHT in a typical ELV payload fairing. An interface to the ELV payload adapter to react launch loads, and an electrical interface for power and telemetry, will be required. Additionally, interfaces with the GSE during the ground processing flow will require access holes in the ELV payload fairing to allow for helium servicing, power, and monitoring via the SFHT GSE. Also, as in the Shuttle launch case, vent interfaces with the fairing are required for both normal and emergency venting. These interfaces should be located to use the same ground service panel on the SFHT as during Shuttle launch processing. The SFHT/ELV structural interface is a deployable interface requiring the use of explosive bolts to allow the SFHT to be separated from the expended launch vehicle on-orbit.

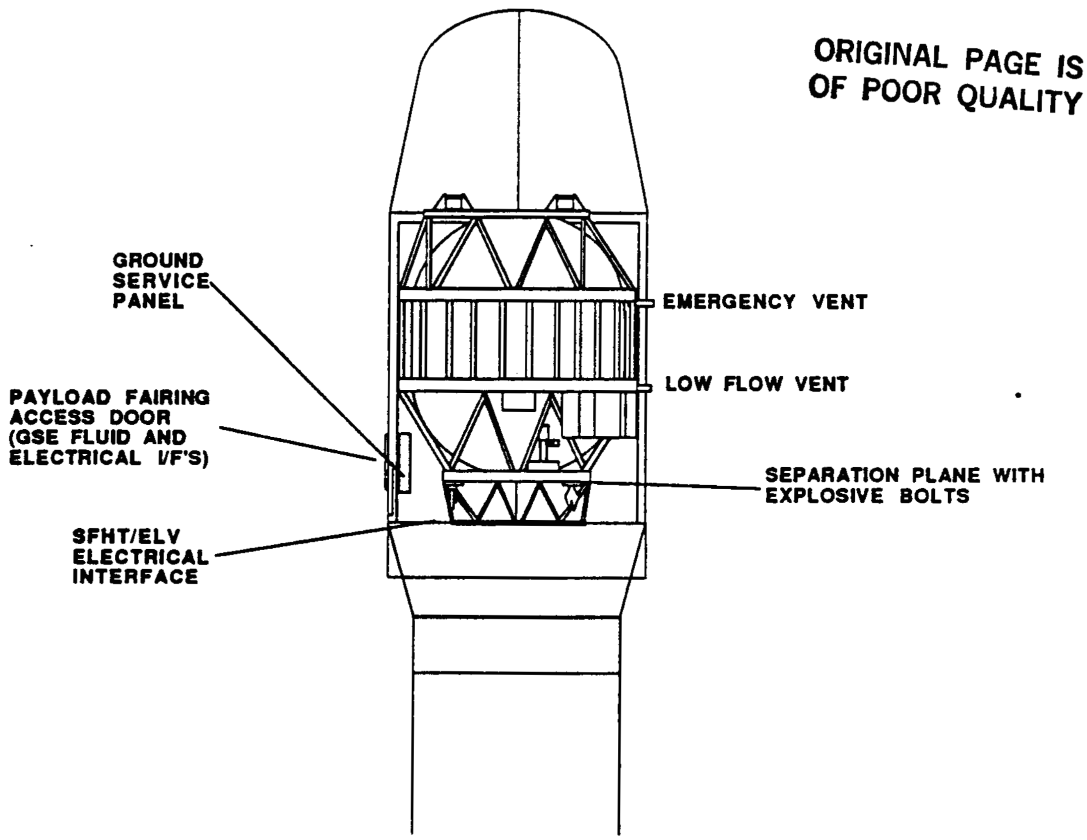

Figure 6.7 SFHT/ELV Interfaces for Delta II ELV

6.1.2.2 Automated versus Crew Operations Trade - An operational consideration associated with any on-orbit fluid resupply operation is the option of using EVA astronauts or an automated device to mate and demate the fluid and electrical couplers required to perform the transfer. In general, EVA operations are preferred when the automated option is too expensive, not versatile enough, not reliable enough for a particular critical operation, or not capable of performing the operation with existing technology. Automated operations should be considered when the operation is hazardous to the EVA crewmember, is less expensive than EVA, when the task required to be performed is routine and repetitive, the operation requires the application of precise and extreme forces or a man is not in space at the resupply location.

In the OSCRS studies, resupply of the Gamma Ray Observatory (GRO) using an EVA crewmember was the baseline. Manual mating of helium couplers will be an integral part of the SHOOT experiment and will demonstrate the ability of the EVA crewmember to handle the helium couplers and vacuum jacketed flex lines. With this background, EVA mating of couplers required for the SFHT will be demonstrated. There are, however, advantages to automatic operations specific to superfluid helium transfer. The long flex lines required (on the order of 20 feet for an STS-based SIRTF resupply operation - see Section 6.1.2.3) result in a large heat leak and pressure drop. For example, the flex lines add as much as 3 watts heat input each, and can weigh as much as 3 pounds per foot if they are vacuum jacketed. An automated coupler mating mechanism would weigh approximately 40 pounds (excluding the couplers) based on current designs. Automatic resupply operations would allow the user spacecraft to be mated directly to the SFHT structure, minimizing the transfer line length. This would provide commonality of SFHT operations regardless of where the resupply operation would take place. Additionally, there are potential hazards associated with the handling of long flex lines in zero-g. Line tethering would be required to avoid inadvertent movement of the line. In addition, the EVA flex lines would need to be purged prior to disconnecting, adding time to the transfer sequence.

Automatic resupply operations would require an automatic coupler mating mechanism on both the SFHT and the user spacecraft. The active side of the coupler mating mechanism would be located on the SFHT and the passive side on the user spacecraft. The active side of the mechanism would be heavier and incorporating it onto the user spacecraft side would save launch costs. However, since the SFHT is returned to the ground frequently, placing the active side of the mechanism, critical to mission success, on the SFHT would allow access for maintenance and enhance reliability. Once the SFHT and the user spacecraft are physically docked, the automatic coupler mechanism would engage the fluid and electrical couplers allowing a minimum line length to be used. Based on these considerations, therefore, it is strongly recommended that automatic resupply operations be encouraged for future users of the SFHT, although the ability to perform EVA operations be included in the tanker design.

6.1.2.3 <u>On-Orbit Resupply Operations</u> - The SFHT Systems Requirements Document (SRD) defines the types of resupply operations that the SFHT must perform. Helium replenishment operations can take place from the Orbiter cargo bay, Space Station, and while attached to the OMV. Satisfying each of these cases requires a thorough definition of the operations for each to determine what hardware and design features are required. The following paragraphs discuss the operations required to satisfy the SRD requirements and define the configuration impacts to the SFHT. In developing these operational scenarios, SIRTF was used as a representative user spacecraft since data on its configuration is more readily available. Discussions with NASA Ames Research personnel were conducted to obtain the latest data on the SIRTF configuration and mission. The baseline resupply/servicing concept is for Shuttle-based resupply. On-orbit instrument change-out is not planned and it is desirable to always resupply SIRTF when helium is remaining to avoid warming up the instruments. Resupply of a warm SIRTF therefore is a contingency operation only.

<u>Resupply from Orbiter Cargo Bay</u> - Resupply from the Orbiter cargo bay is considered the baseline operational case for the SFHT. The Space Station configuration does not include the Servicing Facility; therefore, the current plans are to perform servicing from the Orbiter. The baseline SIRTF resupply mission calls for a dedicated Shuttle flight. The Orbiter would transport the SFHT, an A' cradle, and an OMV to a 500 km orbit. The OMV would then be used to retrieve the SIRTF from its 900 km orbit and transport it to the Shuttle.

The combined weight of the fueled OMV, A' Cradle, and the SFHT is summarized in the table accompanying Figure 6.7. A plot of Shuttle payload capability versus altitude with the SSME's at 104% power and with performance enhancements is also shown in Figure 6.8. The payload weight required for the STS-based SIRTF resupply mission is highlighted in the figure and shows that ~90% of the Shuttle payload capability is required for the mission for the 104% power case and ~70% for the performance enhancement case. Use of a larger tanker or the requirement to launch two of the 6000 liter SFHT's to perform a resupply of a warm SIRTF would require the performance enhancements, using 90% of the payload capability.

Servicing of the SIRTF begins by placing it in the A' cradle. EVA astronauts would then connect and disconnect the SFHT fluid and electrical couplers to SIRTF. The configuration for these operations is shown in Figure 6.9. Orientation of the SIRTF in the cargo bay is not critical except that it is desirable to keep the telescope opening pointing away from the direction of flight to minimize contamination. The SIRTF could be rotated down into the cargo bay using the A' cradle to minimize the distance between it and the SFHT. This helps to minimize the required length of the flex lines. An evaluation of the transfer line length variation was performed to determine the range of lengths possible. The transfer line length can vary significantly depending on the orientation of the user spacecraft relative to the SFHT, as shown in Figure 6.10. The line length can vary from 5 feet to as much as 30 feet depending on the user orientation and location of the fluid couplers. Regardless of the specific orientation, the line length can be minimized by locating the fluid couplers near the user's docking interface and attaching directly to the SFHT.

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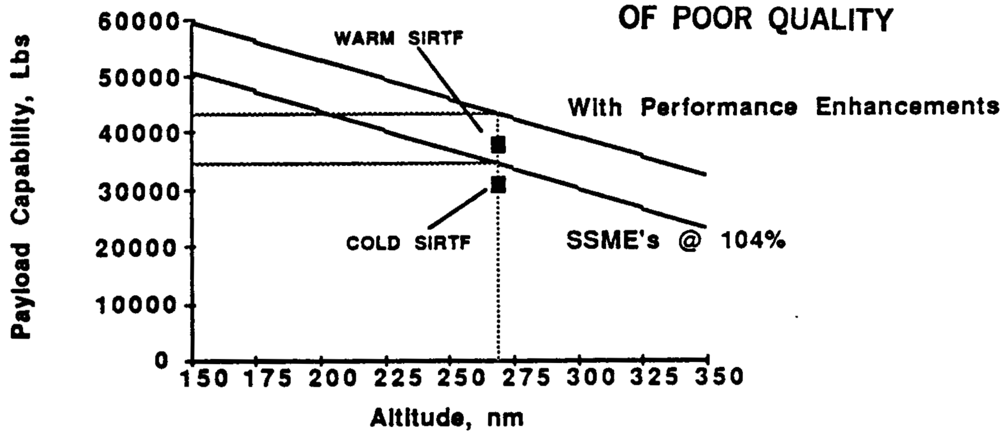

ITEM	WEIGHT TO ORBIT, LBS
A' CRADLE	4906
OMV	18304
SFHT	7200*, 14400**
TOTAL	30410*, 37610**

*COLD SIRTF
**WARM SIRTF (TWO SFHT's)

Figure 6.8 STS Payload Assessment for SIRTF Resupply Mission

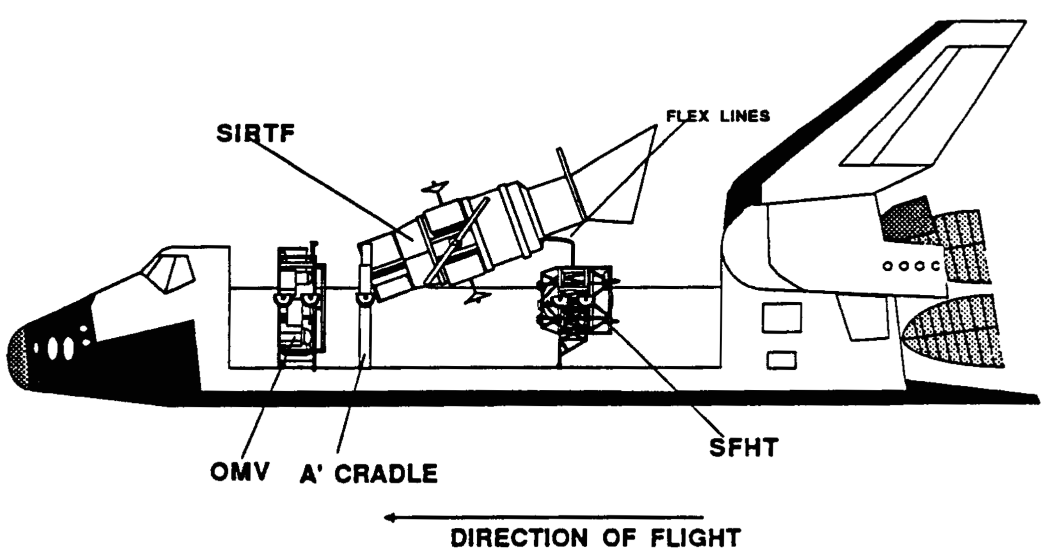

Figure 6.9 Manual Resupply of SIRTF in Cargo Bay

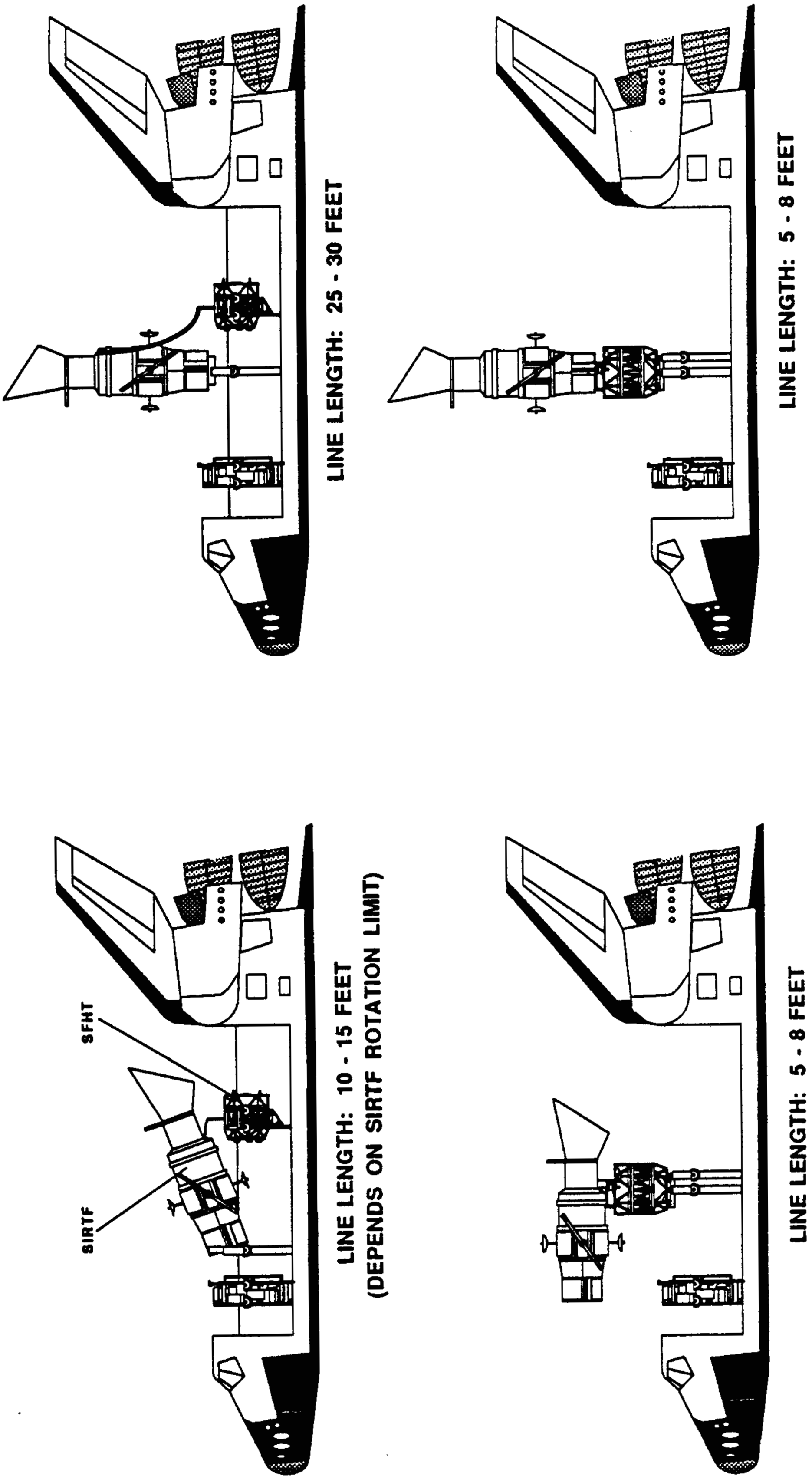

Figure 6.10 SFHT Transfer Line Length Variation

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Handling of long flex lines in zero-g, particularly if they are vacuum jacketed, will present difficulties. The bend radius of the lines is large (~12-16 inches) and therefore packaging the lines on the tanker is difficult. Also, the long lines must be tethered to restrict inadvertent movement while deployed as well as during the stowing process. Methods of deploying and stowing the long vacuum jacketed flex lines required for SFHT manual operations need further development.

To replenish the SIRTF without using EVA, the SIRTF would be directly attached to the SFHT and the fluid and electrical couplers mated by an automatic coupler mating mechanism, as shown in Figure 6.11. Even though EVA astronauts would be required to perform ORU changeout on the SIRTF, automatic resupply would provide benefits for the helium transfer operation by eliminating the long transfer lines and their associated flow losses and heat leak.

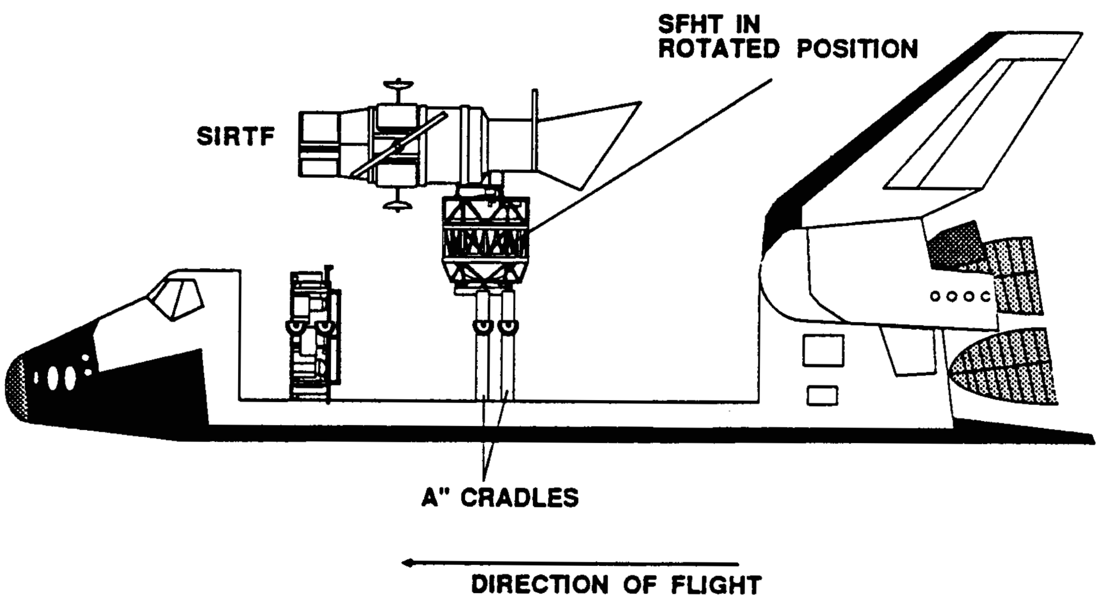


Figure 6.11 Automatic Resupply of SIRTF in Cargo Bay

Resupply at the Space Station - Replenishment of superfluid at the Space Station will be required for several planned attached payloads and experiments located inside the U.S. Laboratory Module. Additionally, servicing of the large observatories such as AXAF and SIRTF could also be performed. The frequency of resupply for the laboratory experiments (30 to 90 days) requires that the SFHT be located at the Station as a semi-permanent supply depot. The drawback to this approach, unlike tankers of storable propellants, is that the continuous boiloff from the SFHT cannot be recovered without adding significant hardware. Therefore, minimization of the boiloff becomes a key driver for the SFHT when it is Station-based.

Resupply operations at the Station can be performed with the SFHT on the truss assembly or with the SFHT in the Servicing Facility when it is in place. The Servicing Facility, shown in Figure 6.12, is an unpressurized structure attached to the transverse boom adjacent to the pressurized modules. The main elements include the Service Bay Enclosure, consisting of four telescoping thermal contamination barriers, the Service Track Assembly, a keel-mounted rail structure that supports Facility equipment such as fluid tankers, the Servicing Facility Manipulator, a track-mounted remote manipulator that is capable of reaching payloads in the

Orbiter cargo bay and anywhere within the Servicing Facility, and the Universal Payload Adapter, an attachment device able to mate with grapple fixtures, FSS latches, and trunnion fittings.

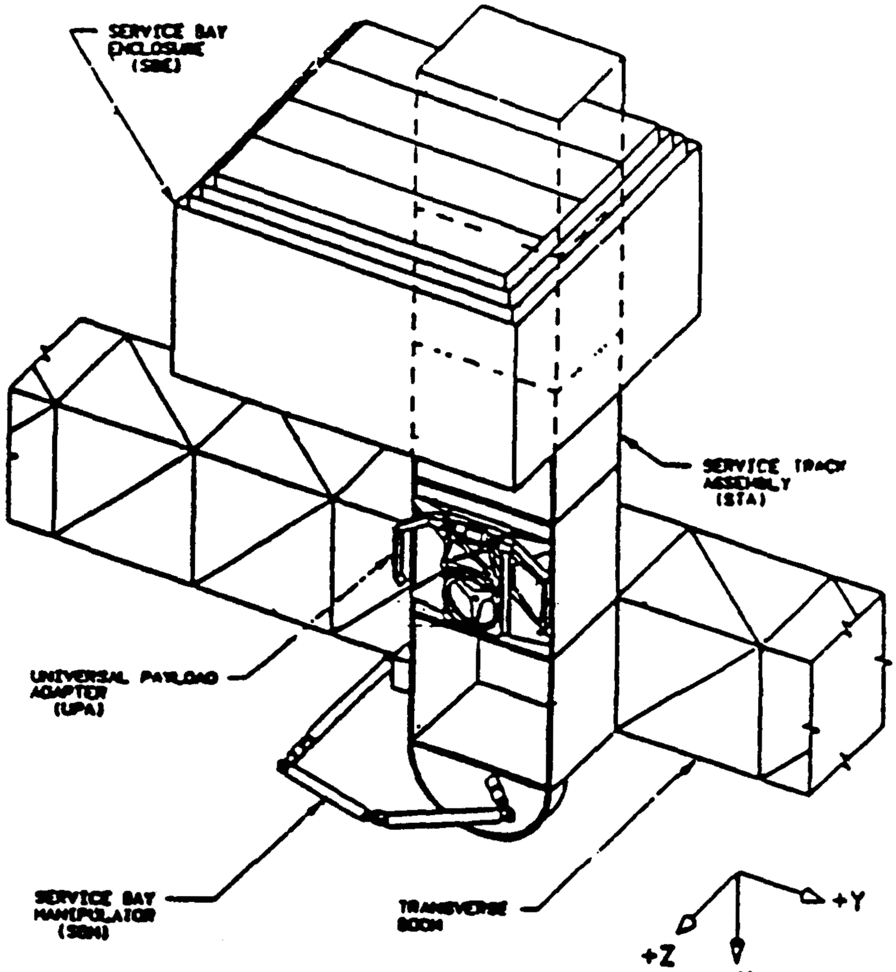


Figure 6.12 Space Station Servicing Facility

Before the Servicing Facility is in place, the SFHT will be stored attached to the truss assembly. As discussed in Section 6.1.2.1, this storage location will require meteoroid and space debris protection plus fluid and electrical umbilcal connections. The most frequent resupply operations (at 30-90 day intervals) will involve experiments such as the MMPF/CPPF and Lambda Point Facility located inside the U.S. Laboratory module. Therefore, it would be preferrable to locate the SFHT close to the U.S. Laboratory to minimize transfer line lengths and movement of the SFHT, provided that the emergency and normal vent exits are located in acceptable locations. The SFHT could be attached to the truss assembly near the U.S. Laboratory with a transfer line running to an interface located inside the pressurized area, as shown in Figure 6.13. If locating the SFHT close to the pressurized modules proves to be unacceptable due to safety or geometrical constraints, then the SFHT would have to be transported to the U.S. Laboratory from an alternate truss storage location using the MRMS.

Servicing of larger users such as the AXAF and SIRTF would require a servicing area on the truss assembly with enough room to accommodate both the SFHT and the user spacecraft. The user could be attached to the truss with flex lines connecting it with the tanker or it could be attached directly to the SFHT interface as would be done during an in-situ resupply operation (see Figure 6.14). Servicing of Astromag would involve moving the SFHT to Astromag's location provided that the necessary utility connections are available at the Astromag location. An alternate would be to leave the SFHT attached to the MRMS for power and data handling.

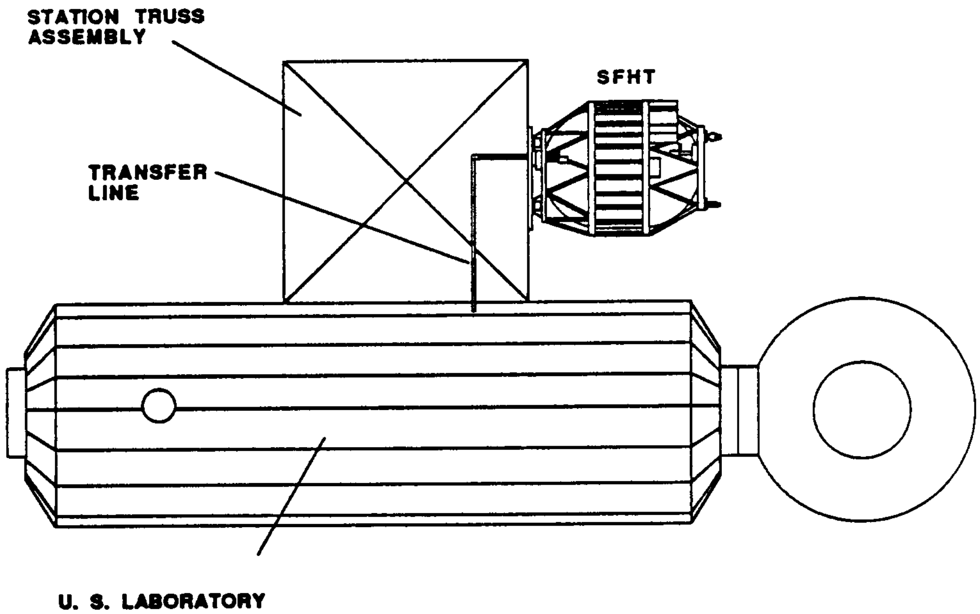


Figure 6.13 SFHT Servicing Operations for U.S. Laboratory Experiments

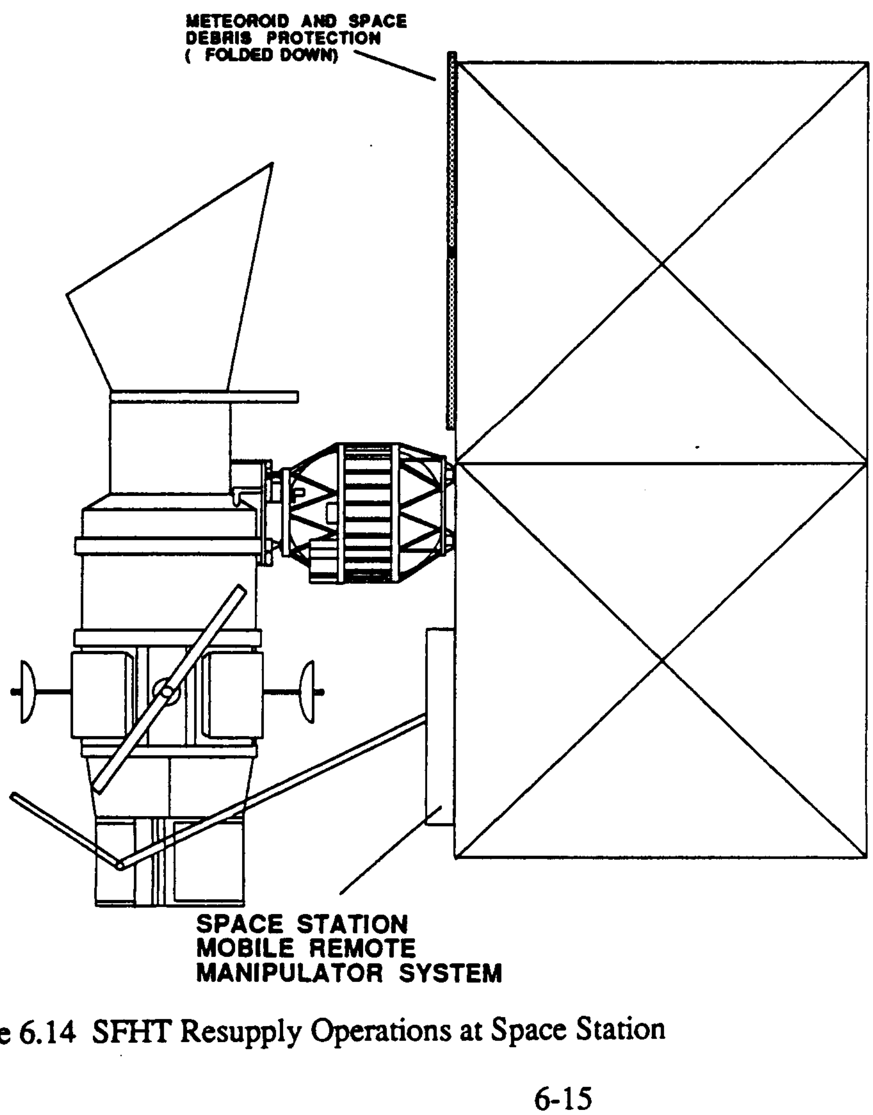


Figure 6.14 SFHT Resupply Operations at Space Station

Remote Resupply Operations - One of the design requirements for the SFHT is that it be capable of resupplying helium to a user at a remote orbital location. Such operations would be performed while the SFHT is attached to the OMV. This requires the SFHT to incorporate structural and utility connections for attaching to both the OMV and the user spacecraft.

Interfaces with the OMV were previously discussed in Section 6.1.2.1. In addition to these interfaces, the SFHT would require a mechanism to dock to the user spacecraft and an automatic coupler mating mechanism to attach the fluid and electrical couplers. A concept for replenishing SIRTF with helium in-situ is shown in Figure 6.15. The front face of the SFHT would be equipped with a structural docking interface such as the FSS latches. A television camera and light system would be required to perform the docking procedure. Once docking is complete, the active half of the automated coupler mating mechanism would mate the fluid and electrical couplers. Two electrical connectors and two fluid couplers would satisfy mission success requirements. Power, and command and data handling, would be provided to the user spacecraft from the OMV via the SFHT, with the resupply process being monitored and controlled if necessary from the ground. Upon completion of the replenishment operations, the SFHT would be detached from the user spacecraft and returned either to the Space Station or to the STS.

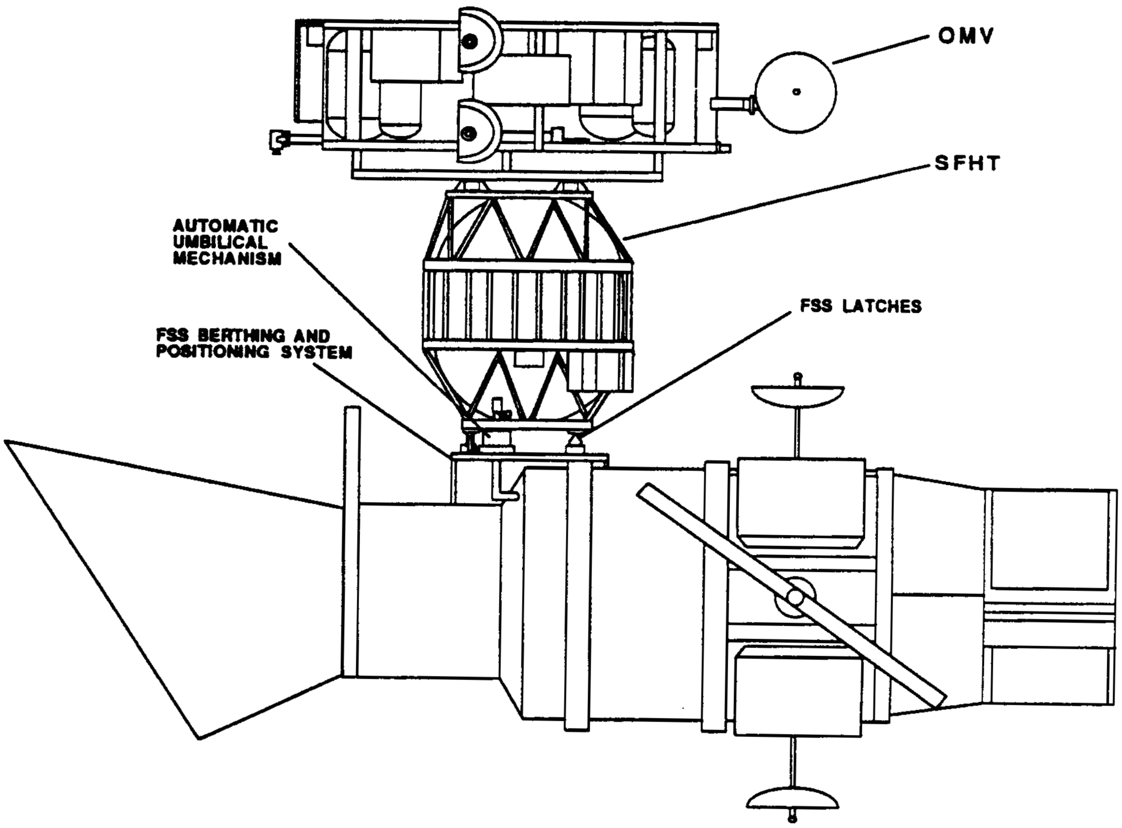


Figure 6.15 SFHT/SIRTF In-Situ Automatic Resupply Interfaces

6.1.3 Fluid Transfer Techniques

6.1.3.1 Transfer Techniques - An analysis was conducted to estimate the total SFHe mass lost during the transfer process. The analytical model employed was that developed during Task 2 with some minimum modifications to the transfer line calculations. The pressure drop calculation in the line was modified to include loss coefficients for various components such as valves and disconnects, as well as the line friction loss. The previous calculation method assumed equivalent line lengths for all components. A calculation was also incorporated into the model to determine pump power requirements that would prevent flashing within the line. The remainder of the analytical model was as originally developed.

The model is shown schematically in Figure 6.16. Various heating effects are included in this model in calculating the vent losses. In the supply tank, both the parasitic heat leak and the thermomechanical effect were used to calculate the vent loss. The transfer line heat leak and the thermomechanical pump temperature rise were used to determine the thermal condition of the

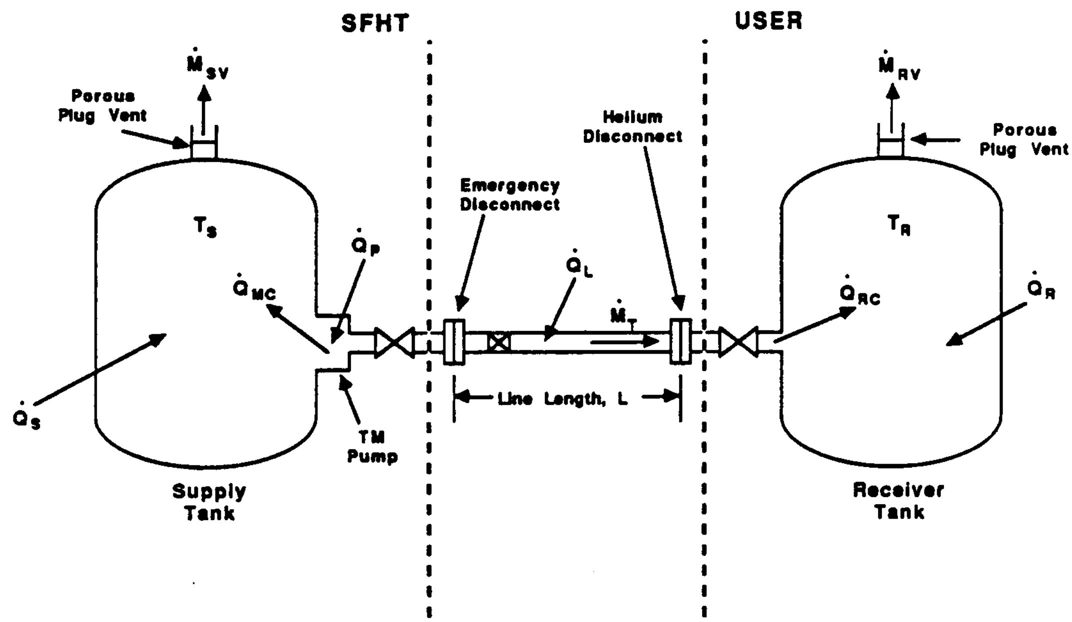
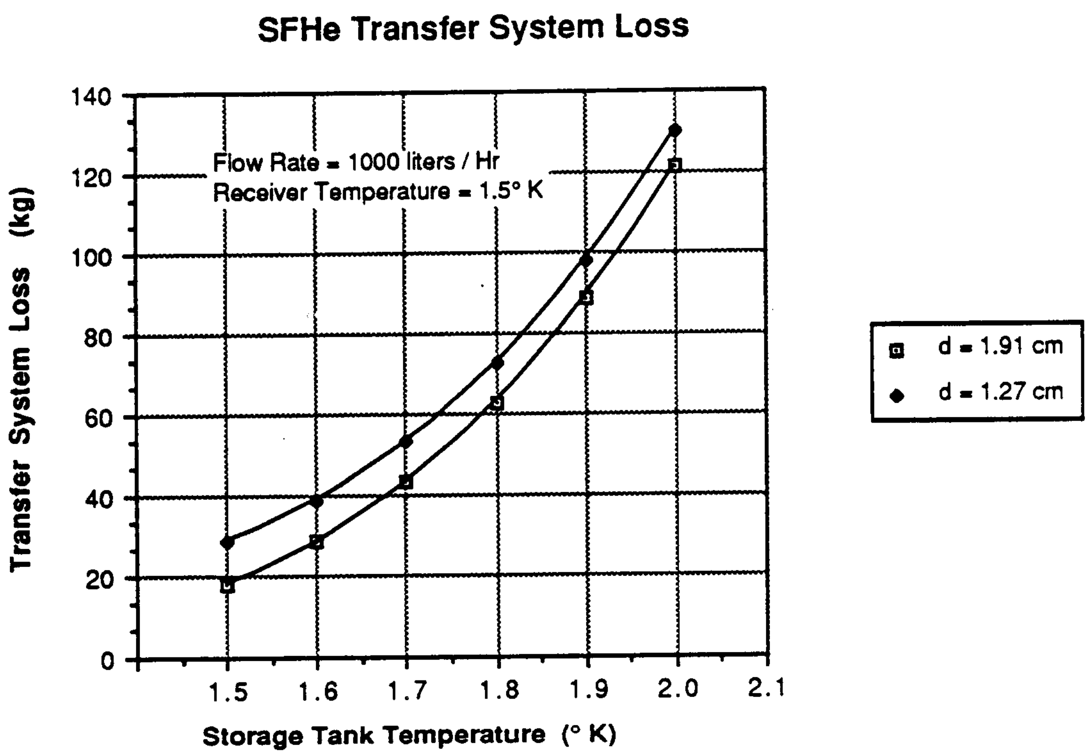


Figure 6.16 Transfer System Analytical Model

transferred SFHe entering the receiver tank. Vent losses in the receiver tank included the amount of helium vaporized to cool the transferred helium to the receiver tank temperature, and the parasitic heat leak. The total vent loss was the sum of the supply and receiver tank vent mass. Assumptions made in this analysis are as follows:

1 - Line Diameter = 0.5-inch and 0.75-inch (1.27-cm and 1.91-cm)
2 - Line Length = 15 ft (4.6 m)
3 - Storage Tank Volume = 6000 liters
4 - Storage and Receiver Tank Parasitic Heat Leaks = 0.2 watts
5 - Total Transfer Line Heat Leak Including Two Disconnects, a Valve, and the Transfer Line = 4.5 watts
6 - Fluid Transfer Rates = 500 and 1000 l/hr
7 - Receiver Tank Temperature = 1.5 K

The calculated SFHe mass and volume lost during the transfer are plotted in Figure 6.17 as a function of storage tank temperature for flow rates of 500 and 1000 liters/hour, respectively. Each plot presents data for transfer line diameters of 1.27 and 1.91 cm. For the low flow rate of 500 liters/hour, the vent losses for the two line diameters differ by less than 3 kg or 20 liters. At the higher flow rate shown, the vent losses differed by approximately 10 kg or 69 liters. Neither of these losses appear to be a major factor in sizing the storage tank volume. These data do indicate a slight advantage in employing the larger transfer line diameter.



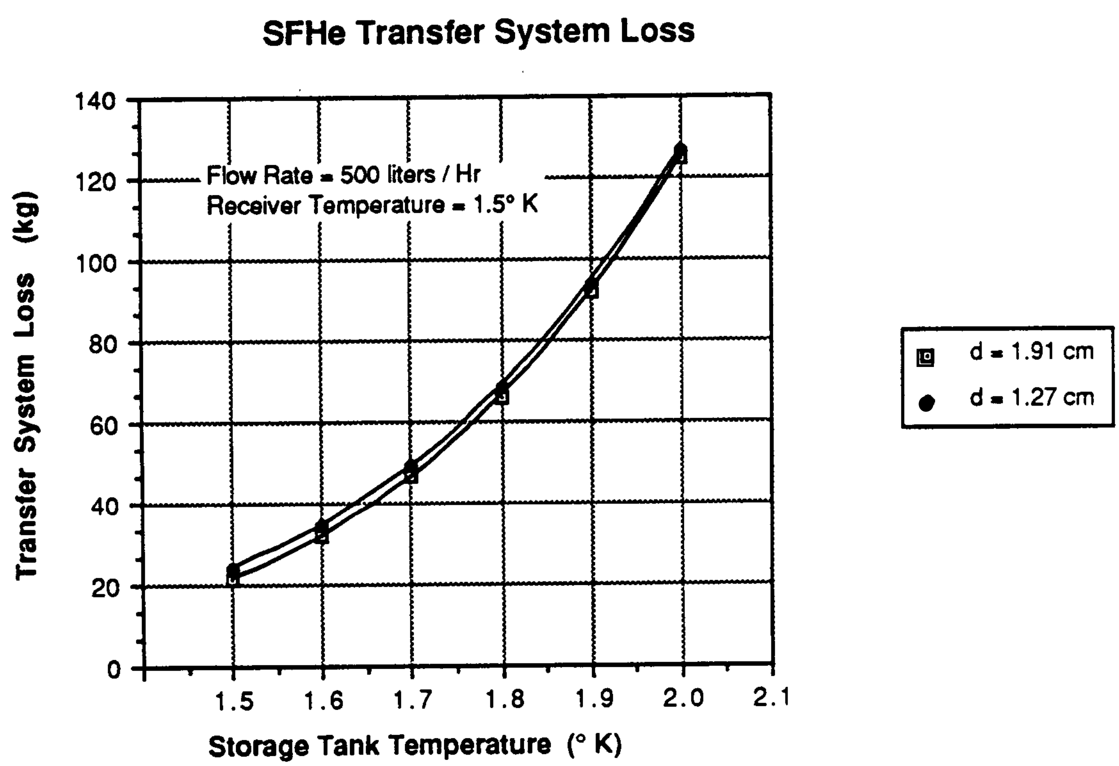


Figure 6.17 SFHe Transfer System Losses

6.1.3.2 System Cooldown - A re-evaluation of the cooldown process was made for the 0.75 inch diameter transfer line. The transfer line length was assumed to be 15 feet. The method for estimating the cooldown requirement was an empirical technique developed by Arthur D. Little, Inc. (Reference 6.8). The transfer line configuration consists of the following components: emergency disconnect, shutoff valve, vacuum jacketed transfer line, and the helium disconnect. All of these components are external to the helium tanker vacuum jacket and are assumed to be initially at ambient temperature (300 K). The mass of each component and its steady state heat leak used in this analysis is presented below. It was assumed that the superfluid helium entered the transfer line at a temperature of 1.8 K. The cooldown process was completed when the system was cooled from the initial temperature of 300 K to 2.0 K. The results of the analysis indicated that the time required to satisfy the above requirements was 1.1 hours. The amount of superfluid helium to do the cooldown process was calculated to be 2.47 kg or 17.04 liters.

Component	Mass kg (lbm)	Heat Leak Watts
Emergency Disconnect	1.36 (3.0)	0.5
Shutoff Valve	2.27 (5.0)	0.5
Transfer Line (Flexible)	3.18 (7.0)	2.3*
Helium Disconnect	13.61 (30.0)	1.2
Total	20.42 (45.0)	4.5

*Assumes 0.5 watt/m line length

6.1.3.3 Receiver Dewar Fill - The SFHT must be designed to provide helium to a variety of user systems requiring resupply in space. Consideration of the thermodynamics in the receiver tank during transfer may be important in defining SFHT requirements, and may provide recommendations for design of future systems that will require resupply. In most resupply missions, the receiving Dewar will be cold, and will not be totally depleted of fluid. It is inevitable, however, that instances will occur where the fluid is depleted and the system will have warmed to the ambient temperature. It may also be necessary to supply systems for the first time in space. Therefore, chilldown of the receiving vessel will in some cases be a requirement before liquid can be transferred.

One approach for tank chilldown is to evacuate the tank to space, then transfer a small quantity of liquid and hold while heat transfers from the tank to the fluid. Repetition of this process a number of times will cool the tank enough for transfer to begin. This method is complicated by diminished heat transfer processes in low-g. Liquid injected into a warm tank will tend to splatter off the tank wall, and the amount of vaporization that occurs in each contact is very small. Also, the heat sink capacity due to vaporization is only a small fraction of the total available, and much more heat can be absorbed by the vapor. Analysis of the cooldown process by injection of liquid is difficult because the low-g mechanics are not adequately understood, but this approach is not likely to be very effective in any event. The use of a cooldown heat exchanger on the tank wall (and probably on the vapor cooled shields) will be more effective, and also amenable to analysis. An adequate heat exchanger would assure full utilization of the heat sink capacity of the cooling fluid, and would minimize cooldown time. It is clear that the details of the user's Dewar design significantly impact the efficiency and adequacy of the resupply from the SFHT. Design impacts associated with helium resupply should be made as early as possible in the user's design process. The cooldown analysis done for SIRTF should also be done for other users so that total fluid allocation can be determined.

If liquid is transferred into an initially empty, precooled tank, part of the first liquid transferred will vaporize, establishing a thermodynamic balance between the temperature of the liquid and the tank pressure. When the pressure reaches the vapor pressure of the entering liquid, vaporization will cease. From this point, the decreasing gas volume requires compression of the gas (with pressure rise) and/or condensation of vapor. The same is true for a tank that is initially partly filled. Once the maximum allowable pressure is reached, further transfer is totally dependent on condensation of the ullage. The heat of condensation must be absorbed into the liquid. For normal cryogens, transfer rate is dependent on heat transfer mechanics within the liquid and the interfacial surface area that tends to decrease as fill progresses. For superfluid helium, however, the rate of transfer is effectively unlimited because of the extremely high rate of heat transfer within the liquid.

Transfer of superfluid helium is therefore less complex than transfer of normal fluids. It is necessary in all cases to provide for the heat sink capacity for the condensation of the vapor, which is normally achieved by conditioning the supply liquid relative to the final required receiver tank condition. If superfluid helium is transferred using the thermomechanical pump, the energy added in the pump will increase the liquid transfer temperature above that in the supply tank, as will heat leak encountered in the transfer line. Depending on supply tank storage temperature and required final delivered conditions, it will probably be necessary to cool the receiver tank during transfer by operation of a thermodynamic type vent, implemented using the porous plug phase separator.

6.1.4 Fluid Subsystem Design

The SFHT mission will vary as user vehicle requirements vary, and cannot be programmed far in advance. Ability to service a variety of user vehicles in any sequence is a desired capability. Basic to this goal is the ability of the SFHT to maintain superfluid helium on orbit for a long period with minimum boiloff losses. Another design goal is to minimize ground operations, particularly after installation in the launch vehicle. This is of particular importance when the SFHT is launched along with other payloads that will vary from flight to flight. These objectives have been addressed, along with considerations of weight, cost, and complexity, in the development of our fluid system conceptual design.

6.1.4.1 Ground Servicing Subsystems - The conceptual design for the SFHT provides an independent, isolated open loop cooling system to condition liquid helium from its initial load condition of about normal boiling point (4.22 K) to superfluid at 1.6 K or below. Referring to the SFHT schematic diagram, Figure 6.18, the fluid conditioning system includes normal helium supply piping from a ground support Dewar, a throttling device to restrict flow of normal helium into a tank heat exchanger, and piping from the tank heat exchanger through one or more VCS heat exchangers to an external connection to a GSE vacuum pumping system. As the helium flows from the normal supply piping through the restrictor, pressure is reduced, and the fluid partially vaporizes. At the lower pressure, the temperature of the two phase fluid will correspond to the saturation temperature at the reduced pressure in the tank heat exchanger. By regulation of the throttling valve, this pressure will be maintained so that a small, but adequate differential temperature exists between the helium in the SFHT inner vessel and the fluid in the heat exchanger. Because of the temperature difference, heat will be extracted from the loaded liquid as it cools, and vaporization will occur in the heat exchanger. The heat exchanger will be adequately sized so that all liquid vaporizes, and only vapor exits the tank boundary.

As the liquid being conditioned cools, the pressure will need to be reduced in the heat exchanger to provide the required temperature difference to drive the heat transfer. This will require gradual closing of the throttling valve. Flow through the heat exchanger is limited by the flow resistance through the total piping system and the capacity of the vacuum pump. The flow will decrease as the tank fluid cools and pressure is reduced in the heat exchanger, since density of the exiting vapor will also decrease. Therefore, the rate of cooling will begin at whatever can be sustained by the pumping and piping systems, and will decrease periodically as the pressure and flow are adjusted. The time required to achieve the cooldown from the initial normal boiling condition to superfluid at 1.6 K or less will depend on the vacuum pump capacity and the size, length, and other features of the flow circuit through the system.

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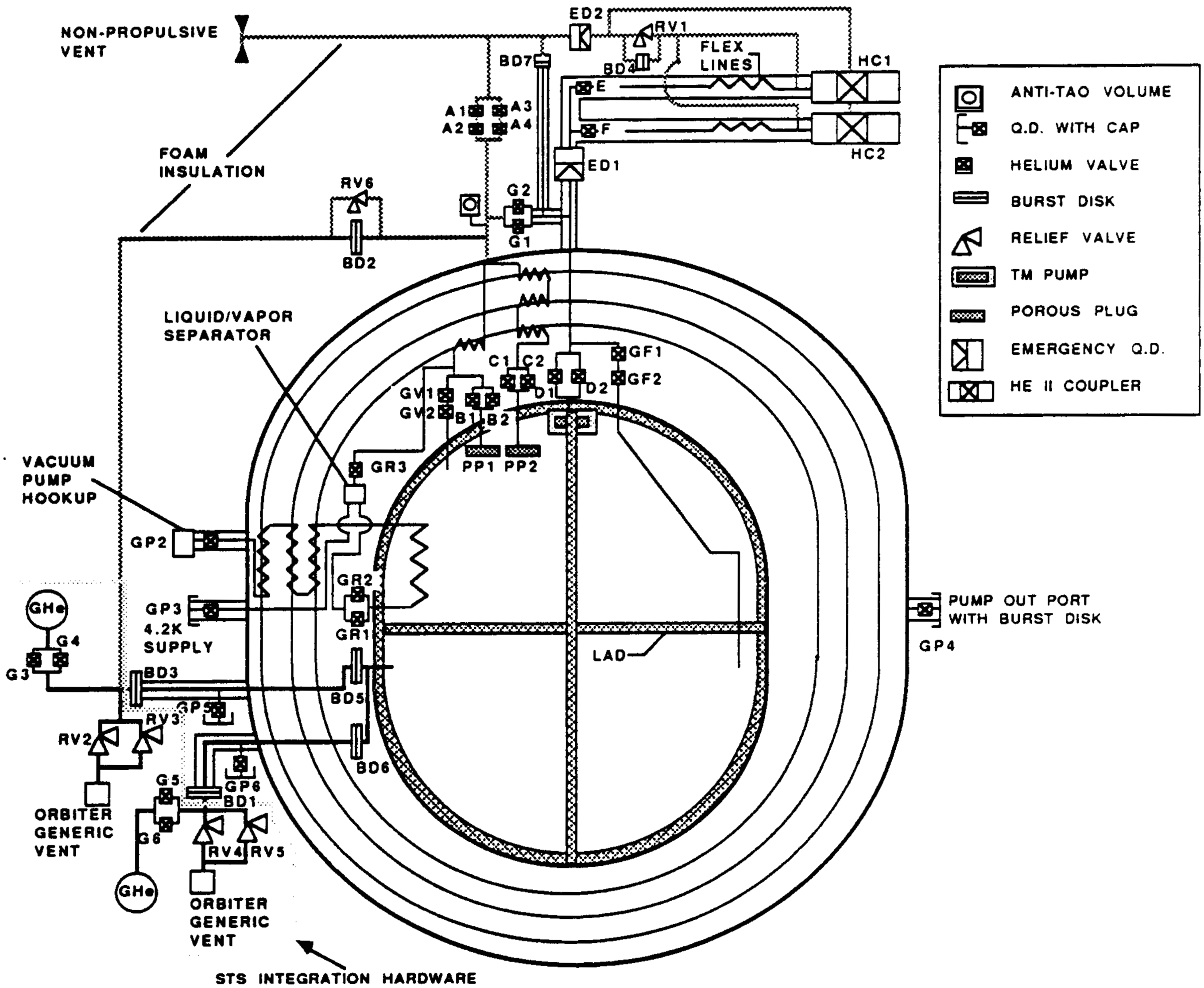


Figure 6.18 Superfluid Helium Tanker Fluid Schematic

As the tank and fluid cool, the liquid helium flow through the restrictor will decrease to the point that it will not be adequate to absorb the heat leak through the transfer line from the external supply Dewar, and this flow will become two-phase. It is imperative, however, that single phase liquid be supplied to the tank heat exchanger inlet metering valve. To accomplish this function, a liquid-gas separator or "keepfull" is installed in the cold region beneath the inner vapor cooled shield. This simple gravity separator is controlled by a vapor outlet valve actuated by a level sensor to maintain it partly filled with liquid. The vapor is vented to atmosphere through a heat exchanger on the inner vapor cooled shield. The keepfull not only provides liquid on a continuous basis, but also assists in reducing the heat leak to the tank during ground operations by maintaining the VCS at or near 5 K, much lower than its normal operating temperature (during space operation) of about 45 K.

Ground servicing of the SFHT will consist of a vented fill of the tank with normal helium, following a normal purge and chilldown operation. The tank remains at approximately one atmosphere during load. When the tank is filled with normal helium to near full, 85% or more, it is temporarily locked up and the open loop refrigeration cooling system is connected to the GSE and operation is started. As the fluid cools to below 4.22 K, the pressure in the tank reduces to below atmospheric. Additional liquid is then slowly added, without the need for venting. If the tank is to be launched in a pressurized (subcooled) condition, a final fill operation will pressurize the tank to about one atmosphere at the time the temperature of the fluid just reaches the lambda point, 2.17 K. At this point, the tank is 100 percent full of liquid with a density approximately that of saturated fluid at the Lambda point temperature. All valves communicating to the fluid in the tank are then closed, and no fluid enters or exits the tank thereafter. As the tank is cooled below the lambda point, the pressure increases because of the reversal of the coefficient of thermal expansion at the lambda point. The maximum pressure that can be reached from this starting condition is about 2 atmospheres, or less depending on the volume expansivity of the tank with pressure. If the launch condition is to be saturated superfluid, then the same procedure is followed, but a small ullage is left in the tank. This will require an accurate method for loading to the desired fill if a small ullage is desired. It may also be necessary to remove some fluid after the tank has reached a low pressure, probably requiring a vacuum pump to remove some helium as a vapor. Because of the simpler procedure, the pressurized state at launch appears more desirable, and is recommended. It is noted, however, that either pressurized or saturated load can be accommodated with the recommended ground servicing system.

Ground support equipment for the helium conditioning and maintenance system consists of a unit containing a normal helium Dewar and a moderate sized vacuum pump. In order to simplify operations, a single GSE unit will suffice. A 750 Liter Dewar, the size estimated to be practical for launch pad operations, is adequate for this purpose. This Dewar will also be sufficient for the initial fill operation, if necessary, even though it will need to be refilled a number of times. A vacuum pump that can operate down to 1 torr or below, with a capacity of 250 or 300 cfm will be adequate. This unit will provide the initial off-line fill and conditioning of the SFHT fluid. It will remain in operation on a maintenance mode (that is, at a minimum flow condition), until time to transport the SFHT. The fully cooled SFHT has adequate lockup capacity to be off line for several days, if necessary. The GSE will be reconnected when possible after transportation, and will reestablish the launch ready fluid condition. Similarly, the GSE unit will be disconnected and the SFHT locked up when the Shuttle cargo doors must be closed prior to launch. Lockup capability is adequate to sustain a ten day launch hold, plus a one day turnaround on launch scrub. Reconnection of the GSE at this point will permit recycling the fluid to the ready state without overpressuring or loss of fluid.

An analysis of the open loop cooldown system was performed to determine pump and piping sizing required to permit conditioning the system in a reasonable time, and to determine the time required to recycle from a maximum launch hold and scrub. This analysis was performed through iterative calculations using two computer models.

The first model determined the flow rate of coolant in the heat exchanger versus internal pressure. The approach was to model the flow network as separate isothermal segments (the tank heat exchanger, each VCS heat exchanger, and the outlet piping), using a previously developed program called ISOSTD. This model had been developed at Vandenburg AFB to analyze the pneumatic systems at the West Coast Shuttle Launch Complex. The program first defines an inlet pressure and temperature, and a vacuum pump inlet pressure. Next it assumes an exit pressure for the first segment and computes a resultant flow rate. The exit pressure is used as the inlet pressure for the next segment, at the new estimated temperature. The process was repeated down the line until the exit was reached. The computed exit pressure was compared with the previously determined exit condition satisfying the pump and the entire routine was repeated until convergence was obtained. This procedure was repeated for a series of inlet pressures, and a plot of flow rate versus inlet pressure was obtained. For the system analyzed as a baseline, with a 250 cfm vacuum pump and 1/2 inch line throughout up to a 2 inch vacuum pump manifold, choking occurred at the transition to the larger line.

The results of the first model were used as input to the second model, where heat transfer between the bulk liquid and the fluid in the heat exchanger was calculated. This permitted developing a profile of flow rate, temperature, and pressure over the total period required to condition the liquid. Natural convection was assumed for the heat transfer from bulk fluid to heat exchanger and forced convection for the internal heat exchange while the tank liquid temperature was above the lambda point. When the fluid was converted to superfluid, heat transfer to/from the fluid was not considered to be a limitation to the process because of the near infininte effective thermal conductivity.

This analysis showed that for the baseline system, with 1/2 inch heat exchanger tube and connecting piping, the SFHT can be cooled from 4.22 K to 1.5 K in about 20 days. The time to recycle from a (conservative) temperature of 2.1 K after a maximum delay launch scrub is approximately 10 days. These times appear to be acceptable. If a faster operation is required, the piping size, and/or the vacuum pump capacity, can be increased. This analysis will of course need to be repeated in more detail, and some parameters determined by test.

To determine the lockup capability, steady state temperatures of the vapor cooled shields and the multilayer insulation were determined by the system optimization program for various coolant flow rates. Using these temperatures as initial conditions, the Cryogenic Systems Analysis Model (CSAM) program was used to perform a transient analysis to determine the rate of temperature rise of the liquid. The starting liquid temperature was held at 1.6 K for this analysis although overcooling may also reduce that temperature. The results are presented in Table 6.2, in the form of the number of days to reach various temperatures, assuming the coolant flows were maintained long enough to reach steady state. Coolant flow was varied on the basis of percent of normal onorbit vent rates. The results show that the 11 day lockup requirement can be easily met, since the nominal space vent rate is approximately (0.21 L/Hr).

Table 6.2 Estimated Liquid Temperature After Hold Period for Various Overcool Conditions

	Hold Time After Lockup No Coolant Flow (Days)		
Coolant Flow Rate Prior to Lockup	To Reach 1.9 K	To Reach 2.0 K	To Reach 2.1 K
0.21 L/Hr (Nominal Space Vent Rate)	6	7.5	9
0.26 L/Hr (125% of Nominal Space Vent Rate)	8.5	10	12
0.31 L/Hr (150% of Nominal Space Vent Rate)	9.5	11	13
0.27 L/Hr (175% of Nominal Space Vent Rate)	11	12.5	14.5
0.42 L/Hr (Double Nominal Space Vent Rate)	11.5	13	15
SFHe Temperature at Lockup - 1.6 K Vacuum Jacket Temperature - 300 K			

6.1.4.2 Dewar Design and Space Fluid Storage Subsystems - Objectives in the design of the superfluid containment system included achieving an efficient tank and vacuum jacket design with low heat leak capability. An effective support system is a paramount requirement for achieving these goals. Other objectives included minimizing internal hardware that would influence management of liquid during low-g space transfer operations, and providing for all piping, valves, and fittings required for the operation of the system without undue complication of the design. An effective space venting system is based on the porous plug phase separator (PPPS) to accomplish the thermodynamic vent function of maintaining pressure in a tank receiving heat leak without the necessity for locating and venting vapor from the tank in space. The vent system is also required to handle a high heating rate that develops as a result of transfer of liquid using the thermomechanical or fountain effect pump.

The conceptual design of the Dewar system is illustrated in Figure 6.19. The pressure vessel is an elongated sphere, with the hemispherical end domes separated by a short cylindrical section. A single ring, made of a structural "T" section, provides the main tank frame. The cylinder is joined to the ring by 4 (or more as required) gusset plates welded between the two. Cutouts in the gussets provide a path for the equatorial liquid acquisiton channel. To accommodate tank supports, the vacuum region is extended into the tank at 8 places through tubes welded in place to the ring frame inside the tank and to the tank wall near the cylinder-hemisphere intersection (on the hemisphere side). Additional stiffeners transmit load from the tubes to the tank frame.

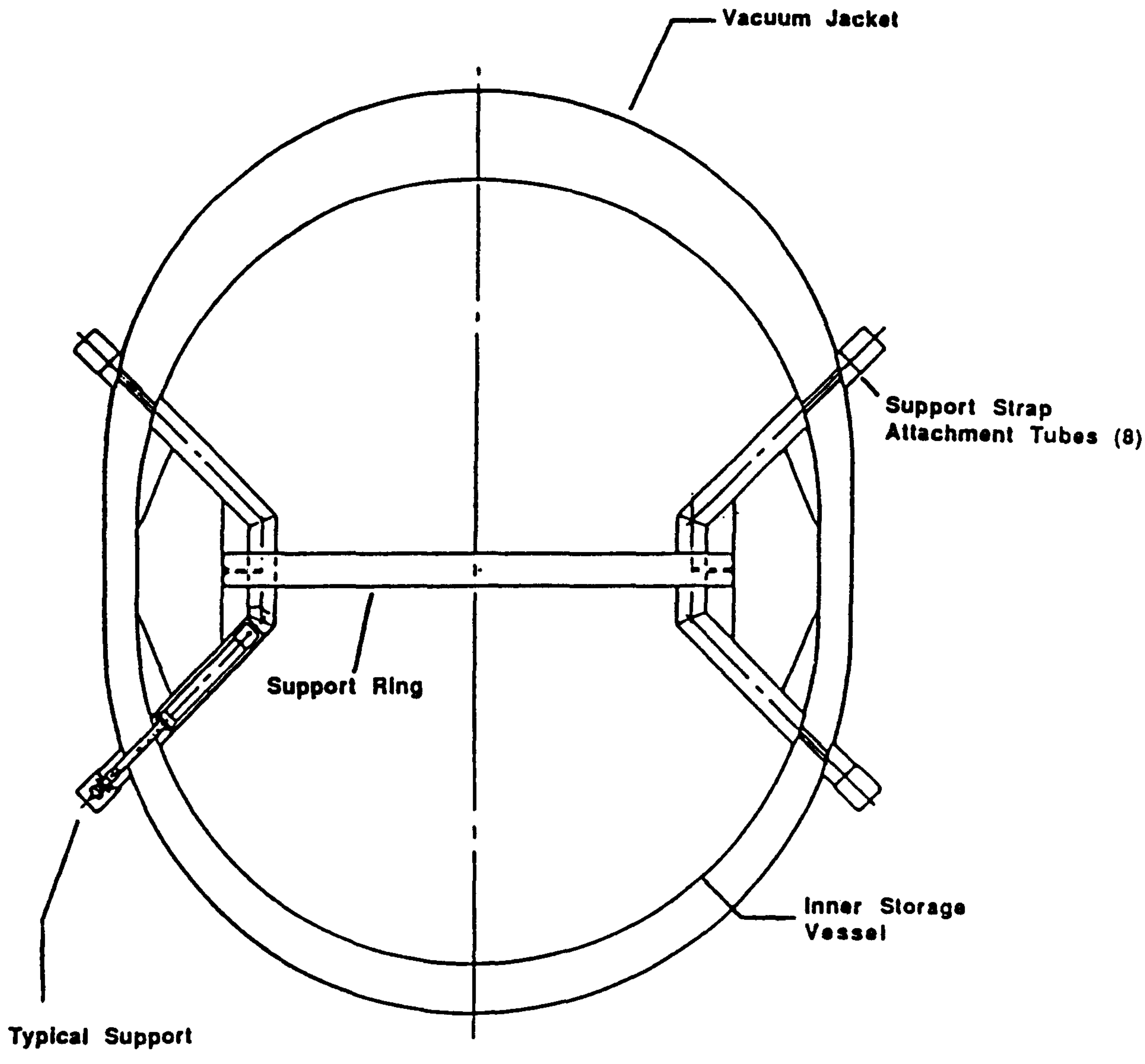


Figure 6.19 Conceptual Design of SFHT Dewar

The tank support load path transfers to alumina composite support assemblies attached near the outside ends of the inserted tubes (see Figure 6.20). At that point, a concentric composite compression carrying tube projects inward near the length of the outer tube. At its inner end, a transition joint transfers the load to composite tension strap assemblies. The tension strap extends through a short outward extension to the vacuum jacket, providing a length of about 2 ft. The thermal path is in series through first the tension strap, to the transition fitting, and back to the metal tube through the composite compression tube. This design uses a minimum number of support penetrations, and achieves a very high thermal resistance per support.

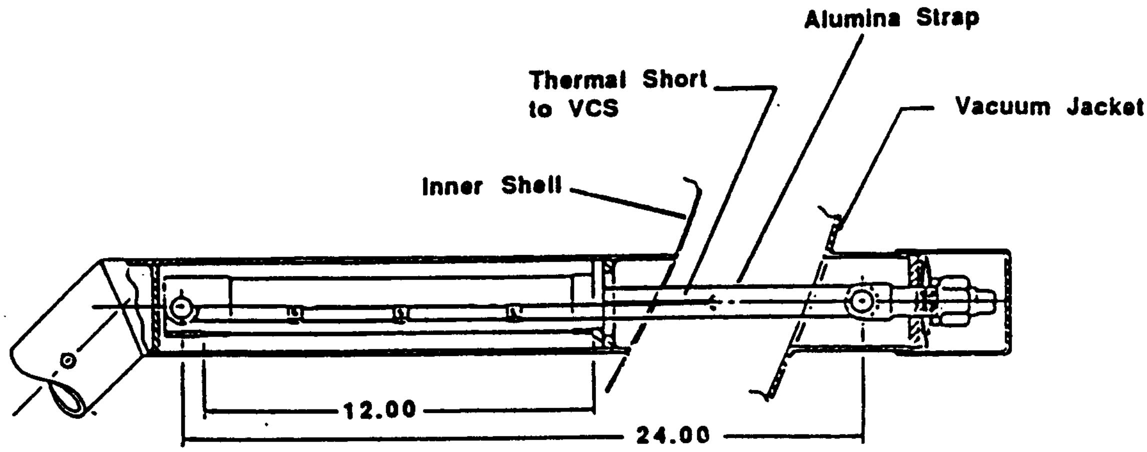


Figure 6.20 Tank Support Member

Thermal contraction on tank cooldown reduces the tank diameter, and the length of both the composite compression tubes and tension straps. To some extent, the shrinkage of the telescoped composite members cancel each other, but the net effect is to increase the length required of the support. To accommodate this requirement, the tension supports are loaded at the outer end through a series of conical (Belleville) washers. The washers provide adequate tension for a warm, unloaded tank, and also for landing loads in the case where an empty and warm tank is returned, but compress as the tank is cooled until they are fully compressed for boost loads with a filled tank.

The technique of lengthening the tank support straps to reduce heat transfer by extending them within the inner vessel and outside the vacuum chamber is frequently used in the design of ground based cryogenic Dewars. Our consultant, Dr. Glen McIntosh, first used this "re-entry" strap in the design of a 750 L helium Dewar in 1959 and on a 7000 gallon helium Dewar delivered in 1960. The second unit was both the largest helium Dewar and largest superinsulated Dewar built up to that time. Re-entry strap supports not only provide a way to increase thermal support lengths but are particularly convenient for Dewars with multilayer insulation and vapor cooled shields. Conventional supports anchored on the outer shell have attachment "bumps". With re-entry supports, the insulation blankets are smooth and shields do not require boxes or irregular cutouts. Installation is easy because the strap penetrations through the insulation are more or less normal to the shell requiring simple cutouts after each layer of insulation is in place. With the Dewar held in a temporary holding fixture, the supports are easily inserted.

Attachment of the flexible thermal shorting straps from points on the straps to the respective VCS is also straightforward. It should be noted that each strap assembly is a complete subassembly that is inserted into the re-entry tube and locked in place. The mechanical attachment occurs near the tube entrance by a simple rotating lock, and all loads are transmitted through this point. The final closeout consists of adjusting the compressive preload on the Belleville washers at the vacuum jacket end from outside, then welding a cap on the tube to complete the vacuum seal. Use of re-entrant strap supports, while greatly increasing the thermal length and reducing support heat leak, is also necessary to achieve the support geometry of our design, since wall-to-wall support members would be very short and would have prohibitively high heat leak. Acceptable alternatives would all require placing the supports at a very flat angle relative to the inner vessel wall with reduction of load carrying efficiency, and/or use of more straps to react all loads.

Heat leak is minimized by use of an efficient thermal protection system. Three vapor cooled shields are located between the pressure vessel and its enclosing vacuum jacket. Vent vapor exiting from the porous plug phase separator system is routed successively through heat exchangers on the vapor cooled shields (inside to out), to effectively intercept a major portion of the heat leak that otherwise would reach the tank through the insulation. These shields also serve to conduct heat that is diverted from the supports, pipes, and instrumentation and control wires. These heat fluxes are shunted from three places on each of the thermal elements to the respective VCSs by copper shunts, and the aggregate heat is transferred to the exiting vent fluid and carried overboard. Exceptions are two pipes that are used for liquid transport, that are left uncooled to minimize heating of the fluid during transfer. All pipes are provided with added length to reduce their heat leak contribution.

The cryogenic system optimization program was used to determine the placement of the MLI, the points of interception for the supports, pipes, and wires, and to predict overall performance. Table 6.3 summarizes these results. For the baseline design the net onorbit heating rate with the vent system operating is estimated at 0.197 w, resulting in a vent flow rate of 0.067 lbm/hr. The optimum configuration for the baseline system places no MLI between the tank wall and the inner VCS. The MLI is distributed on the 3 VCS in the approximate ratio of 13, 34, and 53% from the inner to outer shield. The heat leak and vent rates predicted are believed to be conservative and achievable, and are adequate for the SFHT mission as now envisioned. For longer term storage requirement, a reduction of boiloff can be accomplished by increasing the total MLI thickness, and/or increasing the number of vapor cooled shields. Table 6.4 gives the results of an analysis to evaluate various options for extending storage life.

Table 6.3 Predicted Thermal Design Parameters and Performance for Baseline SFHT

Current Baseline (TVS Operating)	
Total Heat Leak*	0.197 W
Vent Flow Rate*	0.067 LBM/Hr
Shield Temperatures	47, 123, 218 K
Heat Leak by Component Fixed (Pipe) MLI/Radiation Tank Supports Pipes Wires	 0.023 W 0.089 W 0.068 W 0.017 W 0.0003 W
Distribution of Supports (Relative to Intercepts)	0.205, 0.248, 0.267, 0.280
Distribution of MLI	0.0, 0.132, 0.342, 0.526
Distribution of Pipes & Wires	0.205, 0.248, 0.267, 0.280

*Vacuum Jacket Temperature - 300 K

Table 6.4 Options for Increasing On-orbit Lifetime

Alternate	MLI (in.)	No. of Shields	Net Q W	Vent Rate LBM/Hr	Liters @ 90 Days	Liters @ 12 Mo.
Baseline	2.57	3	0.197	0.0648	5548	4166
Alt. 1	2.57	4	0.190	0.0648	5563	4201
Alt. 2	3.5	3	0.158	0.0539	5637	4528
Alt. 3	3.5	4	0.154	0.0525	5646	4565
Alt. 4	4.0	3	0.147	0.0501	5663	4631
Alt. 5	4.0	4	0.142	0.0486	5673	4672
Alt. 6	4.0	5	0.141	0.0481	5676	4686

The vent function is implemented and controlled through the use of porous plug phase separators. A single plug, estimated to be 1 1/4 in. (3.2 cm) in diameter, will provide for normal venting during space hold. This plug will handle an estimated net heating load of 0.13 to 0.22 watts, and its size is scaled from the design successfully used on the Spacelab Infrared Telescope experiment. A second porous plug, or several plugs in parallel, will be required to vent the SFHT at a high rate during the time that liquid is being transferred to a user receiver tank. The apparent heating load is a result of the selective flow of the entropyless component of superfluid helium through the porous plug (thermomechanical) pump, leaving the heat containing fluid behind and resulting in an increase in temperature if this heat is not removed. This apparent heat addition to the supply tank is referred to as the mechanocaloric effect. The high rate venting could be 40 to 200 times as great as the normal venting required during space hold, and a very large diameter plug, or a number of smaller plugs in parallel may be required. A possible alternative is to utilize the tank heat exchanger that is in place for ground conditioning to handle this heating load. This would be accomplished by the addition of a flow restrictor valve between the liquid acquisition device and the tank heat exchanger to operate as a conventional thermodynamic vent system with Joule Thomson (isenthalpic) expansion of the fluid to a lower pressure and temperature. Research on higher capacity porous plug phase separators, and particularly work done on the SHOOT program needs to be followed for guidance in this area.

6.1.4.3 Liquid Acquisition Device Design - The preferred liquid acquisition system concept was selected during Task 2 as previously described in Paragraph 5.1.2.4. The system uses four separate channels joined at their mid-plane by a single, circumferential channel. The channel arrangement provides intimate contact with the bulk liquid under any of the probable acceleration vectors. Each channel has a cross-sectional flow area 3.0 inch x 0.75 inch, and incorporates a single layer of 325 x 2300 mesh double-twilled screen on the 3.0-inch wide wall nearest the tank wall. The channel dimensions were selected assuming that only one channel is in contact with the bulk liquid during draining at 1,000 l/hr under an adverse g-condition of 10-4g. The storage temperature used in the selection process was the lambda point.

In order to evaluate the acquisition system performance, a review of SHOOT acquisition system test results from NASA-GSFC and Martin Marietta's IR&D program was conducted. Estimates of the total pressure loss for each test were made and these values were divided by the channel screen bubble point. The results of these estimates are plotted as a function of the liquid flow rate in Figure 6.21. Factor-of-safety lines presented are where factor-of-safety is defined as the bubble point of the screen divided by the total pressure loss across the screen. It can be seen that all the data points are on or above the line for a factor-of-safety of 2.0. Thus, satisfactory performance of the screen channel system will be obtained as long as the total pressure drop is constrained to be less than or equal to the bubble point divided by 2.0.

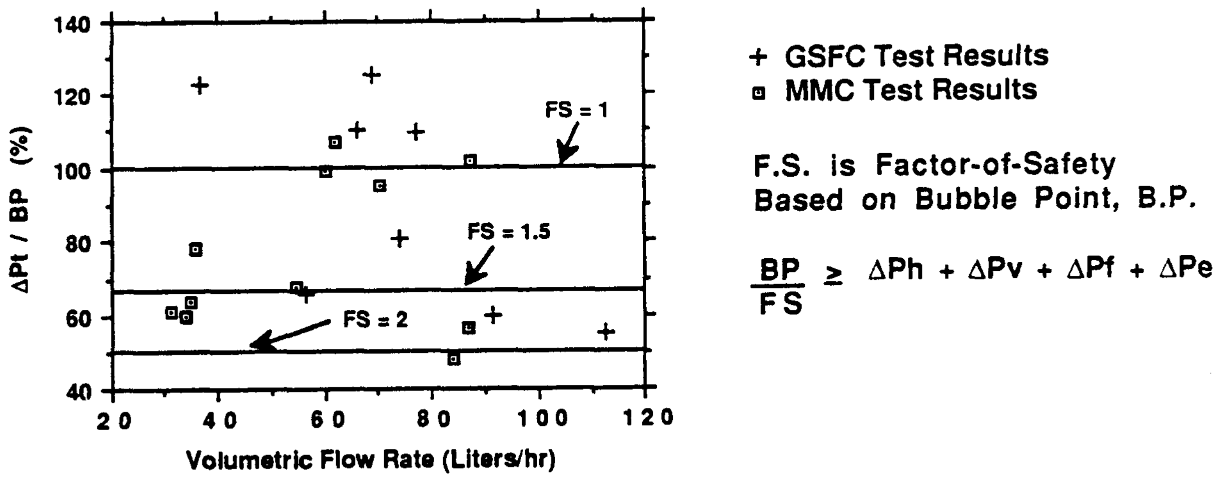


Figure 6.21 Bubble Point Factor of Safety Evaluation

An evaluation of the fluid acquisition system performance was made for a varying acceleration environment assuming a factor-of-safety of 2.0. The results are presented in Table 6.5. The effect of the acceleration magnitude on the screen flow area is presented. As seen, the screen surface area required for the bulk liquid to enter the single channel and assure single-phase flow increases with the magnitude of the acceleration vector. The conventional Armour and Cannon approach to screen entrance losses was used to determine this term in the equation, and appears to be conservative based on the recent data of Van Sciver (Reference 6.9). The requirement is considered to be minimal.

Table 6.5 Liquid Acquisition Device Performance as a Function of Adverse Acceleration Environments

Adverse Acceleration, g/go		10^{-5}	10^{-4}	10^{-3}	10^{-2}
Hydrostatic	ΔP, psi	0.00001	0.00005	0.00051	0.00507
Frictional	ΔP, psi	0.00014	0.00014	0.00014	0.00014
Dynamic	ΔP, psi	0.00039	0.00039	0.00039	0.00039
Screen Entrance	ΔP, psi	0.00526	0.00522	0.00476	0.00020
Total ΔP*		0.00580	0.00580	0.00580	0.00580
Screen Surface Area, sq. in.		10.0	10.3	11.0	19.7
Screen Length, in.		3.3	3.4	3.7	6.6
*ΔP = B.P./2					

Expulsion efficiency of the acquisition device is generally related to the wetted screen areas, particularly at the higher acceleration levels. However, a key operational feature of the screen channel device is the region between the screen and the tank wall. This region can support liquid to a varying height in the tank depending upon the acceleration. This supported liquid height impacts expulsion efficiency in two ways. First, it increases the wetted screen area, reducing the screen entrance pressure loss and the total system pressure loss. The supported liquid height can also reduce or eliminate the liquid puddle volume in the tank if the puddle Bond number is small (< 20). The puddle Bond number was based on the free-surface radius of the puddle. Both of these factors tend to increase expulsion efficiency.

To estimate the support height in the gap between the channel and the tank wall, an analysis of the configuration shown in Figure 6.22 was made. The capillary retention of the fillet interface between the channel and the wall was assumed to respond according to the following equation

$$\Delta P_{CAP} = \frac{\sigma}{R_i}$$

where R_i is the interface radius defined in Figure 6.22 and σ is the fluid surface tension. Note that the interface radius of curvature normal to the plane of radius R_i is assumed to be very large.

The capillary retention, ΔP_{CAP}, will be equated to the hydrostatic head, ΔP_H which is defined as follows:

$$\Delta P_H = \rho \frac{a}{g_c} \Delta h.$$

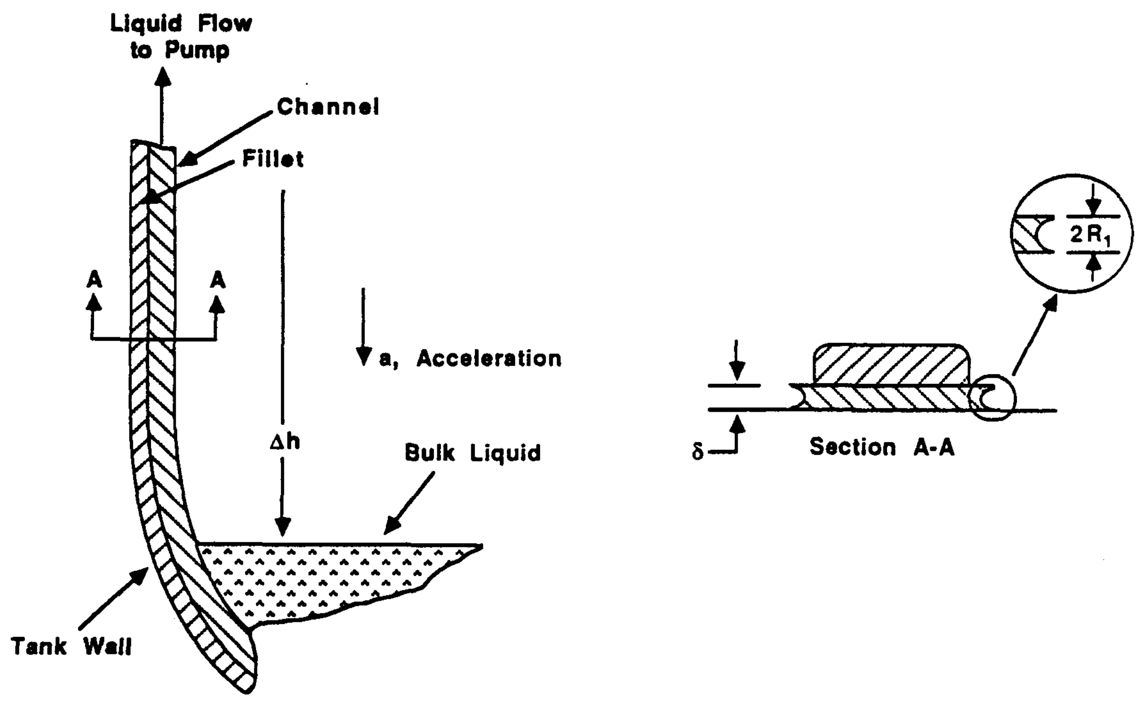


Figure 6.22 Liquid Distribution Between Channel and Wall

The fluid density is ρ, the system acceleration is a, and the supported height, Δh, is defined in Figure 6.22. Equating the two equations,

$$\Delta h = \frac{2\, g_c\, \sigma}{a\, \delta\rho}$$

where δ is the gap thickness between the channel and the wall and is equal to $2R_i$. Table 6.6 presents the calculated support height as a function of acceleration and gap width with the fluid properties at the Lambda point temperature. The liquid volume contained in the gap for a channel 3.0 inches wide is also included in the table. It can be seen that, for an acceleration level of 10^{-5} g, a hydrostatic head far greater than the 96 inch tank height can be supported.

Table 6.6 Channel Gap Liquid Support Height and Volume

(in)	Δh, in.			
	g/g_o	g/g_o	g/g_o	g/g_o
	10^{-2}	10^{-3}	10^{-4}	10^{-5}
0.250	0.3	2.6	25.5	255.0
0.188	0.3	3.4	34.0	340.0
0.125	0.5	5.1	51.0	510.0
0.063	1.0	10.2	102.0	1020.0
(in)	Liquid Volume in Fillets, Liters			
0.250	0	0.3	3.2	11.9
0.188	0	0.3	3.2	8.9
0.125	0	0.3	3.2	6.0
0.063	0	0.3	3.0	3.0
@ Lambda Point and for Baseline Channel Dimensions (3.00" x 0.75")				

Liquid expulsion efficiency, η, is defined as follows:

$$\eta = 1 - \frac{V_R}{V_T}$$

where V_T is the total tank volume and V_R is the liquid residual. The liquid residual, V_R, is comprised of three terms as defined in Figure 6.23. V_C is the volume of the acquisition device channels, 30.6 liters. V_B is the liquid reservoir volume that is not in contact with any channel and is a maximum of 141 liters if the liquid/vapor interface is flat (i.e., puddle Bond number greater than 20). V_A is that volume added to V_B to satisfy the wetted screen requirements presented in Table 6.5. An analysis was conducted to evaluate V_A, V_B , and V_C for various gap

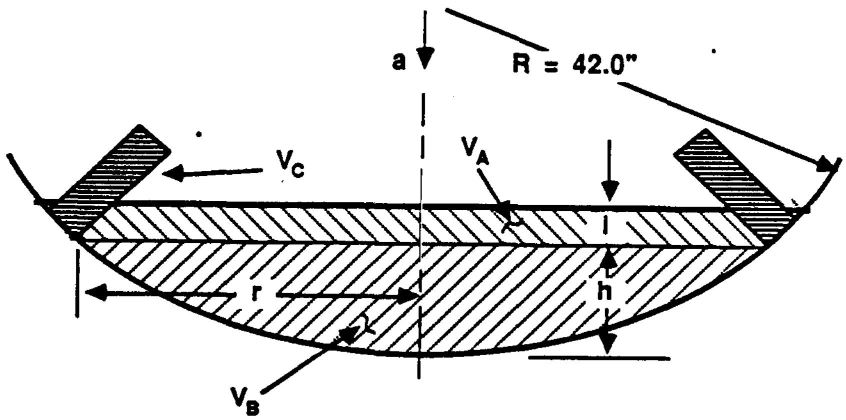


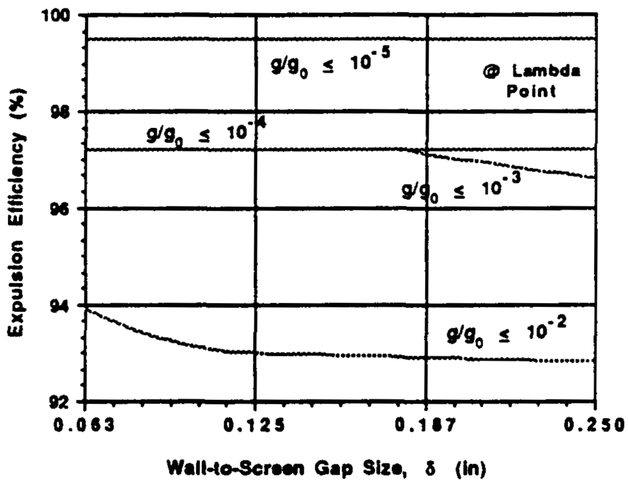
Figure 6.23 Description of Liquid Residual Between Channels

thicknesses, δ, and environmental accelerations. The results are presented in Table 6.7. At 10^{-5} g, the expulsion efficiency is a maximum value because the residuals only consists of the channel volume. At 10^{-4} g, the residuals consist of the channel volume and the bulk liquid not in contact with the channels. Above 10^{-4} g, liquid volume must be added to the bulk liquid to assure that the minimum screen area from Table 6.5 is exposed to liquid. The data from Table 6.7 is also presented graphically in Figure 6.24. For the assumed gap width of 0.25 inches, the expulsion efficiency varies from 92.8 to 99.5 percent depending upon the acceleration.

Table 6.7 Expulsion Efficiency as a Function of Acceleration Environment and Gap Thickness

a/g_0	V_C (L)	V_B (L)	**V_A in L				η (%)	η, %			
			δ=0.25"	0.188"	0.125"	0.063"		δ = 0.250"	0.188"	0.125"	0.063"
10^{-5}	30.6	0*	0	0	0	0	99.5				
10^{-4}	30.6	141	0	0	0	0	97.2				
10^{-3}	30.6	141	37.7	9.7	0	0	→	96.6	97.1	97.2	97.2
10^{-2}	30.6	141	271.3	267.1	258.3	202.7	→	92.8	92.9	93.0	93.9

* Zero because puddle Bo < 20 and liquid surface curvature will contact channels.
** Zero values when hydrostatic stability of fillets assures sufficient wetted screen area at liquid flow termination.



• Settled Liquid Forms A Single Puddle Which Does Not Contact The Screen Channels

$$\eta = 1 - \frac{V_{res}}{V_{tank}}$$

Where Vres is the residual liquid volume and Vtank = 6,175 L

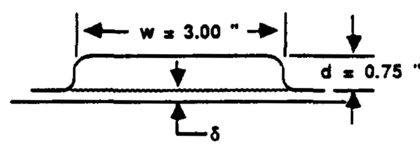


Figure 6.24 Expulsion Efficiency for Worst Case Conditions

6.1.4.4 Emergency Venting - Loss of vacuum can drastically increase heat leak to the SFHT helium vessel, which would result in catastrophic failure if adequate emergency vent capability is not provided. Two modes for loss of vacuum are considered. The first is internal leakage of helium vapor into the vacuum annulus. Only a near microscopic helium leak will change the insulation heat transfer mode to gas conduction, with several orders of magnitude increase in heat leak. Internal helium leakage can occur at any time, and therefore must be considered both in space and under one-g conditions. Leakage of atmospheric air due to damage to the vacuum jacket (the second mode) could cause even greater heating, depending on the size of the air leak, by condensing air on the cold tank.

If anomolous heating occurs in space, there is no assurance that gas or low density fluid would be in the vicinity of the vent exit. This introduces another adverse condition, in that the heating must be assumed to create stratification, or worst case volumetric vent requirements. At the same time, if liquid or high density fluid must be vented, the greatest pressure loss for a given volumetric relief rate will occur, requiring the maximum vent line size. The same assumptions must be made, however, for ground conditions if the tank is totally full, or containing only a percent or two ullage. The agitation caused by high heating rates, combined with the low density of helium, will result in at least significant slug flow at the beginning of the vent. It is noted that the first response to loss of vacuum is uniform distribution of heat through the superfluid with no increase in pressure (pressure will decrease if the tank is initially pressurized) because of the high heat transport characteistics of the superfluid. Once the lambda point is reached, however, the high heating rate will result in stratification that tends to maximize pressure rise. There seems to be no plausible argument that assures that anomolous heating will be uniformly distributed throughout the fluid, which would minimize the rate of pressure rise and required vent rate. This is particularly true for the onorbit internal leak situation where gravity is not available to induce free convection.

We have performed analyses using worst case models for stratification and liquid density in the vent line. How stratification would occur is not known, and low-g testing will probably be required to understand what will actually happen in the space case. To predict the worst possible situation, we assumed that all heating that reaches the tank (after the lambda point is reached) is concentrated into a boundary layer that reaches some given temperature. The lower the temperature assumed, the larger the boundary layer, up to the point where the increasing temperature results in reduction of heat transfer because of the reduced delta temperature. A series of calculations were made, assuming increasing temperatures of the boundary layer, to determine at which temperature the greatest growth in volume (holding a constant pressure by venting) occurs. Figure 6.25 shows the result for two assumed tank pressures, 60 and 80 psia. The greatest required vent rate occurs when the hypothetical boundary layer is about 24 K. This result is certain to be conservative, but the degree of conservatism is not known.

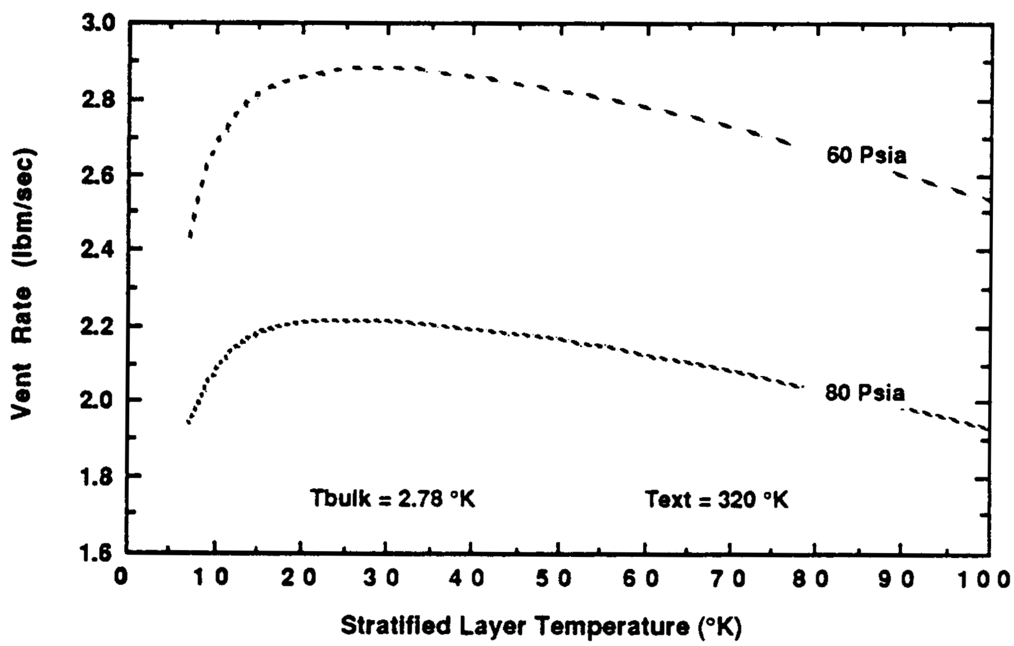


Figure 6.25 Vent Rate Due to Internal Vacuum Leak vs Hypothetical Boundary Layer Temperature

The vent rate predicted is 2.22 lbm/sec for the helium leak case with 80 psia tank pressure. This would require a vent line of 1 in. from the inner tank (through two burst disks, a pressure relief valve, and miscellaneous fittings). It was then determined that 0.116 lbm/sec of air must condense on the inner Dewar to equal the vent rate due to the helium leak, which is the equivalent of an orifice of 0.745 in. diameter in the vacuum jacket. To increase the ability for the emergency vent to handle greater air leaks, we investigated the use of a relatively thin layer of conventional insulation material applied to the inner vessel wall. This insulation would limit, or prevent, condensation of air on the tank wall and greatly reduce the rate of heat transfer resulting from this failure mode. Using typical insulation properties, it is estimated that a layer 1/4 to 3/8 in. thick would limit the heating due to an unlimited air leak to the value resulting from the internal helium leak into the vacuum annulus.

Cork would appear to be an attractive candidate insulation material. It is relatively light and has a low thermal conductivity. However, it would likely need to be sealed to prevent condensation of air within the voids, giving an unpredictable heat transfer. Martin Marietta investigated the use of cork as a cryogenic insulation that would also have good high temperature characteristics in the 1960s. Results from tests performed with liquid hydrogen indicated a tendency for cork to break up due to differential thermal contraction, and in the form that it was tested it did not appear to be acceptable. Experiments using ground cork in an epoxy carrier as a trowellable insulation were more favorable. An outgrowth of this investigation is Martin Marietta's Super Light Ablative (SLA-561). This material is cork in a silicone matrix, and it is used on the Shuttle External Tank in a number of places that are exposed to high heating, both on the liquid oxygen and the liquid hydrogen tanks. An experimental material now being developed by Martin Marietta as aircraft thermal insulation is also being investigated. It will have lower density, but slightly higher thermal conductivity than SLA-561. These are only two of a number of possible candidate materials that could be used for this purpose, including various foams. A major question is whether the materials are suitable for use in a vacuum jacketed Dewar. For foams that entrap gas, there could be a tendency for long term gas evolution that would be detrimental. We have determined that the two silicone based materials discussed above show no significant outgassing characteristics in limited term testing.

Analysis using data for the SLA-561 shows that about 1/4 in. of this material on the tank will reduce the heating due to unlimited air leakage to that calculated above for internal helium leakage. It also shows a slight improvement over the uninsulated case for the internal leak condition, permitting reduction of the vent line from 1 in. to 7/8 in. diameter. With this emergency vent design for each of two redundant vent lines that feed into the 2 in. generic vent line on Shuttle, the hazard of tank rupture or explosion is eliminated. With a small amount of foam on all of the vent lines external to the tank, condensation of significant quantities of air in the payload bay due to a ground failure is also prevented.

6.1.5 Structural/Mechanical/Thermal Control Subsystem Design

The structural/mechanical and thermal control subsystem design features are discussed in this section. These subsystem designs were configured to permit launch compatibility with both shuttle and ELV launches, and use of the SFHT as a space station depot or with the OMV, as well as servicing from the Shuttle.

6.1.5.1 Structural/Mechanical Subsystem - The SFHT is being designed with the versatility to be launched either on the Space Shuttle (STS) or on an expendable launch vehicle (ELV), in which case it would be returned on the STS. An assessment was made of preliminary structural design criteria for the SFHT considering both of these launch options. Our overall design philosophy is that the structure shall possess sufficient strength, rigidity, and other characteristics required to survive critical loading conditions that exist within the envelope of mission requirements. The structure shall survive these conditions in a manner that does not reduce the probability of mission success. The design shall be based upon rational and conservative structural design principles and assumptions. Nonflight conditions shall influence the design to the minimum extent practicable. The structure shall be designed to achieve minimum practical weight. With this overall design philosophy, a set of design criteria were generated to envelope the entire spectrum of potential SFHT operating conditions. These criteria are listed in Table 6.8.

One concept we considered for structurally mounting the SFHT within the Shuttle to minimize the length within the cargo bay, was to orient the Dewar such that its major axis was aligned with the Orbiter Y-axis rather than X-axis. This concept is shown in the sketch of Figure 6.26. This reduces the overall length within the bay by several feet but leads to several other design problems that result in a heavier SFHT with higher heat leak. The total cradle structure tying the tanker to the Shuttle longerons and keel fitting is heavier than if the tank is aligned with the X-axis. Additional structure must be added for OMV and spacecraft/user adapters which is not useful in taking any loads during STS launch. In addition, if the tanker is to be compatible with Delta and Atlas expendable launch vehicles, then the tanker must be able to handle launch loads in multiple axes rather than just along the X-axis. This requires beefed-up support structure which leads to larger heat leaks. As a result of these kinds of considerations, a structural/mechanical support concept was selected that appeared to minimize all these adverse impacts.

Table 6.8 SFHT Preliminary Structural Design Criteria

1. Limit Loads are the maximum combination of loads expected to occur for any condition, based on nominal plus 3X standard deviation. Limit load equals MEOP (maximum equivalent operating pressure) for pressure analysis.

2. Factors of Safety (F.S.)
   - Defined as the number multiplying limit load to compare against
   - allowable loads.
   - Each flight article tested to these levels

	Ultimate	Yield*	Proof
- Shuttle Launch/Landing	1.4**	1.3	1.2
- Titan Launch	1.25	1.15	1.1
- Pressurized Tanks (either launch)	2.0	1.5	1.5
- Pressurized Lines/Fittings (either launch)	4.0	2.0	2.0

   * No detrimental deformation.
   **Must show an additional 1.15 factor on ultimate for instability failure modes.

3. All margins of Safety (M.S.) must be greater than or equal to 0.0.

$$M.S. = \frac{\text{Allowable Load or Stress (Yld. or Ult.)}}{\text{(Limit Load or Stress) x F.S. x F.F.}} - 1.0$$

   where F.F. = 1.15 for Primary Structure Joints
   = 1.0 for all other joints

4. Excessive deformations are not allowed.

5. A worst-case tolerance analysis shall be calculated for all eccentricities.

6. Material thicknesses used in analysis are
   - Structural Strength: less of (1.1 x min. dwg. t) or (nom. dwg. t)
   - Structural Stability: less of (1.05 x min. dwg. t) or (nom. dwg. t)
   - Pressure Vessels: minimum dwg. t

7. All instability failure modes shall be considered ultimate failure modes.

8. Material Properties shall be taken from either
   - MIL-HDBK-5 (A or S values)
   - Manufactureres data is verified to be reliable and conservative
   - Test data statistically converted to A values

9. Fatigue/Fracture Analyses
   - Design to 50 missions of liftoff and landing
   - Include life factor of 4
   - Cycles of maximum limit stress per mission for primary structure (includes factor of 4):
     1000 for metallic structure
     1500 for non-metallic structure (includes 1.5 material uncertainty)
   - To be verified by Fracture Mechanics analysis and/or fatique testing

Table 6.8 SFHT Preliminary Structural Design Criteria (concl.)

10. Mission duration is 12 months maximum from tank fill before liftoff to tank drain after landing.

11. Stress Corrosion Cracking (SCC) shall be controlled either by using Table I, MSFC-SPEC-522A materials or by performing an SCC analysis including residual stresses.

12. Pressure Vessels (internal or external pressure) shall be designed to NBH 1700.7A, and shall support simultaneous pressure and inertial loads.

13. Thermal effects to be considered in analysis include
    - thermal expansion
    - thermally included stresses
    - thermal degradation of material properties
    - creep, etc.

    Limit temperatures are defined as the extreme temperature or gradient expected for any condition. Ultimate temperatures equal limit ± 20°C (where practical) or gradient x 1.2.

14. Stiffness design criteria is defined as the 8 Hz minimum structural mode as supported on the launch vehicle, assuming a minimum damping of 0.01.

15. Critical Load Environments
    The following simultaneous load factors (inertial force factors, to be multiplied by spacecraft weight) envelope all STS (shuttle) and ELV (expendable) load environments. These factors apply to primary structure only. Secondary (non-primary load path components) structure should be designed to random vibration loads of 25 G's or 50 G's for a cantilever support, one axis at a time.

X	Y	Z
+2.3, -5.5*	±2.1	+3.8, -4.5**

    *Liftoff only. Use 2.3 for other cases.
    **Landing only. Use 3.8 for other cases.

    These factors encompass the following environments:
    - Ground Handling/Installation
    - STS Boost
    - STS Abort
    - STS Landing
    - ELV Boost
    - Upper Stage Boost/Maneuver/Docking

    Note that X is positive aft, STS or ELV, Z is positive towards cargo doors, STS.

16. Design Envelope: The spacecraft shall be designed to attach to the STS cargo bay, with an option to launch within a 108 in. ELV envelope.

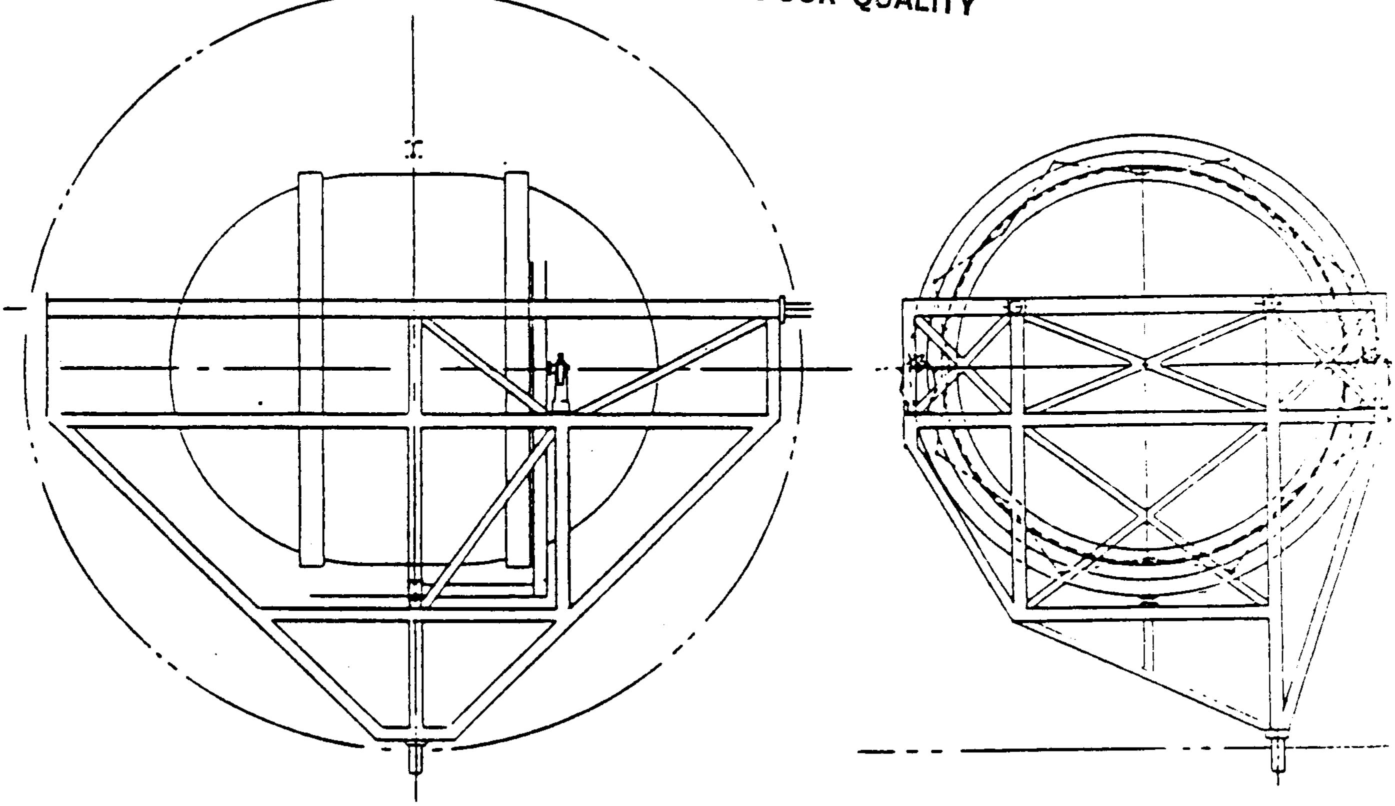
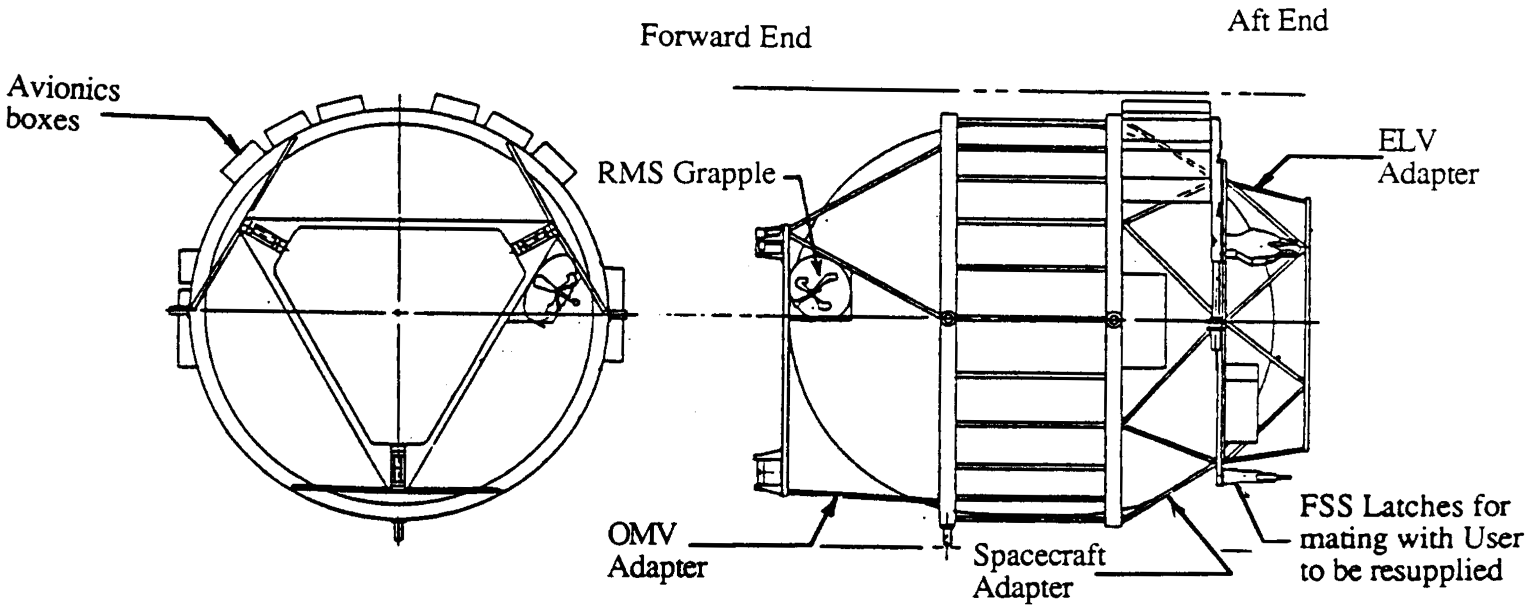


Figure 6.26 SFHT Dewar Axis Aligned with STS Y-Axis

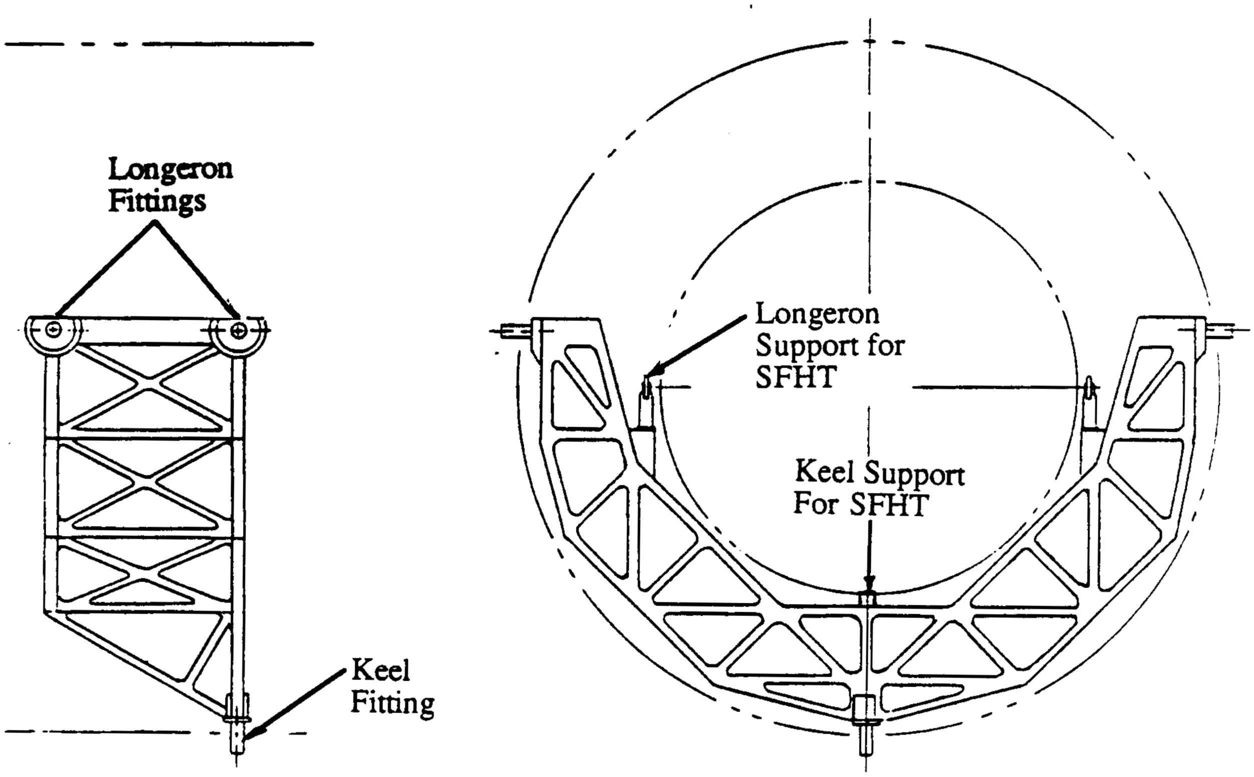
The SFHT structural support concept and STS transport cradle configured to satisfy the design criteria are shown in Figure 6.27. The SFHT configuration for STS launch includes the Dewar vacuum jacket structure, an OMV adapter, a spacecraft adapter for docking with the user on orbit, and a cradle that supports the SFHT in the cargo bay. The ELV scenario includes the Dewar vacuum jacket structure, OMV and spacecraft adapter structures, and an ELV adapter, all of which fits into the 108 inch diameter envelope of the Delta. When the SFHT is launched on an ELV, a cradle will have to be launched on the STS simultaneously for SFHT return to Earth. All the structure shown is aluminum although approximately 50 pounds could be saved by using graphite/epoxy struts for the adapters instead of aluminum.

The Dewar vacuum jacket structure weighs approximately 1290 pounds, although roughly 150 pounds could be saved by using a more expensive chem-milled skin structure which would require development testing. The two hemispheres (wall thickness t = 0.125 inches) are sized for collapse, and to support valving and vapor-cooled shields. A short cylindrical barrel (wall thickness t = 0.188 inches) connects the two hemispheres. Longerons are machined into the barrel to transfer axial load from one ring at the aft end of the barrel to a similar ring at the other end. The rings are key to the structure in that they support the inner Dewar, stiffen the vacuum jacket, hold five pins that attach to the cradle, interface with the OMV adapter and the spacecraft adapter, and support an avionics platform.

The Orbital Maneuvering Vehicle (OMV) adapter weighs approximately 283 pounds. It mounts to the forward ring with six struts that separate FSS/OMV latches from the hemisphere. At the forward end the struts attach at 3 places to a machined triangular frame, on which the latches and two RMS grapple fixtures are mounted. Note that the latches make up 67% of the subsystem weight.



a) SFHT Configuration for ELV Launch (or placement in Transport Crade for STS Launch)



b) SFHT Transport Cradle for STS Launch and/or Return

Figure 6.27 SFHT Structural Support Concept

On the aft end of the Dewar vacuum jacket is mounted the spacecraft adapter, weighing 328 pounds. It is sized for ELV loads since it connects the vacuum jacket to the ELV adapter. Twelve struts space the aft ring from the vacuum jacket. Six separation fittings and three FSS fittings are attached to this ring. Additional equipment, including tool boxes, are mounted on this truss. The redundant vacuum-jacketed transfer lines are also mounted to the spacecraft adapter structure. These lines are flex lines which are not easy to handle, particularly with regard to stowing and unstowing by an EVA astronaut. One concept for packaging these lines is shown in Figure 6.28 where one line is shown both in its stowed and unstowed (ready for mating to user) position.

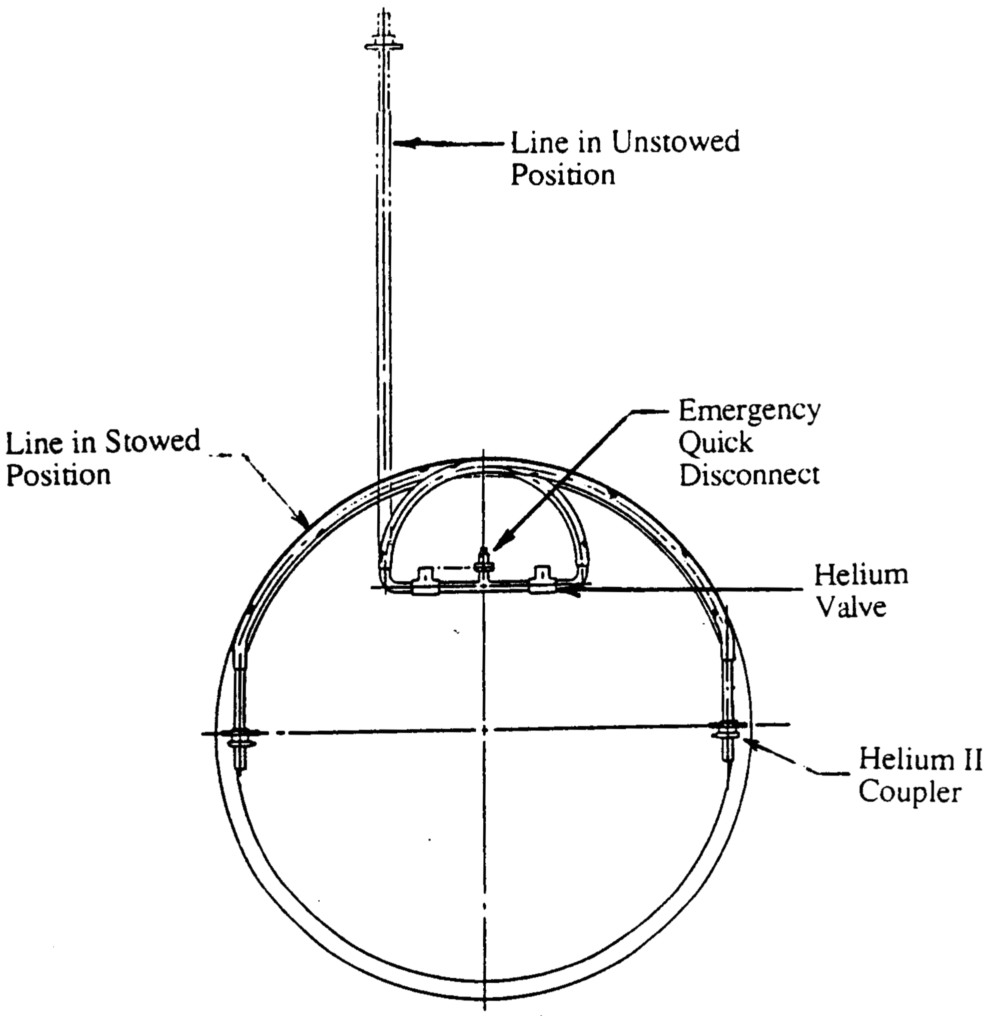


Figure 6.28 SFHT Vacuum Jacketed Transfer Lines in Stowed and Unstowed Positions

The ELV adapter, which stays with the ELV after separation, interfaces at six points to the spacecraft truss. This will be a mechanical, as well as electrical, separation. It weighs 138 pounds and can be built to adapt to any ELV interface diameter and number of discrete attachment points. A Delta adapter is shown in the sketch.

Finally, the transport cradle will be mounted in the Orbiter to support the SFHT at four longeron and one keel latches. Each of these fittings weighs 44 pounds. The transport cradle itself also mounts to the Orbiter with four longeron and one keel fitting. The cradle weighs approximately 1200 pounds based on similar designs we've fabricated and qualified.

The total structural weights for various launch options, using the individual adapter and vacuum jacket weights listed above, are:

3239 pounds for ELV launch and STS return,
3101 pounds for STS launch and STS return,
2039 pounds for ELV launch (single use SFHT).

The contribution of these weights to the total SFHT weights for both STS and ELV launches is shown in Table 6.9. In both cases, OMV and spacecraft adapter weights are part of the SFHT launch weight. As indicated, the only differences in liftoff weights are that the ELV adapter (138-lbs) does not fly during STS launch, and the STS support cradle does not fly during ELV launch.

Table 6.9 SFHT Weight Summary for STS and ELV Launch Options

SUPERFLUID HELIUM TANKER EQUIPMENT LIST	STS Launch			ELV Launch		
SUBSYSTEM	NUMBER	WEIGHT PER ITEM (LBS)	WEIGHT (LBS)	NUMBER	WEIGHT PER ITEM (LBS)	WEIGHT (LBS)
DEWAR						
VACUUM JACKET	1	1200	1200	1	1200	1200
INNER TANK	1	700	700	1	700	700
VAPOR COOLED SHIELD	3	75.3	226	3	75.3	226
MLI	1	80	80	1	80	80
STRUCTURE						
SPACECRAFT ADAPTER	1	289	289	1	289	289
OMV ADAPTER	1	224	224	1	224	224
STS SUPPORT CRADLE	1	1200	1200			
ELV ADAPTER				1	138	138
FSS LATCHES	7	63	441	7	63	441
CRADLE PINS	1	90	90	1	90	90
FLUID SYSTEM	1	180	180	1	180	180
INSTRUMENTATION	1	25	25	1	25	25
AVIONICS	1	350	350	1	350	350
THERMAL CONTROL	1	100	100	1	100	100
TOTAL DRY WEIGHT			5105			4043
HELIUM (6000 LITERS)			1945			1945
TOTAL WET WEIGHT			7050			5988
MASS FRACTION			0.28			0.33

A statics model has been developed of the Dewar and support trusses that interface to the Dewar vacuum jacket. This is shown in Figure 6.29. We have checked static loads of our support concept against the design criteria of Table 6.8 using the tanker statics model. This model would be useful in developing a complete finite element model for verifying dynamic loads once the tanker configuration firms up.

6.1.5.2 Thermal Control Subsystem - A thermal control design has been selected to be compatible with the Orbiter, OMV, and Space Station. The design allows flexibility in orientation so that mission constraints imposed by other vehicles do not occur. Table 6.10 presents the derived thermal control requirements which were used for the thermal control subsystem conceptual design.

Thermal Control Concept - The key features of our thermal control concept are shown in Figure 6.30. The external surfaces on the Dewar and its supporting structure are painted white to limit their temperature excursions in the orbital environments. The avionics equipment is enclosed in two thermally controlled spaces covered with multilayer insulation. Temperature control in these spaces is provided by a movable shade which varies the equipment baseplate's view to space in response to a temperature sensor. This approach allows the avionics equipment to operate over a wide range of orbital environments. The shade was selected over louvers based on heat rejection area requirements to allow efficient operation under conditions of direct solar input.

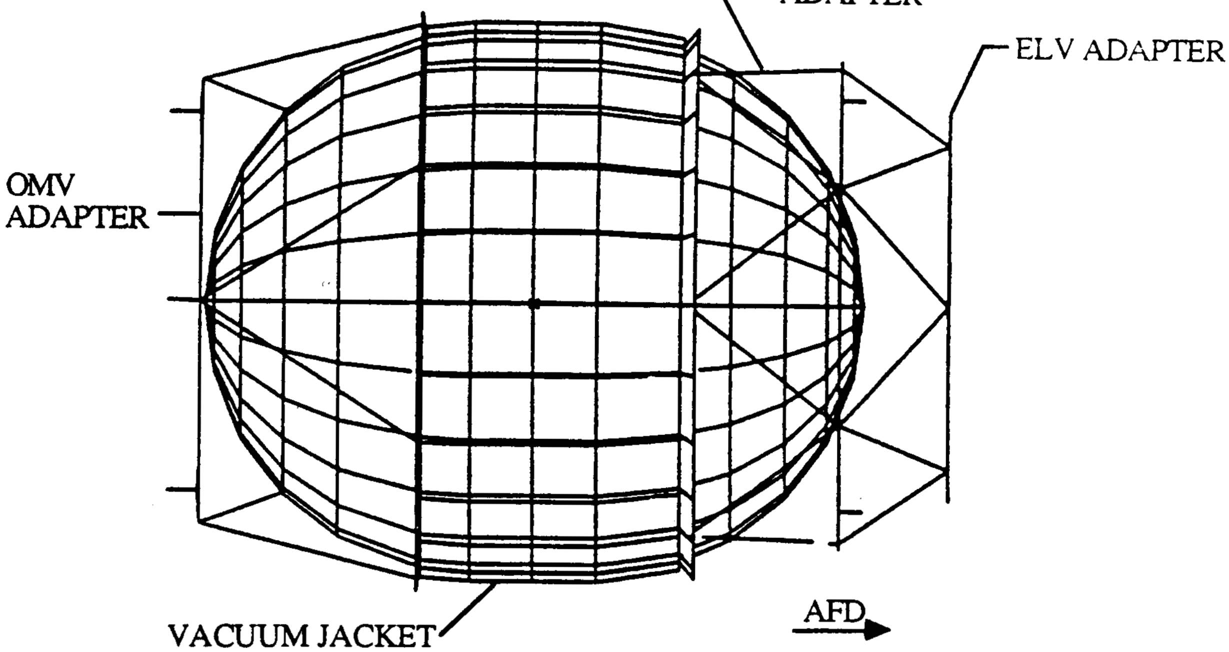


Figure 6.29 Statics Model of SFHT Tank and Support Trusses

Table 6.10 SFHT Thermal Requirements Summary

<u>Environments</u>

- Orbiter Bay - 250 nmi to 270 nmi, Attitudes per ICD 2-19001 including 30 minutes facing direct sun, 90 minutes facing deep space
- Space Station - 250 nmi, Meteoroid shielded enclosure, avg. internal radiative environment 0°C to -35°C
- OMV Operations - 250 nmi to 486 nmi, No attitude constraints imposed on OMV by SFHT
- Sun Angle (Beta Range) - Mission dependent, use 0° to 90° for design
- Atomic Oxygen Fluence - Mission dependent, use resistant materials and coatings

<u>Equipment Temperature Limits (Flight Allowables)</u>

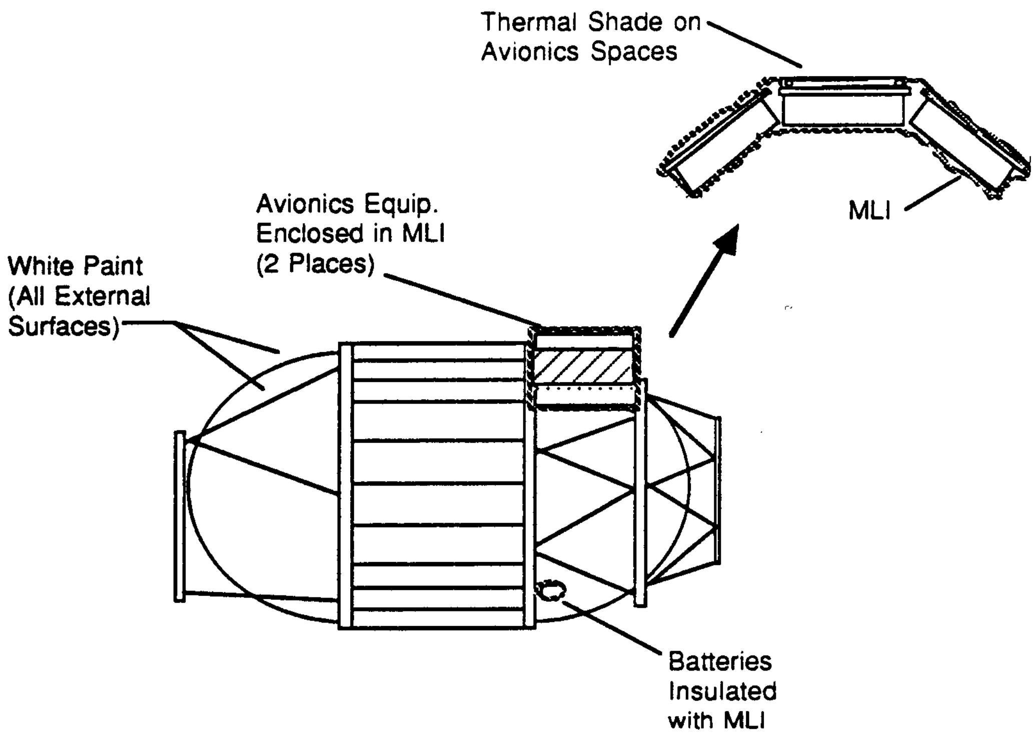
- Avionics Components: -10°C to 45°C
- Battery: -18°C to 32°C
- Dewar Exterior: Provide low temperature environment with low risk, passive approach

<u>Heat Loads</u>

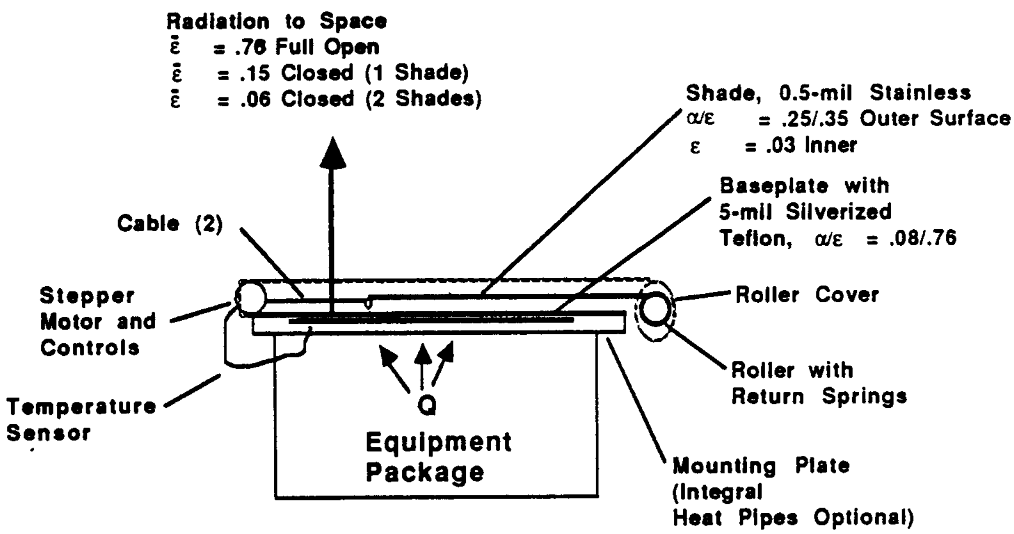
- Hot Case Design: 200 W orbital avg. (includes 20% margin)
- Cold Case Design: 0 W

<u>Thermal Design Criteria</u>

- Heater Power Margins - Design for a 50% margin at lowest predicted temperature and 26V source
- Heater Redundancy - Heater elements will be redundant and each element will have at least two thermostats in series. The primary and secondary circuits will have different temperature set-points. One heater failed "on" will not overheat the vehicle
- Temperature Predictions - Shall be 10°C inside equipment acceptance temperature range. Heater or active control allows predictions to be equal to acceptance temperatures.



a) Thermal Control Concept



b) Thermal Shade Features

Figure 6.30 Thermal Control Concept and Thermal Shade Features

Dewar Exterior Thermal Control - White paint was selected for the external surfaces of the Dewar and its supporting structure. Alternatives include adding additional MLI shields and/or second surface coatings such as optical solar reflectors (OSRs) and silverized teflon. Preliminary analyses of these options indicated that the benefits of these measures (e.g., reduced Dewar surface temperatures) did not justify their added cost and weight impacts.

White paints can provide solar absorptivity-to-emissivity ratios in the range of 0.3 to 0.5 while OSRs and silverized teflon can achieve values below 0.1. For low Earth orbit heat fluxes, this results in average surface temperatures (for the specific case of a nadir-pointed cylinder) ranging from 235 K for white paint to 225 K for the second surface coatings. The savings in helium boiloff for the short duration SFHT missions does not offset the cost and weight associated with OSRs or second surface coatings.

For longer duration storage conditions (e.g., attached to the space station) the SFHT will be parked in an meteoroid protection enclosure that will provide effective shielding from solar inputs. This situation again negates the need for high performance external Dewar surfaces.

Avionics Thermal Control - The high dissipation electronics will be packaged within two thermal control volumes insulated with MLI. Heaters will maintain temperatures above lower limits and a thermal shade will provide temperature control by varying the view to space of the equipment baseplate. The control volumes are designed to 1) allow full power avionics operation in a hot environment with direct solar input to the heat rejection surface, and 2) to minimize heater power in a cold, deep space environment with no external heat fluxes.

Louvers were compared with the thermal shade approach in an analysis which determined heat rejection areas and heater power. The avionics equipment was assumed to operate over the range of -10°C to 45°C. Both devices were assumed to be totally closed at 0°C and to be full open at 27°C. The equipment baseplate was covered with 5-mil silverized teflon.

Figure 6.31 shows the heat rejection area required on each thermal space by the thermal shade and louvers as a function of the equipment temperature. For the purposes of the conceptual design,

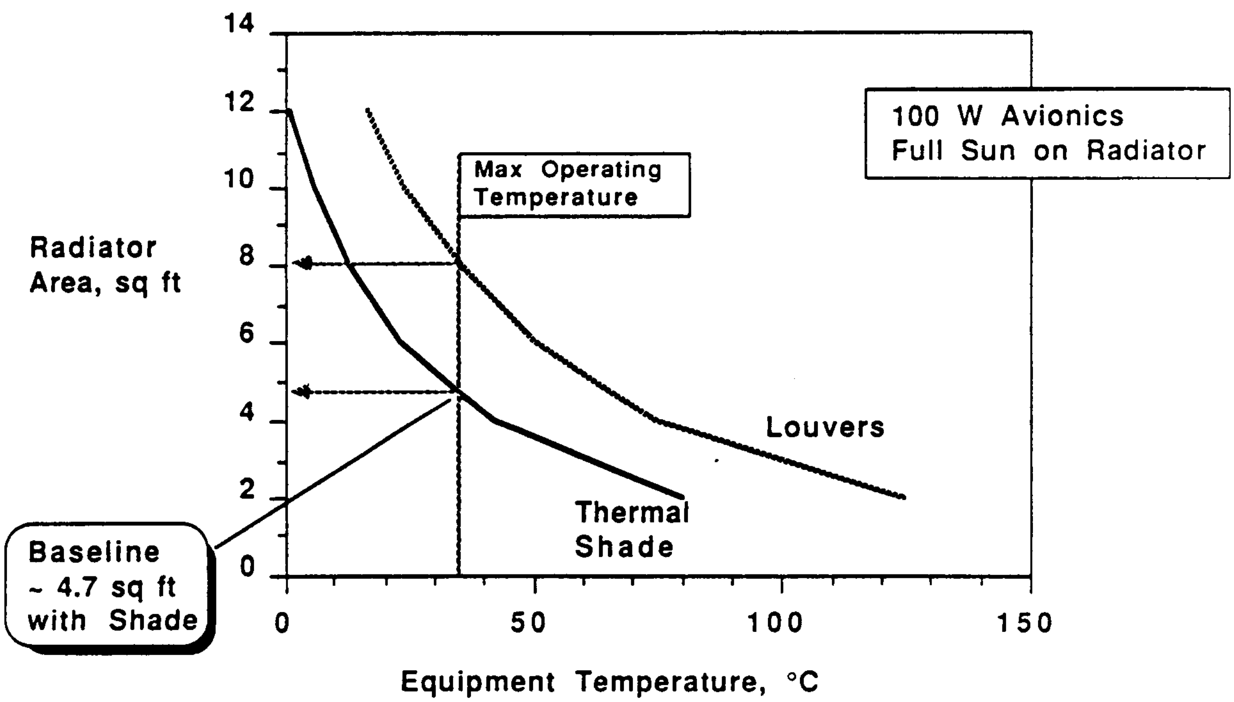


Figure 6.31 Heat Rejection Area Requirement

we have sized the radiator to limit the equipment to 35°C which results in a thermal shade area of 4.7 sq. ft. This area would increase to 8.1 sq. ft. with the louvered approach. Environmental heat fluxes considered in this sizing analysis included full direct solar input and an average of 40 BTU/hr-ft^2 (incident) infrared heat flux.

The analysis also determined the required heater power to maintain the equipment in each space above its lower temperature limit under cold case conditions (e.g., no external heat fluxes and no internal avionics dissipation). The heater power required for each space is 13.5 W with the thermal shades and 25 W with the louvers. Total heater power would then be 27 W for the two spaces with the shade and 50 W for the louvers. This predicted heater power will be reduced directly by any stand-by mode equipment dissipation. A preliminary assessment of this condition indicates the quiescent power would be in the range of 20 W to 40 W, hence there may be no need for heaters with the thermal shade approach.

The above analyses considered orbital environments appropriate for the space shuttle cargo bay and deployed on the OMV. When the SFHT is attached to the Space Station, we have assumed that it will be enclosed in an environmental shroud which provides meteoroid protection. The interior of this shroud must be maintained at -34°C to allow full power operation of the avionics (e.g., 100 W in each avionics space with the thermal shade wide open). Increasing this interior temperature to 0°C would limit the heat rejection rate to an average of 60 W.

The thermal shade has been selected as the preferred approach at this point in the conceptual design, although additional effort is needed to assess cost, reliability and detailed packaging considerations. Two large thermal shades (18 square feet and 12.5 square feet) have been flight-qualified by Martin Marietta on a defense program. Additional development would be required to scale the existing design down to the SFHT requirements. Estimated weight for the two thermal shades is 12 pounds.

Louvers are flight-proven devices with a heritage of high reliability and well understood manufacturing processes. The louvered approach could be easily implemented if the additional area (and mass) can be allocated in the detailed design phase. Estimated weight for the louvers is 16 pounds.

Our analysis indicates that nominal orbiter bay temperatures will range from -73°C to -4°C when the bay is not directly viewing the sun. This is an acceptable environment for all the external elements of the tanker. The two avionics spaces will be located on the tanker structure adjacent to the orbiter doors to maximize the shade's view to space. Electrical heaters and thermostats will be used to maintain minimum allowable temperatures. Since no safety issues are present in the thermal control subsystem, a two-fault system is not required.

<u>External Plumbing</u> - Temperatures of exposed plumbing (valves, vents, lines, etc.) must be controlled to minimize their heat leak. If these components are maintained at 300 K or lower, their heat leak contribution to the 200 K shield is less than 1%. Encapsulating pipes together under a single thermal surface with multilayer insulation will minimize heat gain to the helium tank. White exterior surfaces will minimize temperature due to solar exposure. As mentioned previously, some lines and components will already be covered by foam insulation or a vacuum jacket and thus will not need further temperature control.

<u>Thermal Components</u> - Standard components which are space qualified are available for this design. Film heaters of etched nichrome metal laminated between Kapton film will be used. Mechanical thermostats will be used with an arc surpression circuit on each thermostat to assure long life. The key elements of the insulation used on the two avionics volumes will be comprised of double aluminized Mylar film, Dacron net spacers, filter cloth, Kapton facing, and Gortex Ortho cloth. The Mylar will have an acrylic overcoat to protect the aluminization from water vapor damage which can be experienced during earth atmosphere return. The exterior Gortex Ortho cloth was selected because of its optical properties (a/e = .18/.84) and its toughness. Standard stitching and grounding straps will be used.

The design of the thermal shade is shown in Figure 6.30. The electronic mounting structure is covered with the silverized teflon to maintain a low temperature in a solar environment. The shade is similar to two curtin shades rolled upon each side of the mounting plate. When the plate cools during reduced power modes, a stepper motor pulls the shade closed. The stainless steel shade is highly polished internally which hinders radiation transfer. The shade is pulled further closed with additional reductions in mounting plate temperature. The exterior surface of the curtin is coated with a 1000 angstrom aluminum protected by silicon oxide to limit its temperature in a solar environment. The two rollers are cabled together such that both close equally. The motor control is activated by temperature sensors in the mounting plate.

6.1.6 Avionics Subsystem Design

6.1.6.1 Instrumentation - To properly monitor and maintain the superfluid helium in its desired state, both on the ground and during a refueling operation on orbit, the tanker must provide the capability to accurately monitor the temperature, pressure, and mass of the liquid. To accomplish this the instrumentation baselined for the SHOOT experiment will be baselined for the superfluid helium tanker. The particular sensors identified for the SHOOT experiment provide the accuracy necessary to manage the fluid in storage and during a refueling process as well as providing a proven design concept certified with flight experience.

Temperature measurements will be obtained using Germanium Resistance Thermometers (GRT) and Platinum Resistance Thermometers (PRT). The GRTs provide excellent accuracy in the temperature range of superfluid helium (1.3 K to 2.2 K) and will be used to monitor liquid temperature up to 50 K. To monitor the temperature of subsystems or subelements above 50 K to room temperature (312 K), PRTs will be utilized. Each GRT and PRT will be in a four wire configuration, two wires for excitation and two wires for sensor output. We propose using the Temperature and Pressure Measurement System (TPMS) units developed for the SHOOT experiment to provide the excitation and monitor the sensors. Calibration of the GRTs and PRTs results in accuracies of 1.0 mK below 1.9 K and 5.0 mK above 1.9 K for GRTs, and 4.0 K or better between 50 K and 312 K for PRTs. Accuracies to these levels have been obtained by the SHOOT personnel in lab testing. Excitation will be multiplexed to the GRTs and PRTs to prevent excessive heat input to the liquid. Multiple sensors will be provided to ensure system reliability.

Pressure measurements will be performed with a diaphragm type differential pressure sensor. The diaphragm is of steel construction which allows usage of the pressure sensors in a cryogenic environment. Each pressure sensor will be in a four wire configuration with excitation and sensor monitoring being performed by the TPMS. An AC voltage source will be used for excitation. The AC excitation provides a balanced drive signal to the transducer to reduce the effects of cable characteristics on the transducer signal and to improve the accuracy of the TPMS in monitoring the transducer output signal. Accuracy of the TPMS is expected to be 0.1% of full scale. Multiple pressure sensors will be provided to ensure system reliability.

Liquid mass will be determined by inputting a heat pulse into the helium and monitoring selected GRTs to determine the change in temperature. The rise in temperature is then related to liquid mass through the helium specific heat characteristics. This technique is proven and provides the desired accuracy to know liquid mass; it is being specified by the SHOOT experiment for determining liquid mass. With calibration of the GRTs, accuracies of 3% (SHOOT's goal is 1%) have been obtained in testing by the SHOOT personnel. GRT excitation and monitoring will be via the TPMS units as described for the temperature sensors. For a superfluid helium state, only one GRT is required to determine the liquid mass; to ensure system reliability multiple sensors will be included.

To determine the liquid/vapor level in the Dewar small silicon chips developed by the NASA-GSFC Cryogenics, Propulsion, and Fluid Systems group will be utilized. These silicon chips will be positioned in one of the LAD channels and in the bulk fluid region. The resistance of the chips is markedly different in liquid and in vapor. This resistance variation provides an indication of where the liquid/vapor boundary is when power is applied. Excitation and sensor monitoring will be performed by the TPMS. In a low-g environment He II will leave a film on the sensors, so power will be applied to the sensors for a short time (approximately 50 milliseconds) to burn off the film, followed by a reading of the sensors. If the sensor is in the liquid, heat will be conducted away and the sensor will give a small temperature change indication. If the sensor is in vapor the sensor will indicate a larger temperature change.

Flow measurements will be provided by redundant venturi flow meters. Each flow meter contains two differential pressure sensors for determining the pressure drop within the meter, a low range sensor (0-0.125 pisd) for flow rates of 25 l/hr to 200 l/hr and a high range sensor (0-2.0 psid) for flow rates of 200 l/hr to 1000 l/hr. The rate of liquid flow through the meter is then correlated to the pressure drop. Excitation and monitoring of the flow meter pressure sensors will be via the TPMS, as described for the pressure sensors. The SHOOT experiment has flow rates of 25 l/hr to 800 l/hr and is using a 1.25 psid pressure sensor for the high range end. For SFHT a different sensor with a larger differential pressure span will be required to accommodate flow rates up to 1000 l/hr.

A list of instrumentation within the tanker fluid system is provided in Table 6.11; Figure 6.32 indicates sensor position.

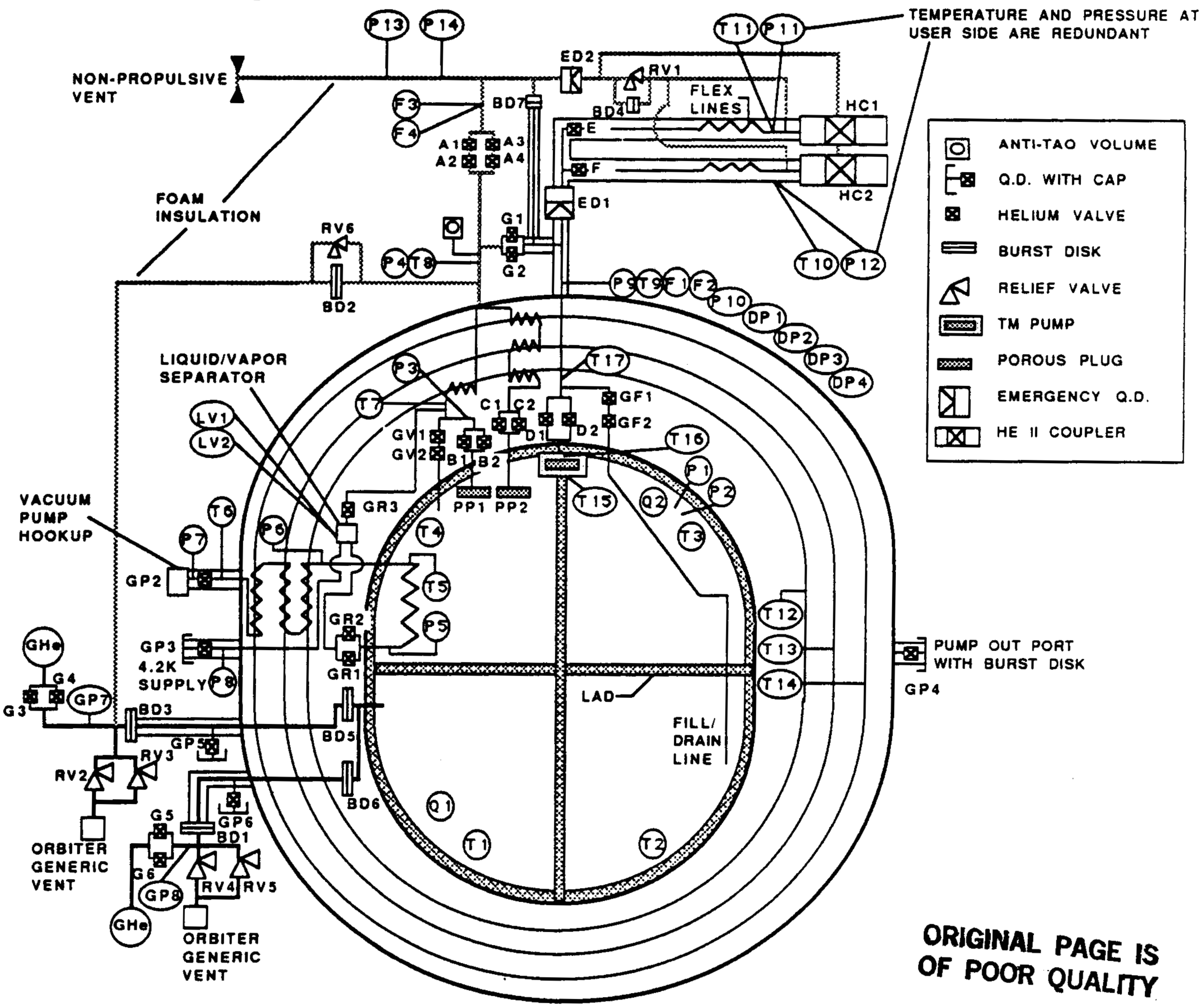


Figure 6.32 Baseline SFHT Dewar Schematic Showing Instrumentation

Table 6.11 SFHT Instrumentation

MEAS. ID	MEASURES	RANGE	SAMPLE RATE	FUNCTION	REMARKS
P1	Tank Press	0-100 Torr	.1/sec	On-Orbit tank pressure	redundant if necessary
P2	Tank Press	0-3 ATM	.1/sec	tank press during gnd/launch ops	redundant if necessary
P3	Phase separator, down stream pressure	0-20 Torr	.1/sec	monitor vent phase separator ops	
P4	VCS exit pressure	0-20 Torr	1/sec	monitor TVS ops	
P5	Ground refrig tank Hx pressure	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P6	Inlet to gnd refrig VCS	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	
P7	gnd refrig exhaust press	0-20 Torr	1/sec	used during fill, conditioning & gnd hold	.
P8	Gnd refrig line supply pressure	0-3 ATM	1/sec	used during fill, conditioning & gnd hold	
P9	fill/drain line press	0-3 Torr	1/sec	used during fill, conditioning, gnd hold, & xfer	(monitor locked-up volume)(may need dual range for xfer)
P10	fill/drain line press	TBD	TBD	monitor locked-up	if required
P11	press in trapped volume (flex line-to-spacecratf)	TBD	TBD		if required
P12	press in trapped volume (flex line-to-spacecratf)	TBD	TBD		if required
P13	overboard vent pressure	0-200 PSI	1/sec	monitor xfer operations	
P14	overboard vent pressure	0-200 PSI	1/sec	monitor xfer operations	redundant sensor
DP 1	pressure drop in F1	0-2.0 psid	1/sec	monitor xfer operations	
DP 2	pressure drop in F1	0-0.125 psid	1/sec	monitor xfer operations	
DP 3	pressure drop in F1	0-2.0 psid	1/sec	monitor xfer operations	
DP 4	pressure drop in F1	0-0.125 psid	1/sec	monitor xfer operations	
T1-T4	internal tank temps	0-5K	1/sec	monitor He temp during gnd & flight ops	
T5	gnd tank Hx exit temp	0-5K	1/sec	monitor loads cooldn & gnd hold operations	
T6	gnd refrig VCS exit temperature	100-300K	1/sec		
T7	VCS inlet temperature	100-300K	1/sec	monitor TVS/VCS performance	
T8	VCS exit temperature	200-300K	1/sec	monitor TVS/VCS performance	
T9	transfer line temp	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T10	temp at disconnect	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T11	temp at disconnect	0-5K/ 0-300K	1/sec	monitor chilldn/ transfer temp	
T12	VCS #1 temp	0-100K/tbd	.1/sec		
T13	VCS #2 temp	0-200K/tbd	1/sec	monitor VCS perform	redundancy as req-tbd
T14	VCS #3 temp	100-300K	1/sec	monitor VCS perform	redundancy as req-tbd
T15	FEP inlet temp	0-5K	1/sec	monitor pump pressure	
T16	FEP outlet temp	0-10K	1/sec	monitor pump pressure	
T17	transfer line temperature	0-5/0-300K	1/sec	mont chilldn/xfer temp	redundancy
Q1	quantity of SFHe in tank	0-1000Kg	1/sec	tank gauge	
Q2	quantity of SFHe in tank	0-1000Kg	1/sec	tank gauge	redundancy-if required
V1	FEP heater voltage	0-30VDC	1/sec		HLVS data
V2	FEP heater voltage	0-30VDC	1/sec		HLVS data
I1	FEP heater current	0-1.44 Amp	1/sec		HLVS data
I2	FEP heater current	0-1.44 Amp	1/sec		HLVS data
F1	transfer flow rate	TBD	1/sec	monitor xfer operations	venturi flowmeter
F2	transfer flow rate	TBD	1/sec	monitor xfer operations	venturi flowmeter
F3	overboard vent flow rate	TBD	1/sec	monitor vent system operations - backup to mass gauge	
F4	overboard vent flow rate	TBD	1/sec	monitor vent system operations - backup to mass gauge	redundancy

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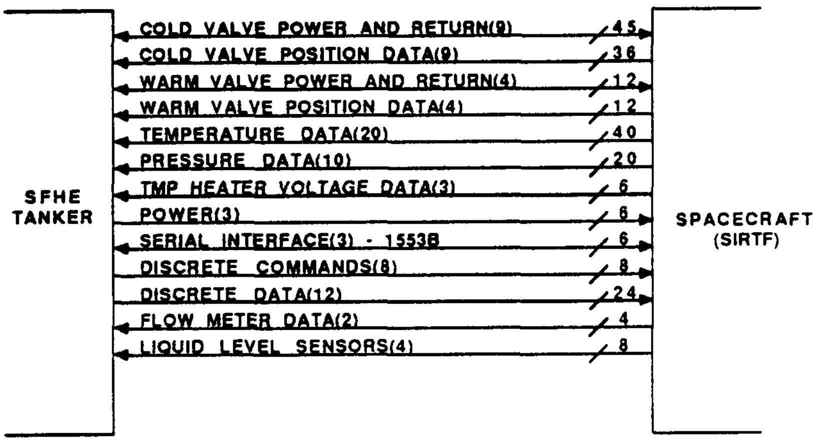
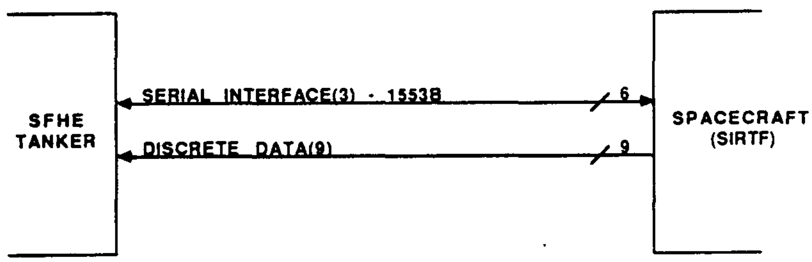
6.1.6.2 Tanker Avionics Subsystem - The SFHT avionics subsystem is designed to provide the capability to command, control, and monitor the SFHT during a superfluid helium resupply mission. The design requirements as referenced from the System Requirements Document are as follows:

a) Provide electrical interfaces to the receiving satellite and to the Orbiter. These interfaces include power, command, and control and monitoring,
b) Provide power distribution, control, and monitoring for both SFHT and the satellite,
c) Provide valve control and monitoring for both SFHT and the satellite,
d) Provide control and monitoring of mechanisms associated with berthing and emergency separation,
e) Provide instrumentation as required to operate and monitor SFHT,
f) Provide signal conditioning of SFHT and satellite data,
g) Provide the man-machine interface for crew control of the resupply operation, from the Aft Flight Deck of the Orbiter. The man-machine interface includes provisions for operator inputs, alphanumeric and graphic displays of SFHT and satellite data, and caution and warning data displays and annunciation.

The interface to a satellite will provide the capability to monitor and control the satellite in a powered-up or powered-down condition. Figure 6.33 shows interfaces configured for the SIRTF satellite. The interfaces were discussed with the AMES Research Center personnel working SIRTF. If SIRTF is in a powered-down condition the interface provides power, commands, and monitoring of the SIRTF. Power to the satellite will be 250 watts maximum, DC,



a) Spacecraft Interface with SFHT Providing Power and Control



b) Simplified Spacecraft Interface with SFHT

Figure 6.33 SFHT-Spacecraft Interface with SFHT switch-controlled by the crew in the AFD. The amount of power was sized to meet what was considered an average power requirement for a limited number of functions on the satellite side of the interface; this is consistent with what the OSCRS tanker considered for its satellite interface. Discrete commands, bilevel monitors and analog monitors are provided to control and monitor a limited number of satellite functions. The TPMS and HLVS will provide the control and monitoring of valves and sensors that are compatible with the TPMS and HLVS interfaces. Any other commands and/or monitoring requirements will be meet by the tanker subsystem. The AFD subsystem used to control and monitor the tanker subsystem will be used to control and monitor the satellite. Command actuation will be a two stage process with caution and warning being available for a limited number of parameters. A serial link (1553B) is available to the satellite if the satellite wants the capability to transmit all system status to the tanker instead of being limited to a few monitoring channels.

In a powered-up condition the satellite avionics is operational and all communication between the tanker and the satellite occurs through the 1553B serial interface. The tanker will transmit commands to the satellite control system, which will control its own subsystems. Monitored satellite data will be collected by the satellite and transmitted to the tanker to be processed and displayed on the AFD displays. No power will be provided to the satellite.

Simplifying the interface between the tanker and the satellite can be accomplished by requiring that: 1) the satellite operate off its own power source, and 2) the satellite provide control of its own fluid subelements. Figure 6.33 also shows the simplified tanker-to-satellite interface. All interaction between the tanker and the satellite will be via the serial interface (1553), with no discrete commands. Commands to the satellite can be uplinked or stored within the AFD CPUs memory with the crew initiating all commands from the AFD. Data is collected by the satellite and transmitted to the AFD subsystem for processing and/or downlinked to the ground. In this simplified approach the command and monitoring interface is less complex and wire count is reduced. The AFD CPUs will verify all satellite-bound commands to ensure mission success and safety. The tanker CPUs will remain transparent to satellite-bound commands. The discrete data in the interface is required to determine proper mating of the electrical connectors in the tanker-to-satellite interface. This simplified SFHT-to-satellite interface is just one of many possible interfaces. The interface needs to provide flexibility but not introduce changes to the avionics to accommodate every satellite. Interface standardization is an important need between the superfluid helium users and the SFHT developer.

The SFHT avionics, which will meet this diverse range of user requirements, can be divided into two sections, AFD subsystem and Tanker (cargo bay) subsystem. Figure 6.34 shows a block diagram for the SFHT flight system, assuming that we retain much of the redundancy and fault tolerance put into the OSCRS avionics design.

The AFD subsystem provides the man-machine interface for crew monitoring and control of the resupply operation. The subsystem is triple redundant and provides two fault tolerance to commanding and monitoring SFHT and the satellite. The control of the SFHT and the display of data is performed on flat panel color displays with touch-screen command capability. An overlay film (resistive, capacitive, or LED-matrix) on the surface of the display provides the touch-screen capability. The crew will control the resupply process by actuating commands from software generated graphics shown on the displays. Each CPU, hardwired to a dedicated display, will monitor and process signals from the displays and transmit the appropriate command or commands to the tanker subsystem through a dedicated serial interface (RS422). To prevent inadvertent valve operations by the crew, command actuation will be a two stage process (validate/correct) before transmitting the command to the tanker.

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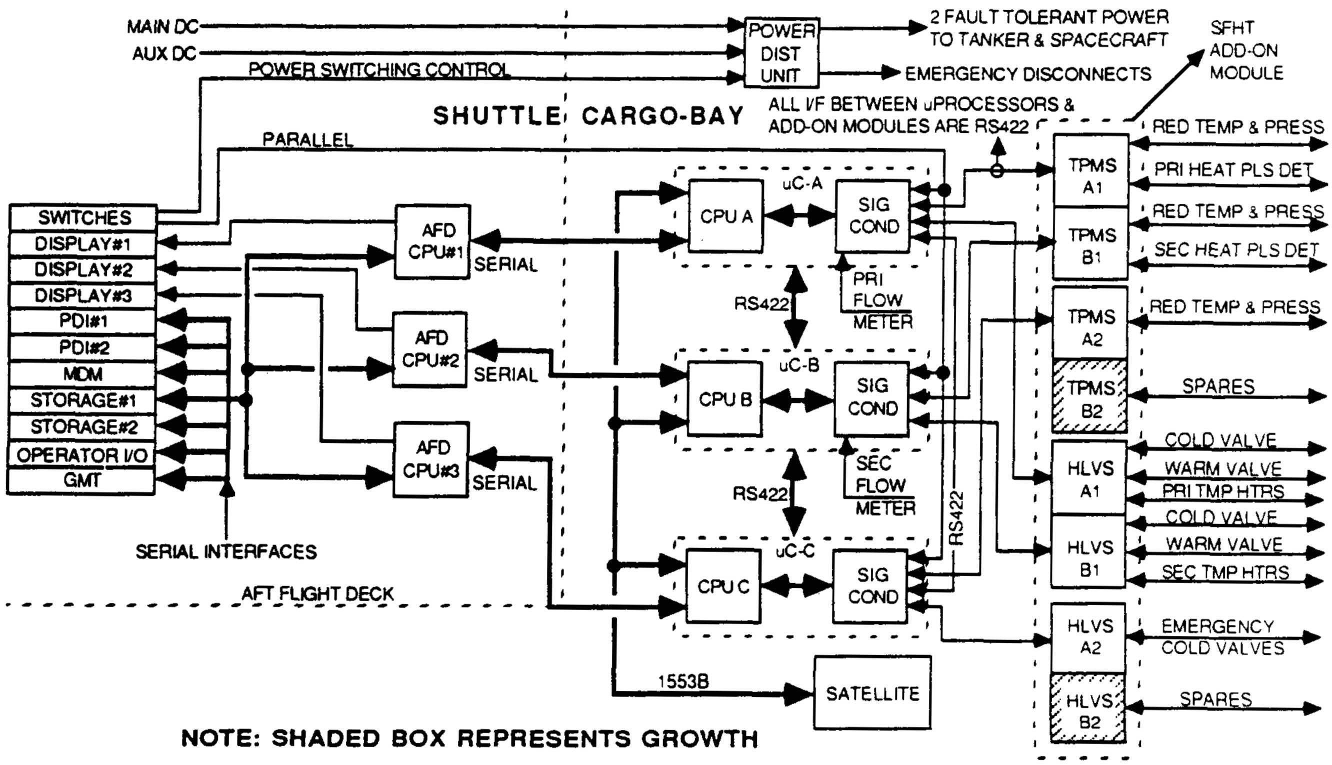

Figure 6.34 SFHT Avionics System Diagram Assuming Maximum Commonality with OSCRS Avionics

Monitoring of SFHT and satellite data, and providing the information to the crew, will be controlled by the CPUs. The CPUs acquire data from the tanker subsystem through the serial interface, and process the data and control the display of data on the three flat panel displays. Since each display is controlled by a dedicated CPU, data displayed on a given screen can be the same or independent of data displayed on the other screens. Interconnections will exist between the CPUs for sharing of SFHT and satellite data, and CPU housekeeping data. This provides the capability to warn the crew of a CPU malfunction if one of the CPUs is having difficulty. The crew can then take the necessary action to correct the problem or shut down the problem CPU. Caution and warning will be provided for selected tanker and satellite parameters. The CPUs will compare monitored parameters to set points stored in memory. These set points will indicate when a parameter is approaching an out-of-limit condition and/or is actually out-of-limits. A visual warning will be shown on the display screens indicating to the crew the problem parameter(s) and, if required, procedures to correct the problem. The touch-screen displays will also provide the capability for the crew to review and change, delete or add set points on parameters any time during a mission.

Orbiter interfaces required by the AFD subsystem are the Payload Data Interleaver (PDI) and the Multiplexer Demultiplexer (MDM). The PDI will be utilized for downlinking data. Two channels are required, a primary channel for real time data and a secondary channel for stored data. During a lose-of-signal to the ground monitoring station, SFHT and satellite data will be recorded. When the signal to Earth is restored all stored data will be transmitted via the secondary channel. This is required so that real time data is not compromised when transmitting stored data. The MDM interface provides an optional interface to the Orbiter General Purpose Computer (GPC) as well as a path for downlinking data if the link to the PDI fails. The link to the MDM is via the serial I/O channel. Due to the interface constraints on a payload by the Shuttle, two of the AFD CPUs will interface to the PDI with the third CPU interfacing to the MDM. Mass storage will be provided in the event of loss-of-signal to the ground by the Orbiter or TDRSS. Two storage devices are provided for redundancy, each with the capability to hold up to 400 megabytes of data. Control will be via one of the three CPUs.

Part of the AFD subsystem is a switch panel that will be used in place of the Orbiter Standard Switch Panel. This panel will provide switches for control of elements in both the AFD subsystem and the tanker cargo bay subsystem. Figure 6.35 shows the panel concept used for OSCRS. For the SFHT the safing circuit control and the switches for the control of heaters would not be required. The numeric keypad and the track ball would be operator I/O devices for control of the cursor on the small display, and for inputting commands. The small display would be used for limited control and monitoring of SFHT in the event of a power problem where the available power level was limited and the AFD subsystem needed to reduce the power load on the Orbiter.

Power to the AFD subsystem will be two-fault tolerant. Power sources are main Orbiter power for mission success, Auxiliary power for mission safety, and battery backup in the event of Loss-of-Service from the Orbiter. The battery is required to provide the crew the capability to control the actuation of tanker pyrotechnic devices to activate the emergency disconnect to ensure satellite-to-tanker separation. Table 6.12 gives a list of power requirements, and weight and dimensions for the AFD avionics.

Table 6.12 SFHT AFD Avionics Power, Configuration and Weight Summary

Item	Avg. Power (Watts)	Peak Power (Watts)	Weight	Dimensions (Cubic Inches)
Computer	150	213	40	2808
Display (3)	15	15	15	427.5
Mass Storage	24	24	10.4	300
Total	189	252	65.4	3535.5

The tanker cargo bay subsystem provides the control and monitoring interface to the tanker subsystems and the satellite. The cargo bay subsystem is triple redundant and provides two-fault tolerance to commanding and monitoring the satellite and safety critical subelements within the tanker. The tanker avionics will be single-fault tolerant to ensure mission success. As was shown in Figure 6.34, each tanker CPU has a dedicated interface to an AFD CPU for command and data interactions. The signal conditioning portion of the CPU handles the acquisition of data with the other tanker subelements and the satellite. Interfacing will exist between the CPUs for sharing of SFHT and satellite data, and CPU housekeeping data. This provides the capability to warn the crew of a CPU malfunction.

Control and monitoring of the tanker valves and sensors will be performed by electronic units developed for the SHOOT experiment. The Temperature and Pressure Measurement System (TPMS) will provide excitation, monitoring and data processing for the temperature and pressure sensors within the tanker and satellite fluid system. The Heater, Level Detector, Valve Control System (HLVS) will provide control and data monitoring for valves and heaters. The TPMS and HLVS require a RS422 interface in order to communicate with the tanker avionics. The tanker avionics can support the RS422 interface but due to the number of RS422 interfaces per card (3) presently in each CPU an extra card will need to be added to each tanker CPU to accommodate the extra interface needs. Figures 6.36 and 6.37 show block diagrams for the TPMS and the HLVS, respectively. Each unit is single-fault tolerant internally. For the TPMS, one-half is

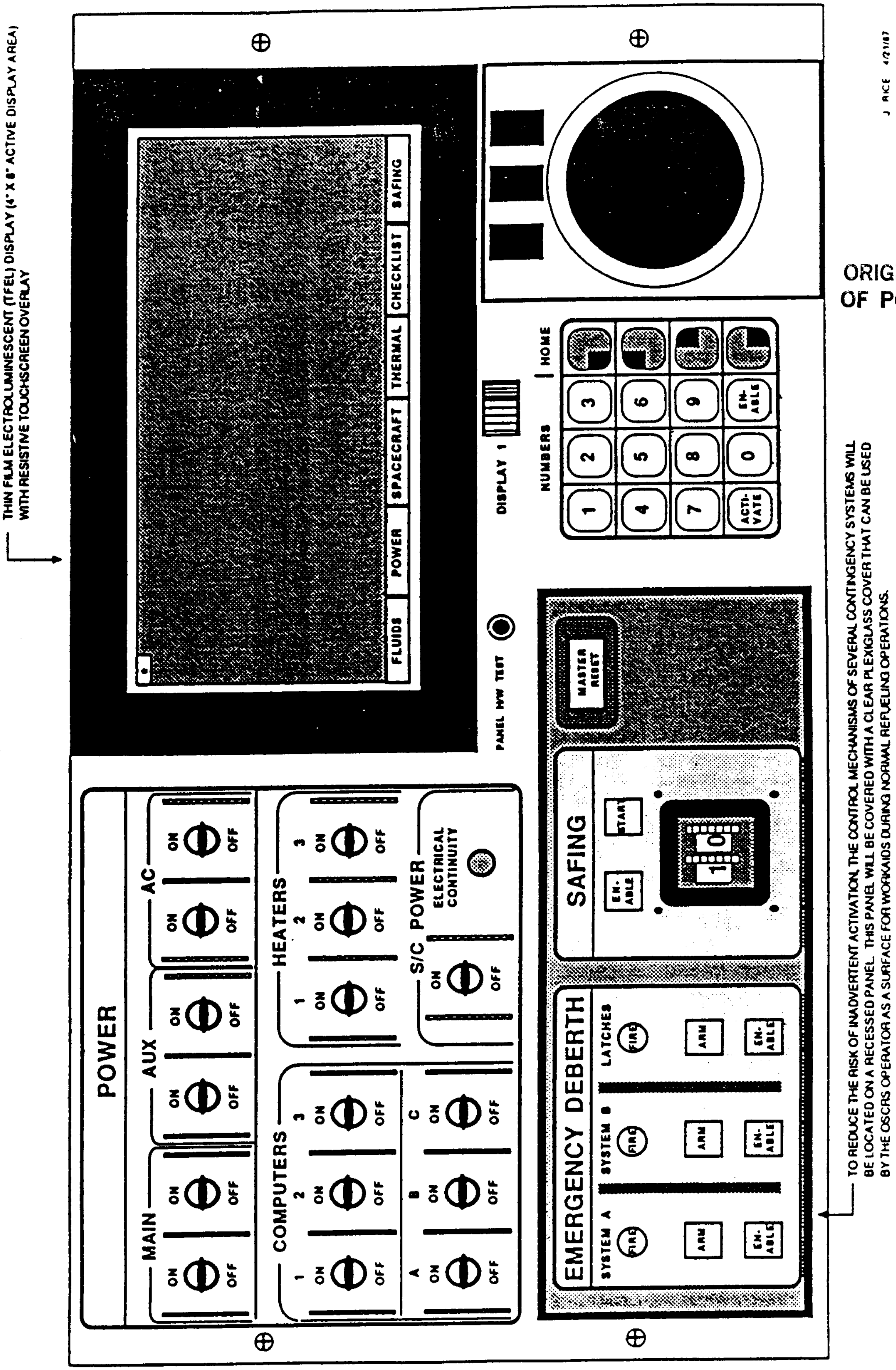

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Figure 6.35 Hardwired Panel for AFD Control and Display

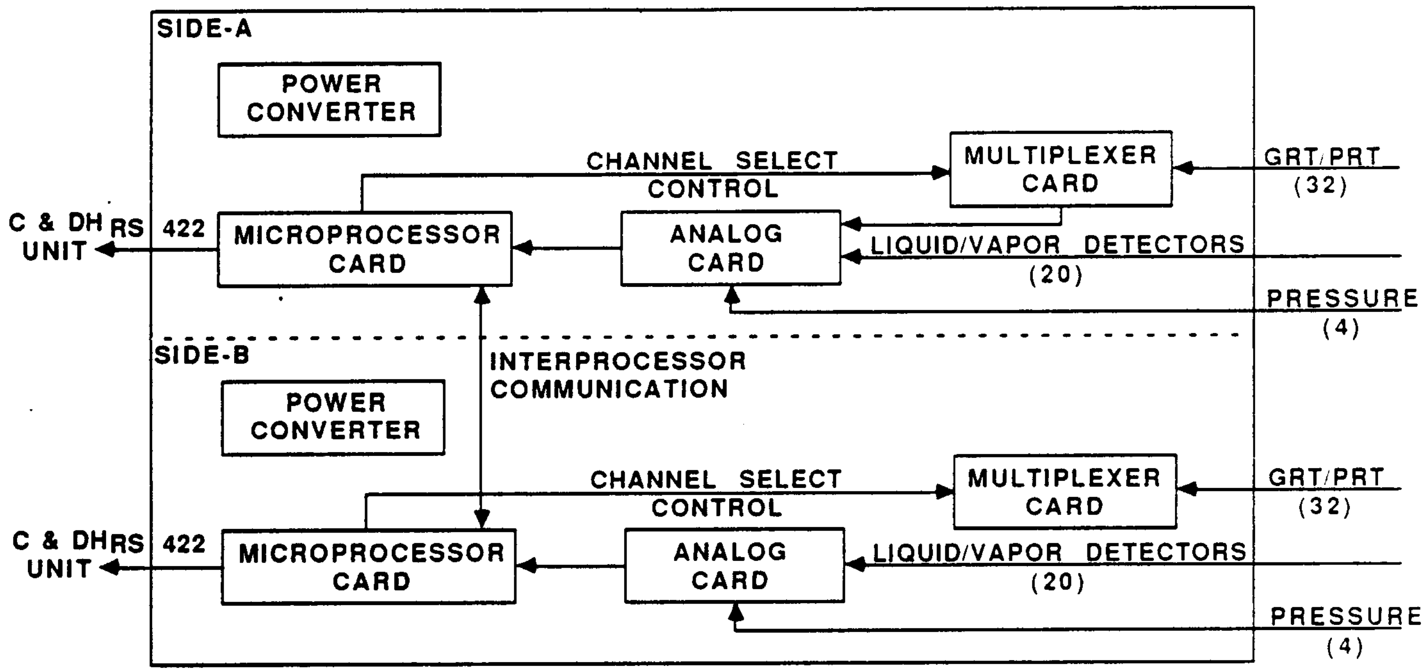


Figure 6.36 TPMS Block Diagram (Reference 6.10)

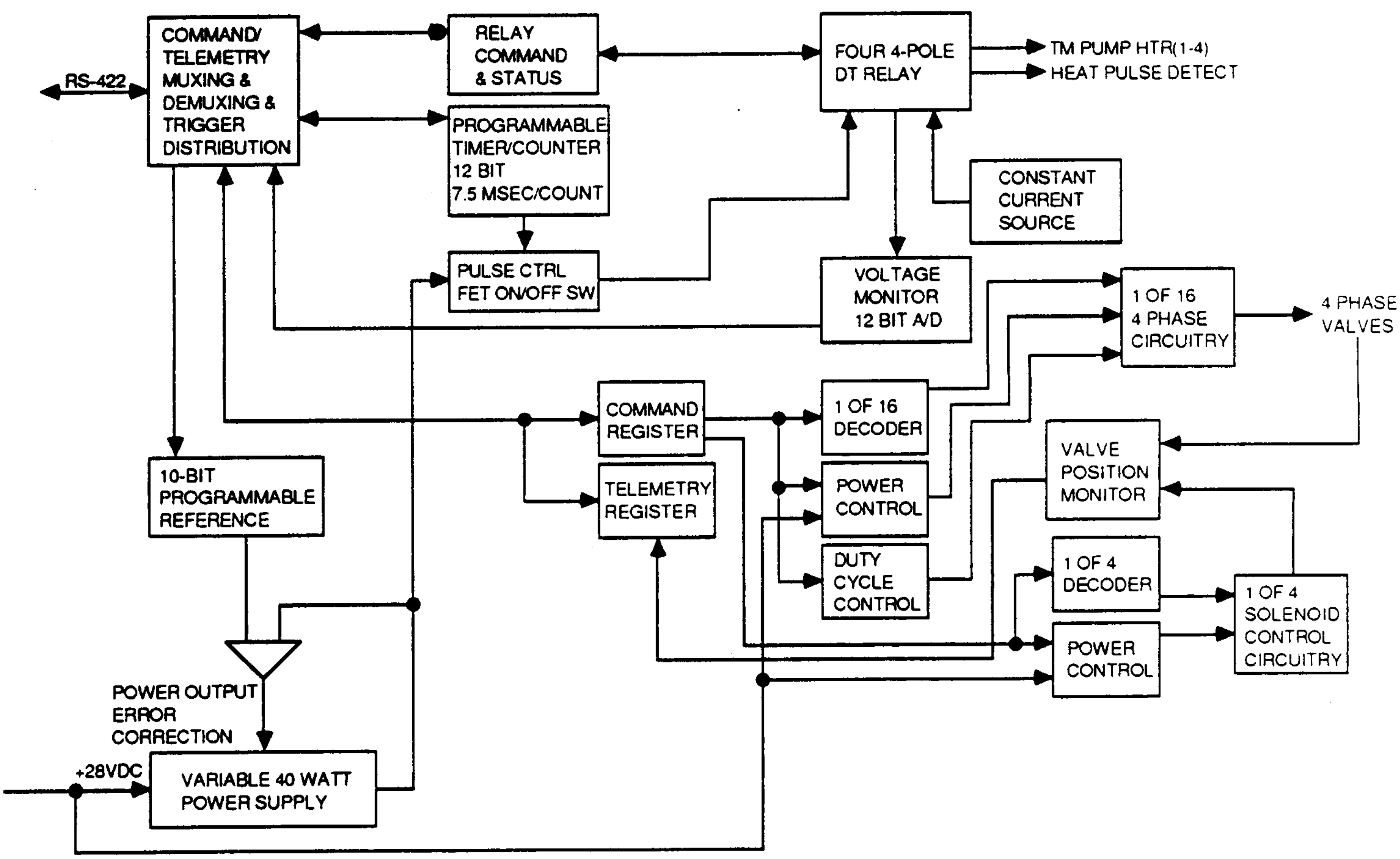


Figure 6.37 HLVS Block Diagram (Reference 6.10)

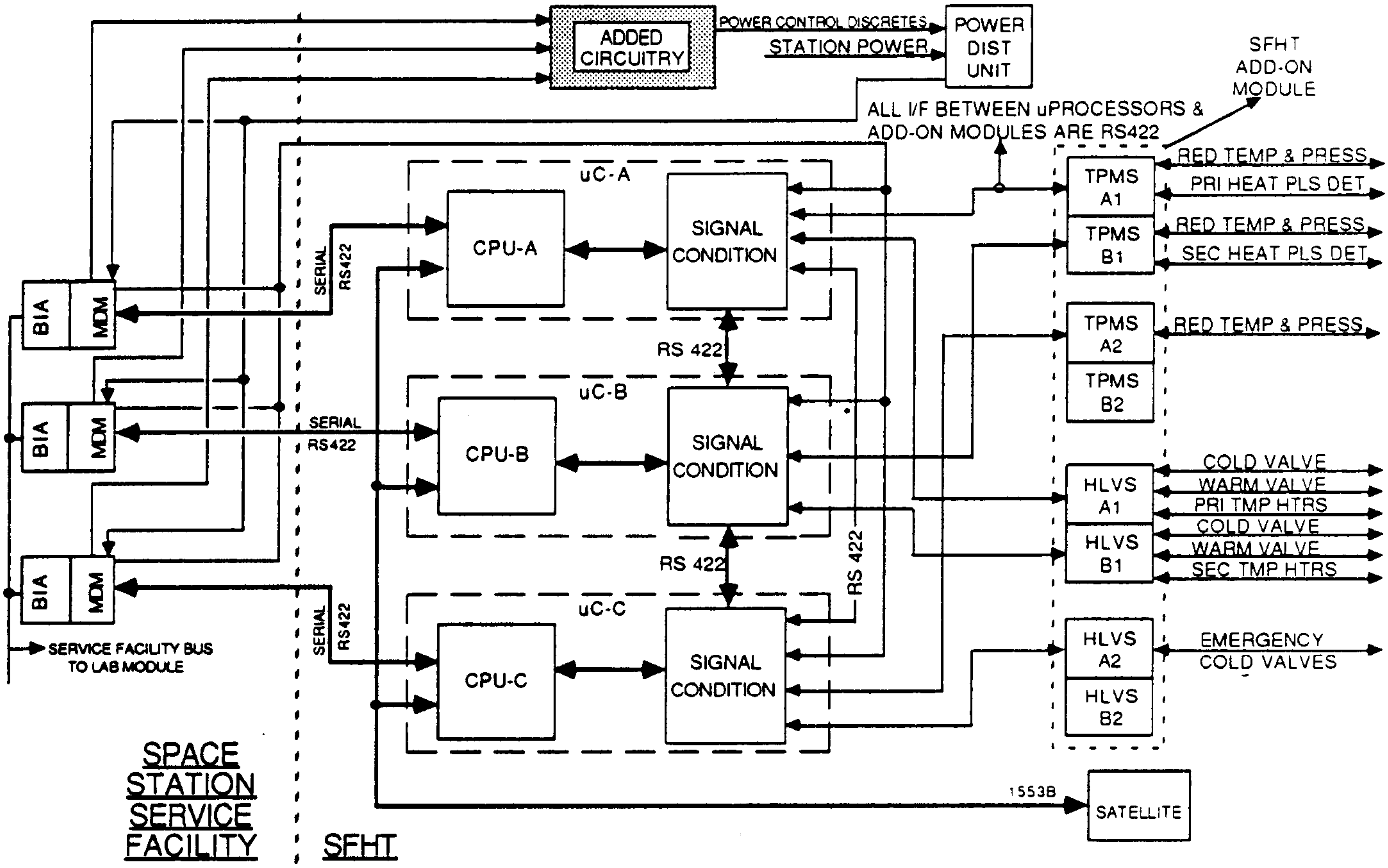
called the master and the other half slave. The side selected as master is determined at power-up. Both the master and slave sides are powered-on, with each side having an independent interface to one of the tanker CPUs and monitoring a unique set of temperature and pressure sensors. The master side communicates with its CPU and to the salve side. The slave side communicates with its CPU only after a failure of the master side. A failure of the master side that inhibits it from communicating with the tanker CPUs or acquiring sensor data will require that the crew shut down the master and designate the slave as master by issuing a command. Any other failure may not require a change over of sides or temporary loss of operation. Any change over in sides will interrupt the flow of sensor data from the problem TPMS unit until the slave side is activated. The failure within one TPMS unit will not inhibit the performance of the second TPMS from providing sensor data. If a failure occurs to the master side of both TPMS units, then a total loss of insight from sensor data occurs until a slave side is activated. For the HLVS, only one-half of each HLVS unit is powered up at a time. Each side has an independent interface to one of the tanker CPUs and controls both cold and warm valves. Depending on the failure within the operating side (failure to communicate with the tanker CPUs) the crew may be required to power-off the problem side and activate the backup side. This change in sides will cause a temporary loss of control of the valves. If the failure (loss of control of a valve) does not constitute a change in valve position, then there is no loss of HLVS functions or operations. During the Phase B design study, this issue should be addressed in greater detail and appropriate modifications or additions to the design identified.

Power to the tanker cargo bay subsystem will meet the same requirements as for the AFD subsystem; main Orbiter power for mission success, Auxiliary power for mission safety, and battery backup for Loss-of-Service. Table 6.13 gives a list of power requirements, and weight and dimensions for the SFHT cargo bay avionics.

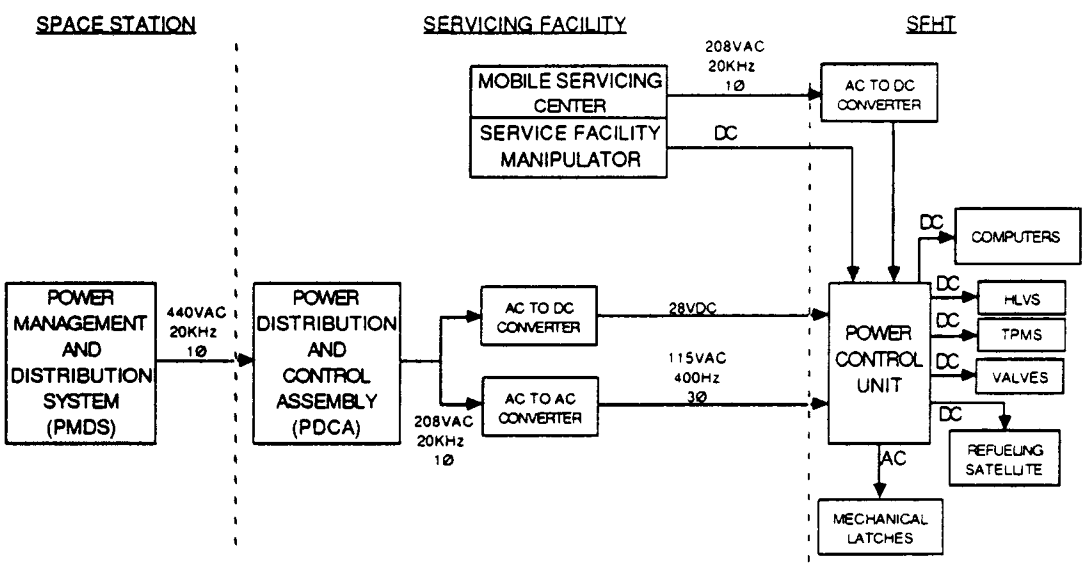
Table 6.13 SFHT Cargo Bay Avionics Power, Configuration and Weight Summary

Item	Avg. Power (Watts)	Peak Power (Watts)	Weight	Dimensions (Cubic Inches)
Computer	60	180	63	3959
Power Distribution Unit	6	15	26	1620
TPMS	50	50	60	1568
HLVS	60	240	200	5888
Thermomechanical Pump	40	40	TBD	TBD
Mass Gauging	40	40	TBD	TBD
Valves	--	14	TBD	TBD
Battery	--	--	16	240
Total	256	579	365	13275

6.1.6.3 SFHT-Space Station/OMV Interfaces - In addition to the interfaces with the Orbiter, the tanker must provide the capability of mating to Space Station (truss or MRMS) for commands, data handling, and power. This requires that the electrical interface between SFHT and Space Station meet the same fault tolerance and be capable of emulating or matching the same interface between SFHT and the Orbiter, but with minimum impact to the SFHT avionics. Figure 6.38 shows a block diagram of the power, command and data handling interface to Space Station. The



a) COMMAND AND DATA HANDLING



b) POWER

Figure 6.38 SFHT-Space Station Avionics Interface electrical characteristics for the power, command and data handling interface have not been defined at this time. For command and data handling at a truss interface, Space Station provides an interface capable of mating with SFHT without changes to the avionics. The interface meets SFHT two-fault tolerance requirements and provides the same serial link (RS422) that SFHT had with the Orbiter. For control of the tanker and the satellite, Space Station will have the provisions to replicate the functions of the Orbiter AFD subsystem, including touch-screens for control and display of data with a computer system capable of running Space Station-provided software or the software that was used for the Orbiter AFD subsystem. For power at a truss interface, Space Station will provide the capability of meeting SFHT fault tolerance and power requirements. Main Station power is 208VAC, 20kHz, single-phase. Equipment required to provide SFHT with the proper DC and AC voltage levels will be provided by Space Station. Added circuitry will be required by the Power Distribution Unit to allow control of SFHT power by Space Station discrete commands.

When interfacing to the MRMS an electrical interface will be required if a satellite is to be refueled while SFHT is attached. Command and data handling provisions are the same as those at the truss, using an RS422 serial link. The MRMS power provisions are the same as main Station power, 208VAC, 20kHz, single-phase. The `SFHT will need to provide power converters on its side of the interface in order to get the required DC and AC power levels.

If the SFHT were to be quasi-permanently based at Space Station, several options exist for basing the avionics subsystem on Space Station. The block diagram of the basic SFHT avionics was used as a reference with two variations considered as shown in Figure 6.39. The line marked "option 1" is for SFHT to have all avionics on SFHT, and Space Station to provide the functions that were provided by SFHT AFD equipment aboard the Orbiter. For this option the only change required to SFHT would be to the input circuitry in the Power Distribution Unit (PDU) for power switching control. The input circuitry was designed for interfacing to hardwire switches. Since Space Station will not provide any hardwire switch capability, changes to the PDU interface to replace the switch control will be required to accommodate MDM discrete commands. This could be a permanent change, eliminating some hardwire switches from the AFD design. For option 2 the tanker CPU and signal conditioner units would be moved to Space Station. For this option to work two changes would have to made to the SFHT avionics: 1) an interface unit would have to be designed that would allow the avionics left on the SFHT to communicate with the Orbiter when in flight as well as communicating with Space Station when based there and, 2) the PDU would have to be split in two parts, one part required to interface to the Orbiter to provide power to the SFHT avionics, another part required to interface to Space Station to provide power to the Station-based SFHT avionics.

Basing the SFHT at Space Station requires that total avionics capability as previously defined for the Orbiter-based SFHT be provided to accomplish a resupply mission. While in transit in the Orbiter to the Space Station, the SFHT will not perform a resupply; the SFHT need only be capable of providing health and status data to the crew. Either option previously illustrated will permit the on-orbit resupply. Option 1 carries the most avionics weight, and this translates into significantly greater costs for repeated launches. Option 2 carries a complete avionics package for the initial launch but the avionics can be configured as individual ORUs and some of these units can be installed at Space Station at a location that meets the avionics thermal requirements. A weight and cost savings is thus achieved for successive launches to Space Station with option 2. A very attractive feature of the Space Station interface would be the availability of an Embedded Data Processor (EDP) that could be used to replace the SFHT CPUs for applications where the SFHT avionics are Station-based. Figure 6.40 shows what the SFHT-to-Space Station interface would be using the EDP and dividing the SFHT avionics. The TPMS will stay on the SFHT for monitoring fluid data, and providing the data to the crew when in the Orbiter and to the Station when docked. The HLVS will be located at Space Station to provide the control interface for the SFHT.

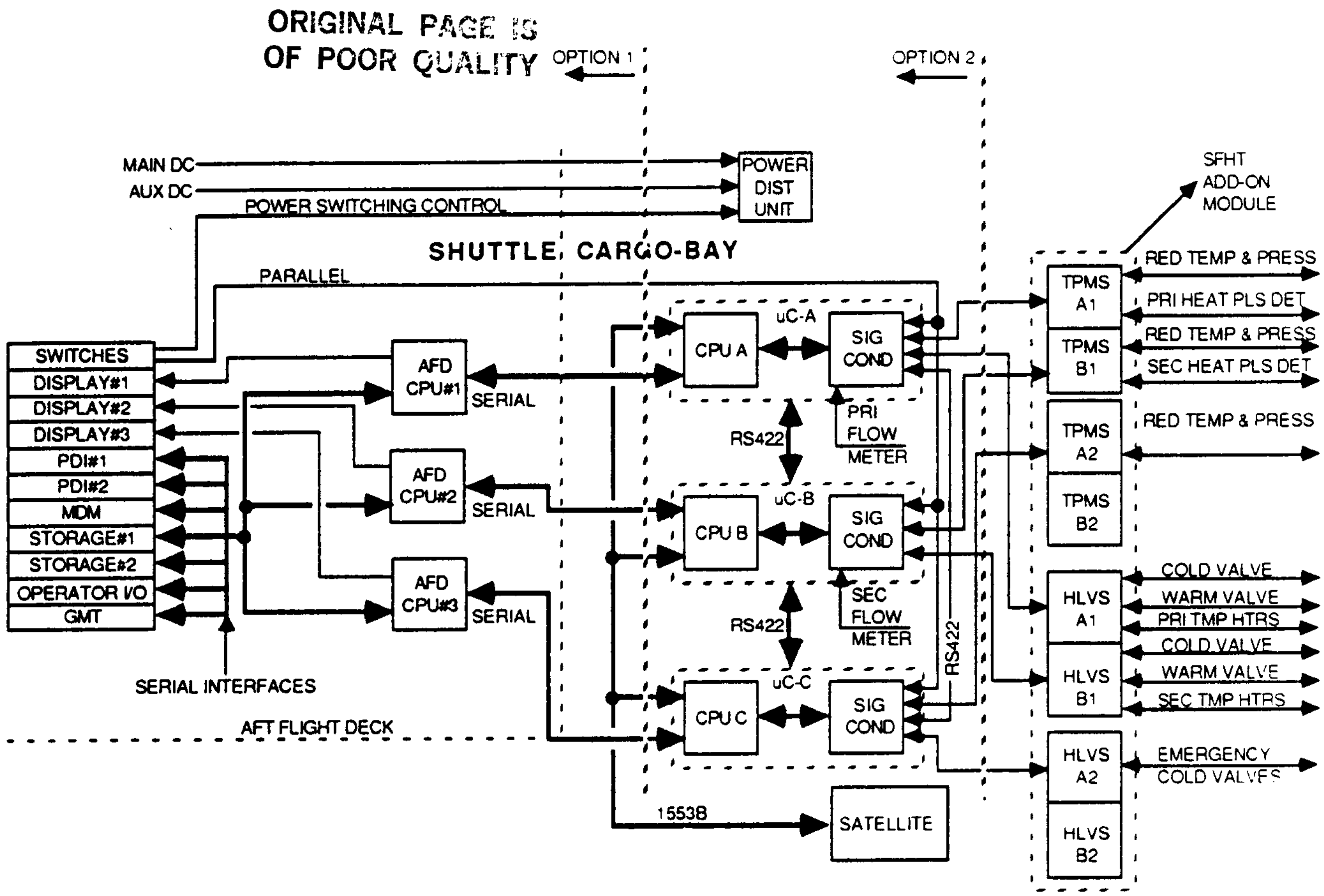


Figure 6.39 Options for Basing Some SFHT Avionics at Space Station

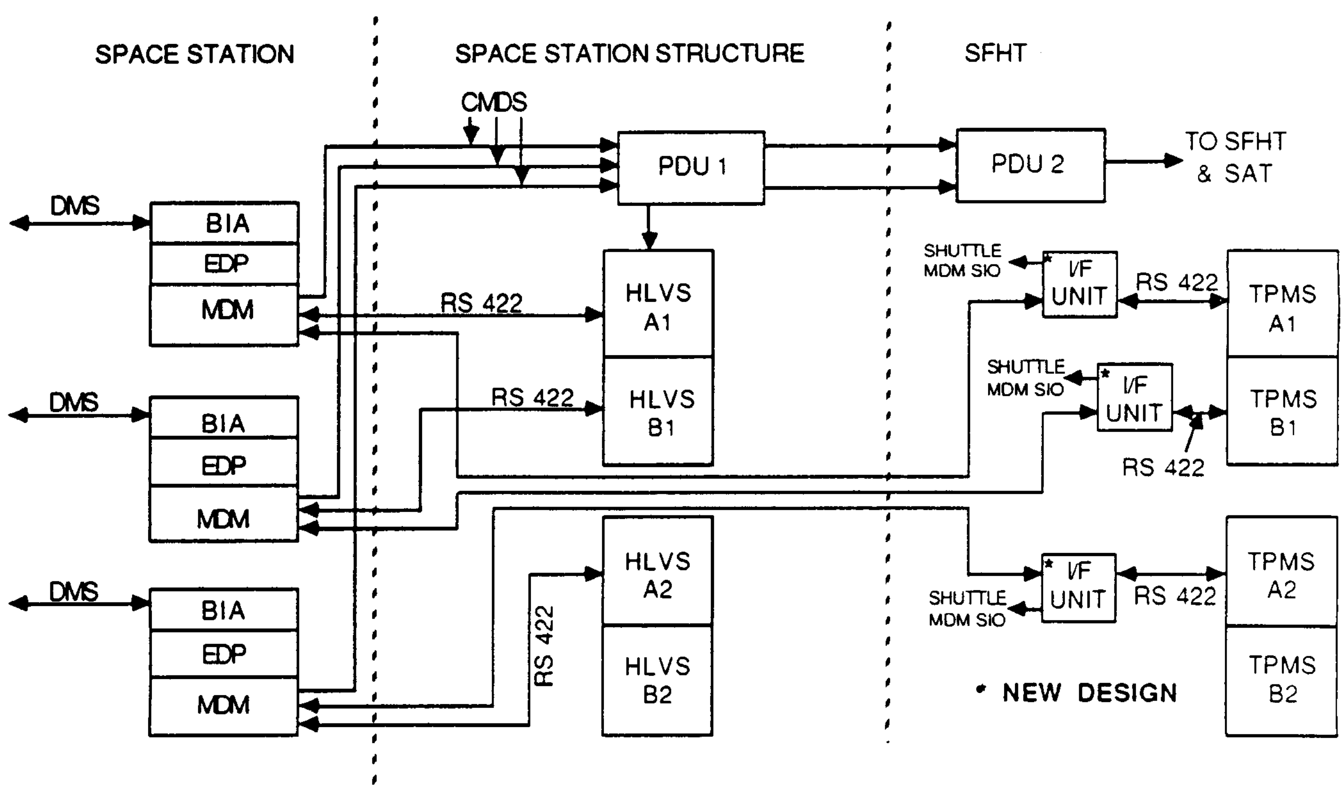


Figure 6.40 SFHT-to-Space Station Interface Using an Embedded Data Processor

The SFHT requirements for interfacing to the OMV for power, command and data handling are the same as those when interfacing to the Orbiter or Space Station. Due to the uniqueness of the OMV interface, an OMV-dedicated interface will be required by SFHT. Figure 6.41 shows a block diagram of the SFHT-to-OMV interface. OMV-provided power to an attached user is single-fault tolerant. Power will be DC, 1kwatt continuous peak for 5 hours, controlled by the OMV with power protection being provided by the tanker. Extra power is possible with the addition of a battery kit; providing 56.3 kWhr at 1.8 kW continuous peak power. Command and data handling provisions from OMV are provided by two interfaces, each single-fault tolerant. These are the Command and Telemetry Data Bus (C&TDB) and the Serial Command and Telemetry Bus (SC&TB). To meet two-fault tolerance requirements, the SFHT will need to connect to both interfaces.

The SC&TB has a serial interface only, with no discrete commands, nor bilevel or analog monitoring. The type of serial interface (RS422, 1553B, etc.) provided is TBD. The C&TDB provides a serial interface, discrete commands, and bilevel and analog monitoring capability. The interface characteristics are TBD. For the SFHT to interface to the C&TDB, Remote Units (RU) will be required by SFHT avionics. This will add weight and cost to the tanker avionics.

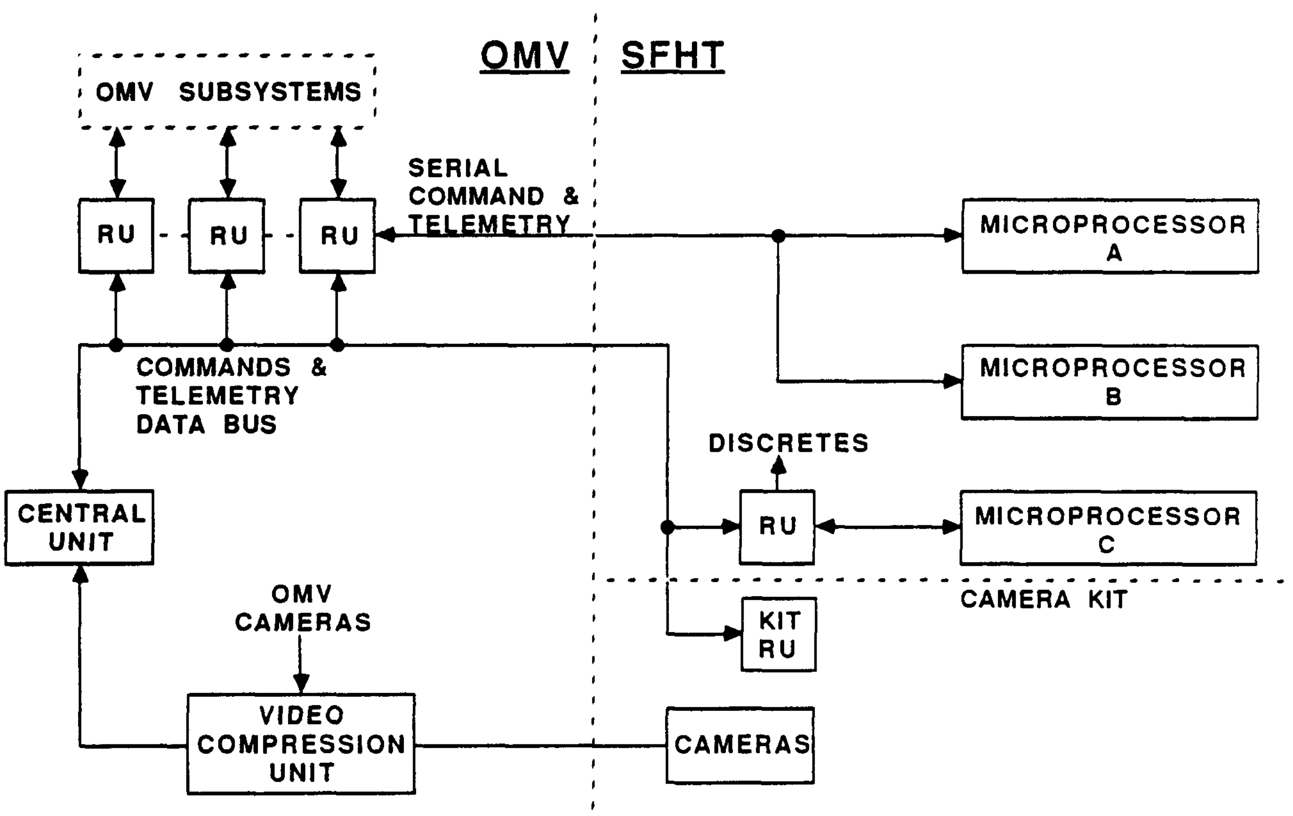


Figure 6.41 SFHT-OMV Avionics Interfaces

Several concerns exist regarding the OMV-to-SFHT interface. When the OMV is performing a maneuver, no command or telemetry to or from the tanker will be available, leaving no insight to the tanker status. The OMV documentation shows no mass storage devices, such as tape recorders; therefore, all commands and telemetry must be accomplished in real time. The payload I/F needs better definition. We also believe the RUs should be government furnished equipment (GFE).

To limit the number of electrical interfaces required on SFHT and save weight, cost, and system complexity, it is recommended that the truss I/F utilize the same I/F as that required for the Orbiter and the MRMS I/F utilize the same I/F as that for the OMV. The requirements across the interface (power, commands and data handling) are thus the same for both interface sets. This will also require that the electrical connectors and pin-outs be standardized for both interfaces.

6.1.6.4 <u>SFHT/OSCRS Avionics Commonalty</u> - The SFHT avionics discussed in the previous section were derived from the OSCRS avionics. The two tankers handle different fluids but the requirements on avionics to control and monitor each tanker are similar. Figure 6.42 shows the tanker module AFD and cargo bay package that can remain common for both the OSCRS and

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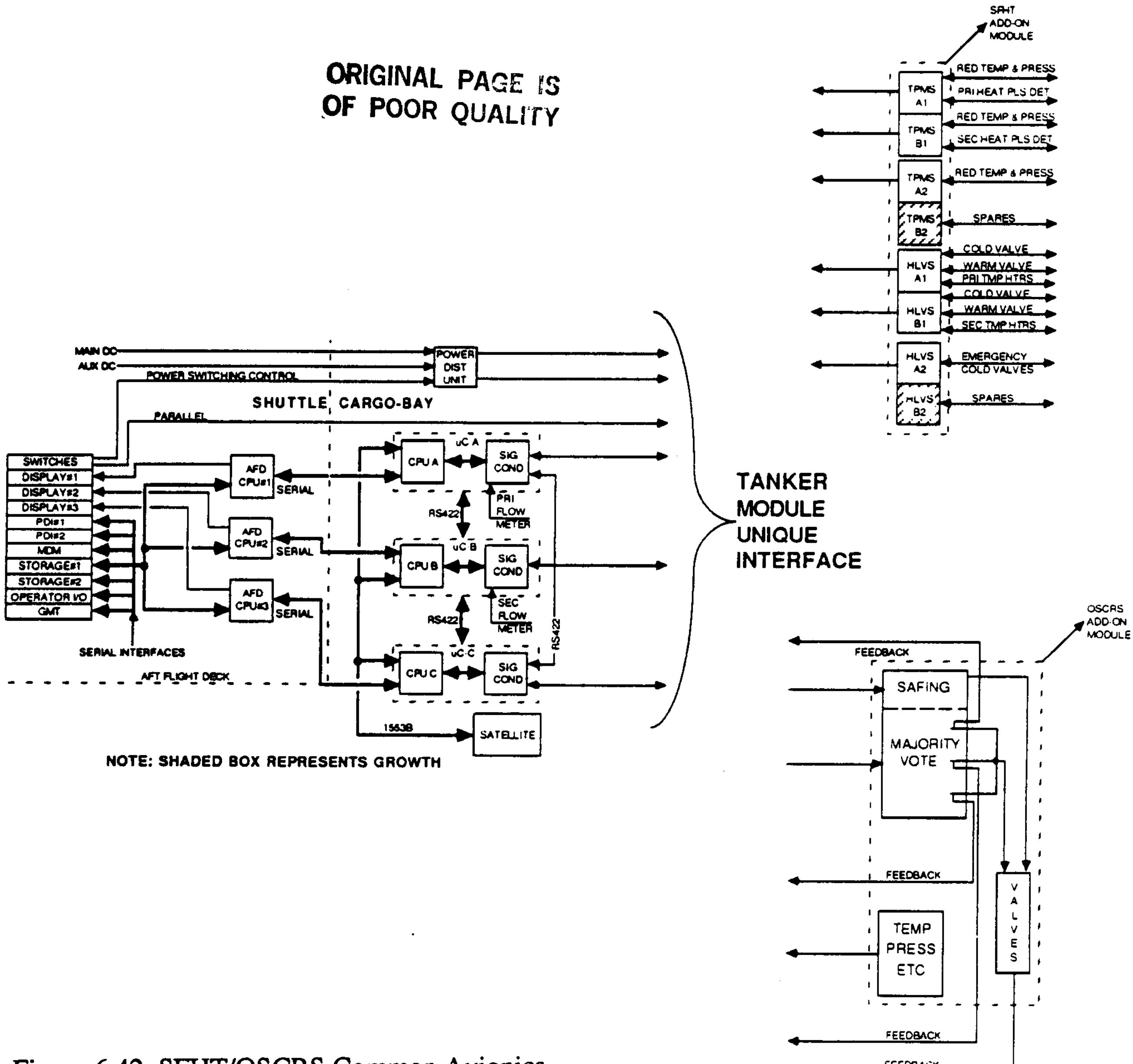


Figure 6.42 SFHT/OSCRS Common Avionics

SFHT tankers. The common tanker avionics exist from the orbiter AFD to the tanker CPUs. The two block diagrams on the right of the figure show the SFHT and OSCRS add-on modules that will interface with the standard tanker module interface. This part can be considered as an add-on module that completes the tanker avionics subsystem. Common avionics for different tankers shortens Orbiter crew training and provides an interface that becomes familiar to the crew. Hardware is standardized. Software can be developed in a modular fashion. A common software package can provide control of the common avionics with a software add-on packet that provides commands and data processing, and display control, that are unique to each tanker.

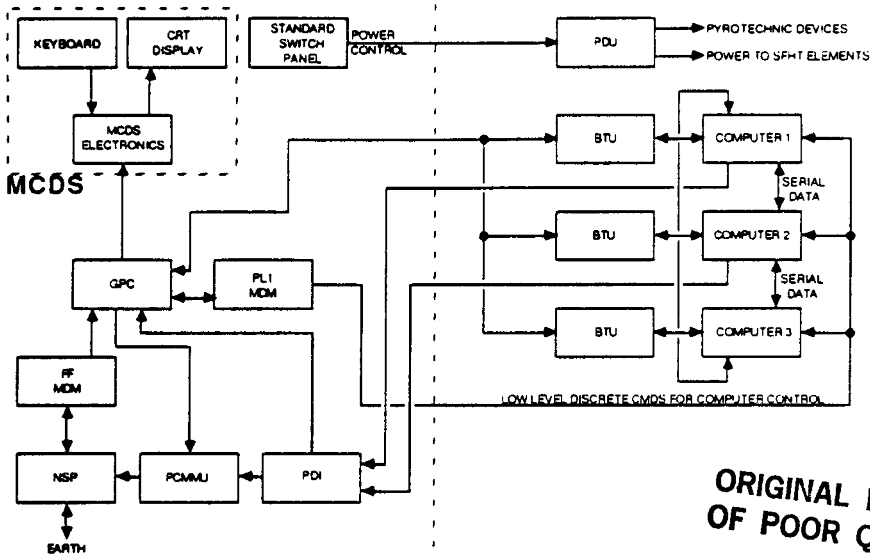
Since the Challenger accident, NASA-JSC safety and mission integration has reassessed the desirability of having all safety-critical operations be monitored and controlled by the GPC. In Section 6.1.6.5, we address how the overall avionics of the SFHT can be simplified if we use the GPC interface and don't try to maximize commonality with the OSCRS avionics concept. This is possible because the SFHT has a significantly less safety-critical design and operational scenario than does the OSCRS.

6.1.6.5 <u>SFHT-GPC Interfaces</u> - The orbiter GPC is required to control and monitor any payloads in the cargo bay that are classified as a hazardous payload or have hazardous operations. Any SFHT safety critical control and monitoring would be required to be input through the GPC. The GPC would replace the SFHT AFD control system and interface with the tanker avionics through one of several options. Figure 6.43 shows the interface options.

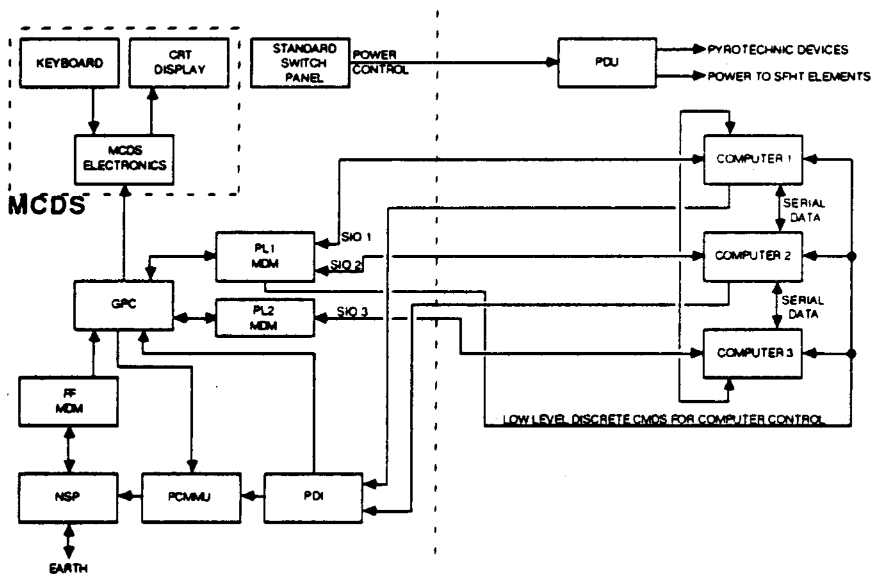
In Option 1 the tanker interfaces to the GPC via Bus Terminal Units (BTU) through the GPC data bus. The data bus is single-fault tolerant with one bus on the starboard side and one bus on the port side. To maintain two-fault tolerance between the tanker and the GPC, three BTUs are required. This may cause a manifesting problem because two BTUs are allowed per payload. The GPC communicates with only one BTU when interacting with the tanker CPUs. This single interaction may limit insight into the tanker avionics because the crew would have to assume that the tanker CPU is functioning properly. This single interaction also adds complexity to the software in the tanker. The CPU that communicates with the GPC now has to relay commands as well as acquisition data from the other tanker CPUs. PDI and MDM links that were made through the AFD subsystem will be part of the tanker subsystem. Two CPUs communicate with the PDI and the third CPU interfaces with the MDM. This will require some tanker CPU hardware and software design and development in order to handle the interfaces.

In Option 2 the tanker interfaces to the GPC through SIO channels. This requires three SIO channels to meet tanker fault tolerance requirements, creating a manifesting problem because only two SIO channels are allowed per payload. The communication provided between the GPC and the tanker CPUs is the same as that for the BTUs in Option 1, with the GPC interacting with only one SIO channel at a time. The links to the Orbiter interfaces are the same as in Option 1.

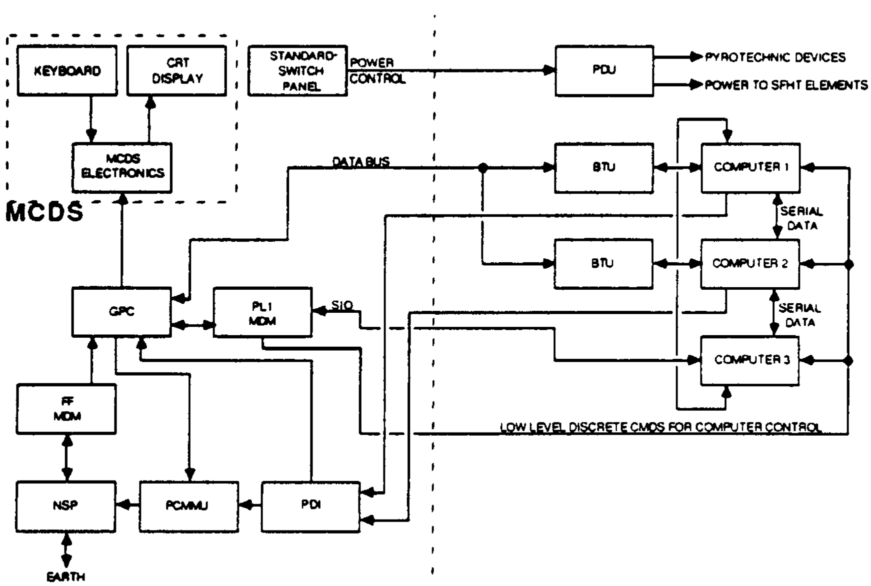
In Option 3, the tanker interfaces to the GPC through a combination of Option 1 and Option 2. This option has the GPC interacting with the tanker avionics through two interfaces, the data bus and a SIO channel. Two GPC links are via BTUs with the third GPC link via the MDM SIO channel. This combination of GPC links keeps the tanker within payload allocations, which are two BTUs and one SIO channel. The BTU links are the primary link, with one BTU on each data bus. The MDM SIO channel is used in the event of a failure of both data bus links. The GPC still interacts with only one link to the tanker avionics at a time, which still presents a problem of insight into tanker health and status. The links to the Orbiter interfaces are the same as in Option 1.



a) OPTION 1



b) OPTION 2



c) OPTION 3

Figure 6.43 SFHT-GPC Avionics Configuration Options

In all options, the GPC has the capability to control and monitor the tanker and satellite in a refueling mission. The GPC provides 40 commands and 40 parameters as a standard payload allocation. Further work is required to determine if these 40 commands and parameters are enough control and insight into the tanker operation to ensure efficient and successful operation of the tanker and satellite. Also the impacts on mission success and safety with the GPC communicating with only one CPU need to be addressed.

Another approach to using the GPC is that shown in Figure 6.44. In this configuration Option 3 is used for the GPC control of the tanker avionics with the GRiD computer providing display of tanker and satellite data. The GRiD system has the capability to display data in graphic form (instead of tabular form) like the original AFD display system, but without touch-command capability. The GRiD is flight qualified and can interface to the tanker avionics through several standard interfaces without any hardware changes required. Similar to the three GPC options shown in Figure 6.43, there still exist the issue of adequacy of the 40 commands and 40 parameters. The impacts on mission success and safety need to be addressed.

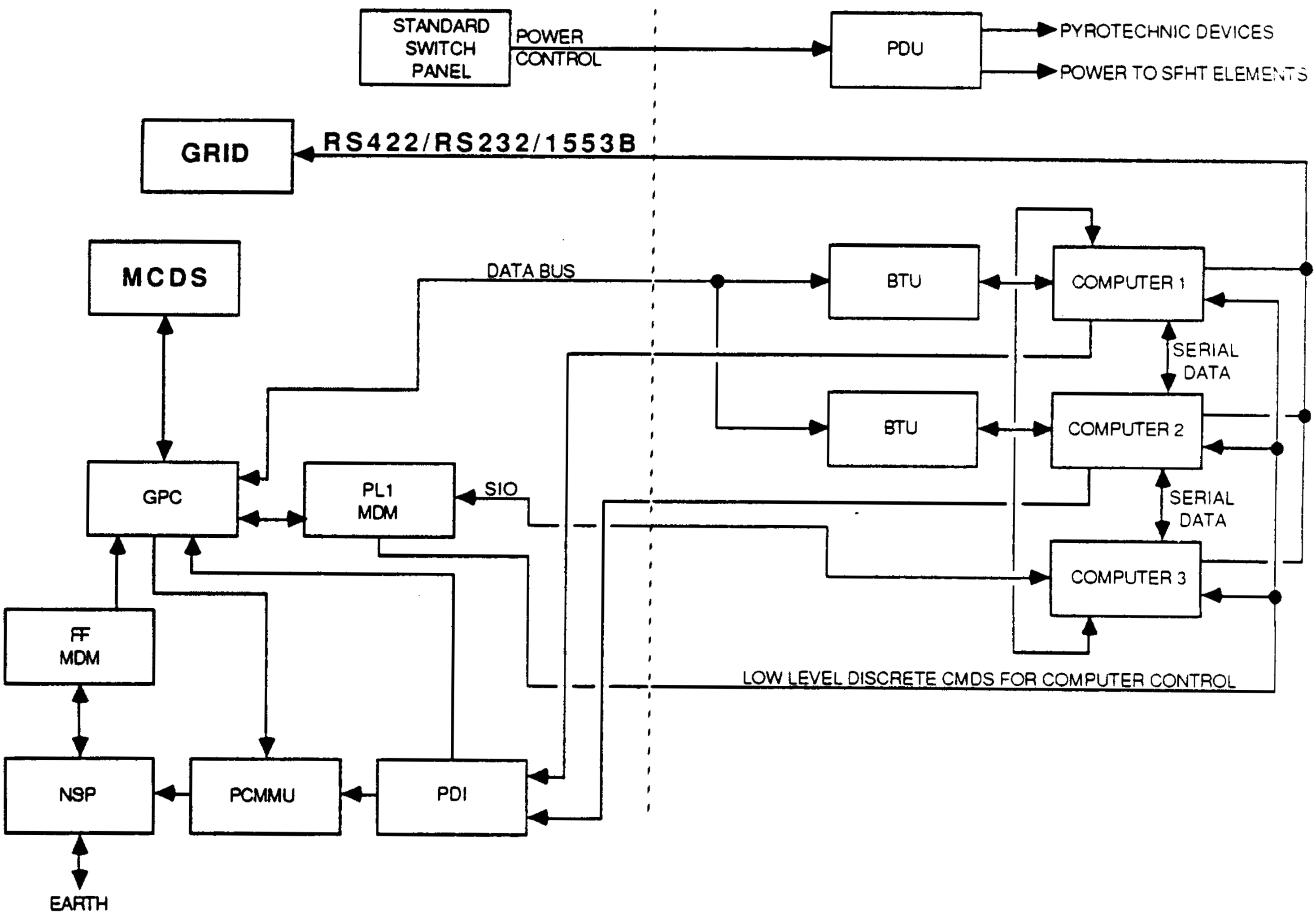


Figure 6.44 SFHT Avionics Option Using the GRiD Computer on the AFD

6.1.6.6 SFHT Avionics Simplification - The present design of the tanker avionics meets the requirements as stated in the System Requirements Document, Attachment A of the Statement of Work. Due to the characteristics of the superfluid helium tankers, we have compiled a number of comments and recommendations regarding updates and changes to the avionics portion of the specification when it is revised. These include:

- Two-fault tolerant for mission safety critical items only. The only safety critical items for the avionics are: providing power and control to the pyrotechnic devices, providing two-fault tolerance to monitoring prior to activation of the emergency disconnect, and providing data to the crew when an EVA is in progress.

- The avionics shall be capable of meeting safety requirements and accomplishing all required functions without using the Orbiter GPC. The avionics can be simplified if the GPC is used to control and monitor the tanker.

- Two-fault tolerant to prevent inadvertent operation of safety critical valves. There are no safety critical valves for the SFHT. Total loss of control of the valves in the worst case will only cause lockup of the Dewar, resulting in pressure rise and relief through the burst discs. The motor driven valves have a 15 to 20 second opening time which is too slow to control a safety critical situation. Other tanker subsystems provide two-fault tolerance to controlling safety critical situations.

- Two-fault tolerant to safing tanker and spacecraft. The tanker provides mechanical two-fault tolerance for maintaining the Dewar in a safe condition in the event of avionics failure. At this time, the interface between the tanker and the satellite is undefined. It is assumed that the satellite fluid system will provide the same mechanical safing as that in the SFHT, thus eliminating the need for two-fault tolerance for safing by the avionics.

- Two-fault tolerant to providing caution and warning, independent of the GPC. Use of the GPC permits a reduction in the AFD control and display system. Data would not be displayed in graphic form, but in tablular form.

- Two-fault tolerant to monitor and control safety critical pressure and temperature sensors. The avionics will be two-fault tolerant to monitoring safety critical sensors, but the capability to control these parameters may not be possible. The mechanical devices (valves) have an operational time that inhibits controlling any safety critical pressure or temperature.

- Graphically display SFHT and spacecraft data independent of the GPC. The use of the GPC to display data reduces the SFHT AFD system needs when compared to the OSCRS. The GPC does not have graphics capability; after a failure of the SFHT AFD system, the tanker would be powered down and the GPC would be used for monitoring only.

Figure 6.45 shows a simplified tanker avionics concept. One string of tanker avionics has been removed. The remaining two strings provide one-fault tolerance for mission success. A new design (unit A) would be used if the avionics reduction was limited to the hardware on the tanker. This would not require use of the GPC. A new design (unit B) would be used if the avionics reduction also applies to the AFD system. This removes one AFD CPU and display. Unit B would monitor data and interface to the GPC via the MDM analog channels. The GPC would provide the third link for collecting data and providing it to the crew.

6.2 FACILITY REQUIREMENTS AND GSE DESIGN

Facility requirements for both STS and ELV launches of the SFHT were addressed including identification of both mechanical ground support equipment (MGSE) and electrical ground support equipment (EGSE) for mixed fleet operation.

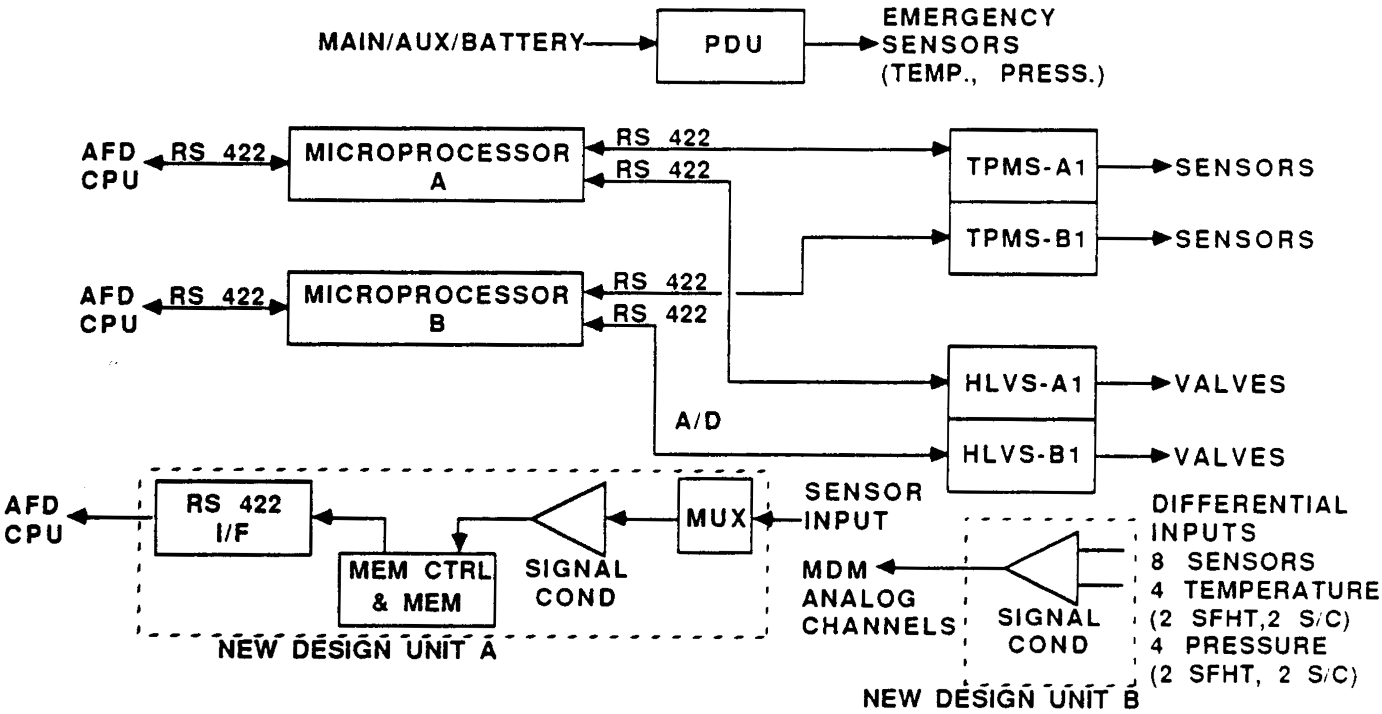


Figure 6.45 SFHT Avionics Simplified Block Diagram

6.2.1 Facilities

6.2.1.1 STS Launch Facilities - Facility capabilities and limitations are an important consideration in the design of the SFHT fluid subsystem and GSE, and the planning of the ground processing flows. Early in the study, our discussions with KSC personnel established some basic groundrules on what facilities could be used to process the SFHT for an STS launch, and these facilites were toured for familiarization. The Payload Hazardous Servicing Facility (PHSF) was identified by KSC as a potential servicing and storage facility for the SFHT. The PHSF is capable of supporting hazardous operations including assembly, testing, propellant transfer, and explosive system operations. It consists of a hazardous operations service high bay connected to an airlock with overhead cranes for handling of payloads. Storage, maintenance, check-out, and helium servicing of the SFHT could be performed in this facility.

The Payload Changeout Room (PCR) at the Shuttle launch pad is a facility designed to install payloads into the Orbiter cargo bay in a protected environment. The Payload Ground Handling Mechanism (PGHM), inside the PCR, is used to insert and access payloads within the cargo bay. The SFHT would be transported vertically to the PCR from the PHSF using the Payload Cannister and Transporter, and then inserted into the cargo bay. The SFHT GSE would then be brought to the PCR and placed at the level closest to the SFHT bay location. The layout of the PCR and the relative locations of the PGHM and the Orbiter bay are shown in Figure 6.46.

One of the more important design considerations for the GSE is its location in the PCR relative to the SFHT. Various options were examined and are summarized in Figure 6.47. The first case shows the GSE located on the fixed platforms on either side of the PGHM. The total distance between the GSE and the SFHT is estimated to be 35-40 feet. The next case has the GSE located on the PGHM providing close access to the SFHT. The drawback with this approach is that the PGHM is limited to ~1500 lbs maximum weight and the GSE weight plus support personnel

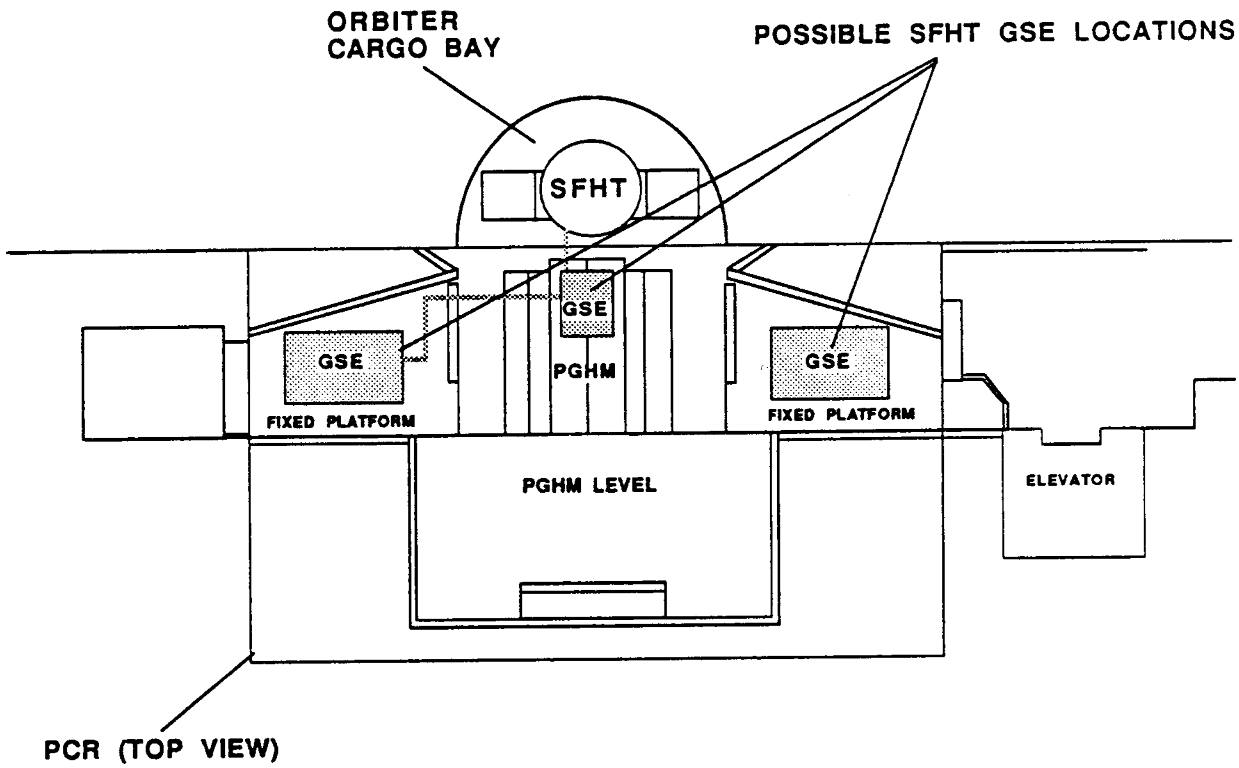


Figure 6.46 Configuration of the Payload Changeout Room Showing SFHT and Associated GSE Relative Locations

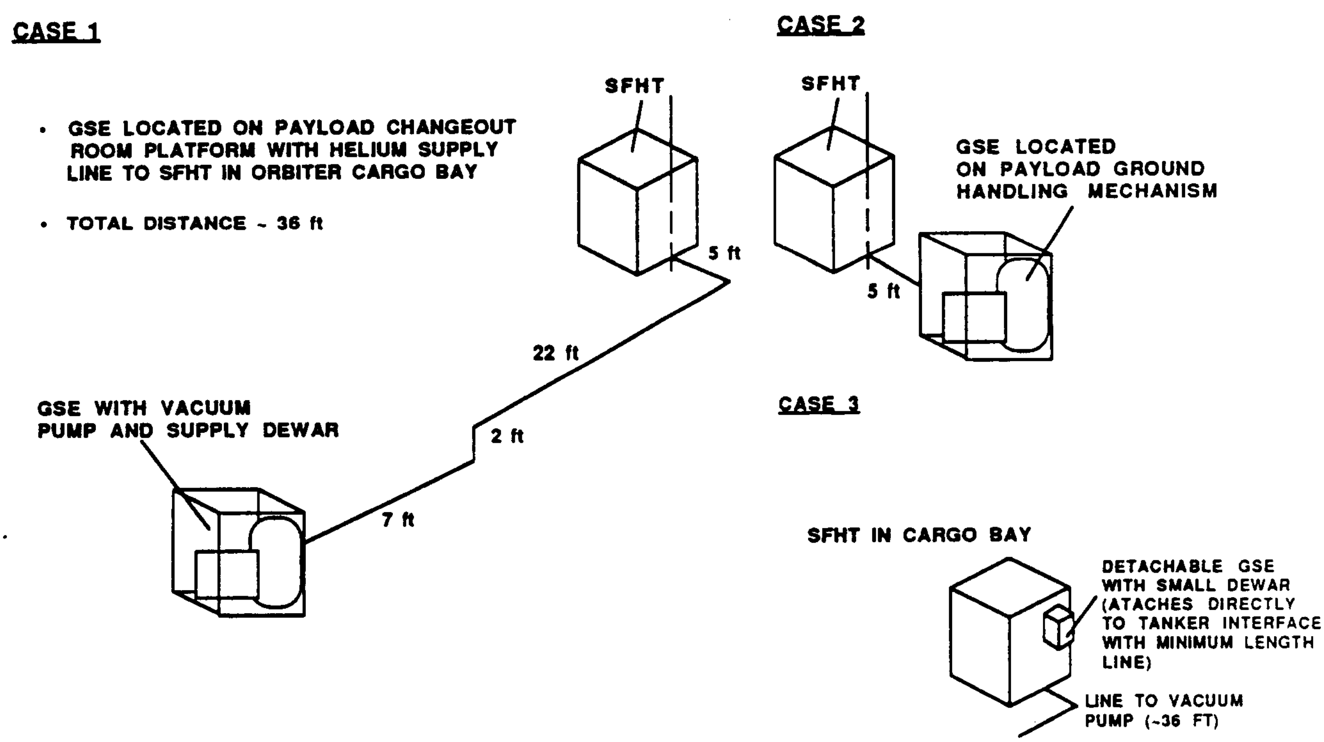


Figure 6.47 Options for GSE Location in the PCR

must not exceed this limit. The third case involves attaching a small GSE supply dewar directly to the SFHT structure to eliminate any helium transfer lines. KSC personnel were consulted for inputs to the three cases (Reference 6.11). The result was that case 1, with GSE located on the PCR fixed platforms, is the most likely scenario due to weight and size limitations on the PGHM. Also, it was determined that the GSE with a 750 liter dewar was the largest size that could be accommodated inside the PCR due to the weight limitations of the platforms.

6.2.1.2 ELV Launch Facilities - The launch sites for the various ELV's all have similar accommodations and limitations. For processing of the SFHT, the PHSF could be used regardless of whether the SFHT was being launched on the Shuttle or an ELV. Therefore, the only difference is the accommodations at the launch pad itself. A typical ELV launch pad facility consists of an environmentally controlled work room, work platforms, hoists, and various utility supplies. As with the PCR, there is limited volume for a large amount of payload GSE. However, since the SFHT would be transported to the pad only days before launch (as discussed in Section 6.3.1.2) minimal GSE would be required.

A concept of pad facilites required to support the SFHT is shown in Figure 6.48. Work platforms are provided at various levels to allow access to the SFHT and to support the GSE if it is required. Interfaces for overboard venting to the outside of the environmental shelter will be required, particulary for an emergency vent.

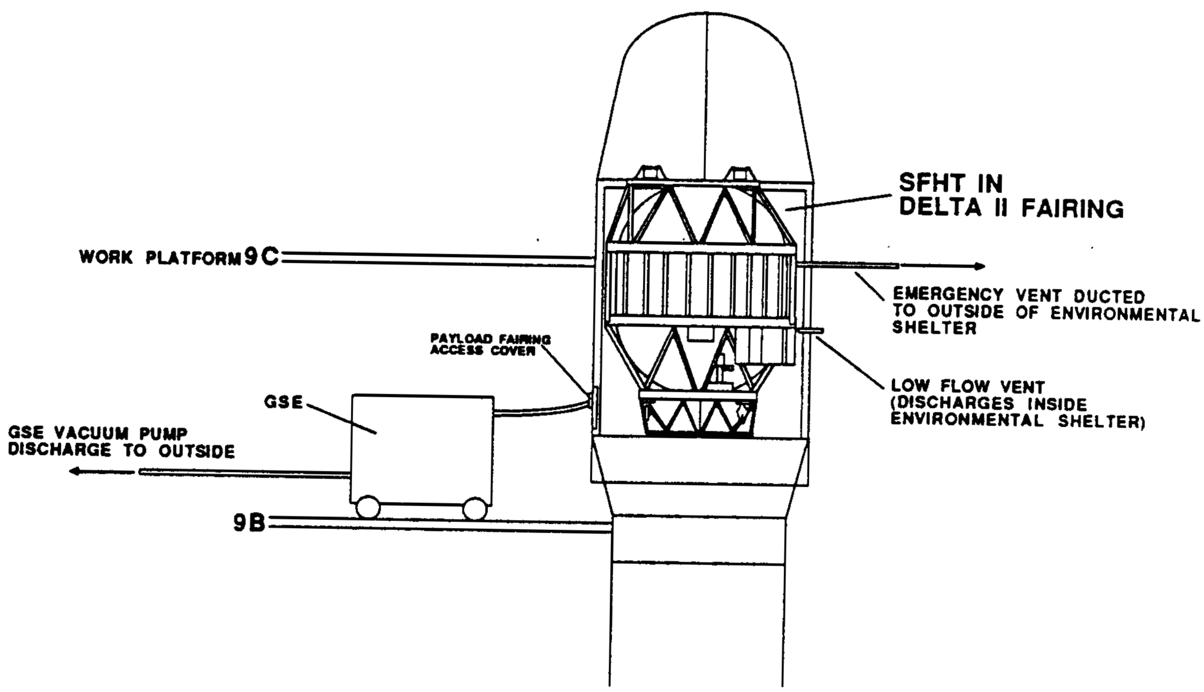


Figure 6.48 ELV Launch Pad Facilities to Support the SFHT

6.2.2 Ground Support Equipment (GSE)

6.2.2.1 Mechanical GSE - Requirements for the SFHT GSE both at the offline facilities and at the launch pads were identified. The mechanical ground support equipment consists of those SFHT unique items (including fluid) that are required to assemble, handle, process, test, and support the in-line and off-line activities of the SFHT flight hardware at the launch site, including payload integration operations with the Orbiter or ELV. Most of this equipment also supports various phases of fabrication, assembly, and test in addition to unique test fixturing and tooling. The mechanical GSE required at the PHSF will be used to cool and initially fill the SFHT. This will be accommmplished using normal helium from a trailer. The rest of the mechanical GSE will consist of a portable liquid helium Dewar with approximately 750 liter capacity along with a vacuum pump. Once the SFHT is filled, thermal conditioning through the internal heat exchanger will begin using the portable GSE Dewar and vacuum pump system. This portable GSE will also be used at the PCR and at the ELV launch site. The GSE Dewar and vacuum pump would be sufficiently small to satisfy the weight and volume constraints of the launch pad facilities.

A list of the MGSE identified for the SFHT is given in Table 6.14. Commonality of the SFHT MGSE with the OSCRS and SIRTF MGSE was assessed to identify potential areas of common development. The helium MGSE, particularly the portable helium supply Dewar, could be shared with SIRTF since the SFHT and SIRTF will have comparable quantities of helium. Similar areas of commonality need to be addressed in future studies.

6.2.2.2 Electrical GSE - The EGSE will be required at the off-line facilities to control and monitor SFHT fluid subsystem valves and instrumentation during system level testing, software development and verification, and prelaunch and post-landing ground servicing. During operations at the pad, however, only those components in the closed-loop thermal conditioning system need to be activated. The EGSE will be capable of simulating all Orbiter-to-SFHT interfaces such as the MDM and PDI, as well as SFHT-to-Spacecraft interfaces. The EGSE will also provide the capability of simulating sensor responses, both within the SFHT and on the spacecraft. Figure 6.49 shows the block diagram. During servicing and deservicing the SFHT flight system in the Shuttle may not be accessible. The EGSE duplicates the flight system to permit control and monitoring of the tanker.

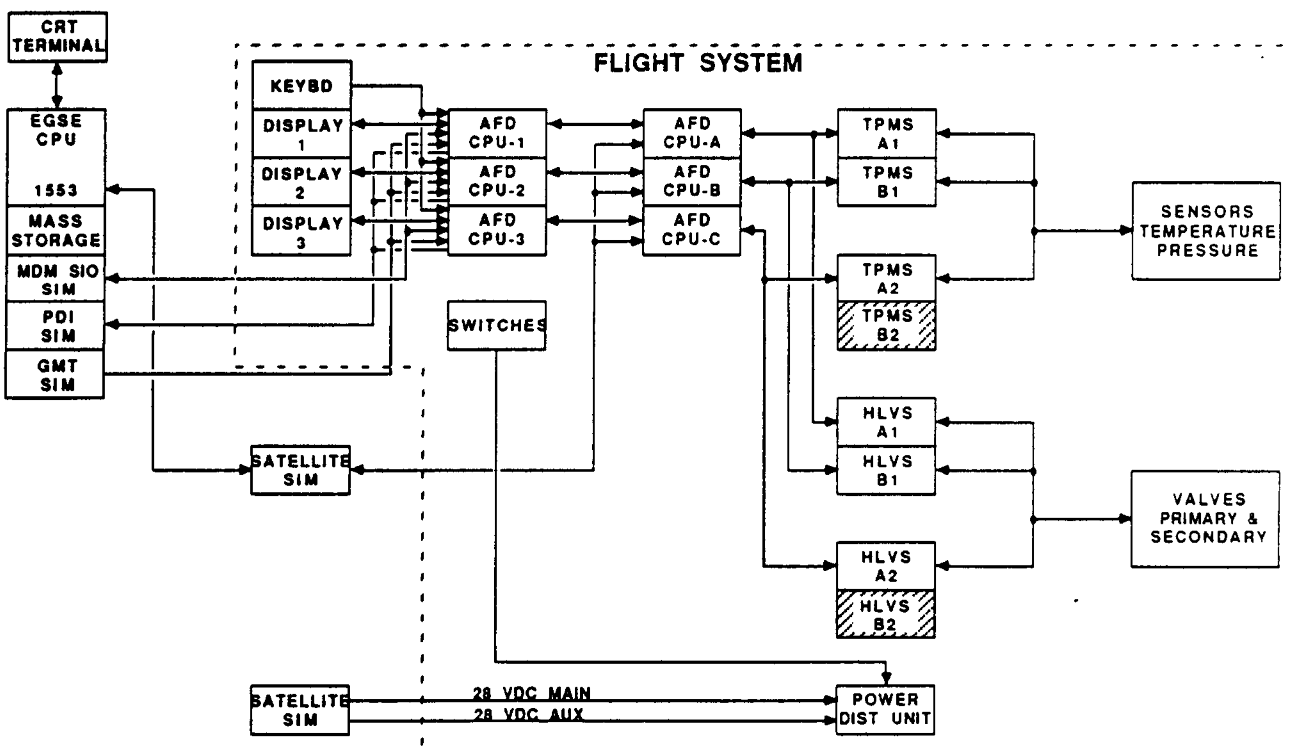


Figure 6.49 Block Diagram of EGSE

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Table 6.14 SFHT MGSE Required for Processing

ITEM	CATEGORY	DESCRIPTION/FUNCTION
LHe STORAGE/SUPPLY	EXISTING	SEMI-TRAILER NORMAL HELIUM DEWAR FOR CHILLDOWN AND INITIAL FILL
LHe PORTABLE SUPPLY	NEW OR SIRTF SHARED	PORTABLE 750 LITER DEWAR FOR PAD OPERATIONS
VACUUM PUMP	NEW OR SIRTF SHARED	ESTABLISH DEWAR GUARD VACUUM
PORTABLE GSE VACUUM PUMP	NEW	SUPERFLUID CONVERSION THROUGH INTERNAL HEAT EXCHANGER
FLUID SUPPORT KIT	NEW	MISCELLANEOUS COMPONENTS (ADAPTORS, FLEX LINES, Q.D.'s, ETC.)
CALIBRATION KIT	NEW OR SIRTF SHARED	MEETS SFHT UNIQUE SENSOR CALIBRATION NEEDS
GHe PRESSURIZATION	NEW OR OSCRS SHARED	SUPPORTS SFHT PURGING, LEAK CHECKS, AND BLANKET PRESSURE MAINTENANCE
CONTAINER	NEW	PROVIDES FOR ENVIRONMENTAL PROTECTION DURING TRANSPORT, HANDLING, AND STORAGE
SLINGS	NEW OR OSCRS SHARED	USED TO LIFT, ROTATE, AND POSITION THE SFHT IN VERTICAL OR HORIZONTAL DIRECTION
FIXTURES	NEW	ACCOMMODATES SFHT REORIENTATION FROM HORIZONTAL TO VERTICAL AND VISA VERSA
WORKSTANDS/PLATFORMS	NEW OR OSCRS SHARED	PROVIDE ACCESS TO SFHT SERVICE AREAS
MLI STORAGE	NEW OR OSCRS SHARED	PROVIDES FOR STORAGE AND REPAIR CAPABILITY OF BLANKETS

During transport operations to the launch pad the ground personnel will need the capability to monitor the condition of the Dewar. This will require a small portable, battery-powered unit that will provide excitation for a limited number of sensors(two temperature, two pressure), to monitor and display the sensor data to the ground personnel as required. The weight of the unit would be approximately five pounds and dimensions approximately 6" X 6" X 4".

6.3 OPERATIONS

SFHT operations were evaluated beginning with initial off-line ground processing, proceeding through the lift off, ascent and on-orbit operations, and concluding with the descent, landing and post-landing operations. Both STS and ELV launch options were addressed.

6.3.1 Ground Servicing

Ground servicing operations are an important consideration in the design of the SFHT. Limitations both in time and facilities at the launch site are key factors in identifying the requirements for the ground operations. Earlier in the study, we held a meeting with KSC personnel to discuss ground processing scenarios and options for the SFHT for both an ELV and Shuttle launch. Based on this meeting and subsequent conversations, ground operation flows were developed for each of the launch options, identifying timelines, operations steps, and facility requirements. The following sections discuss the results for both Shuttle and ELV launches.

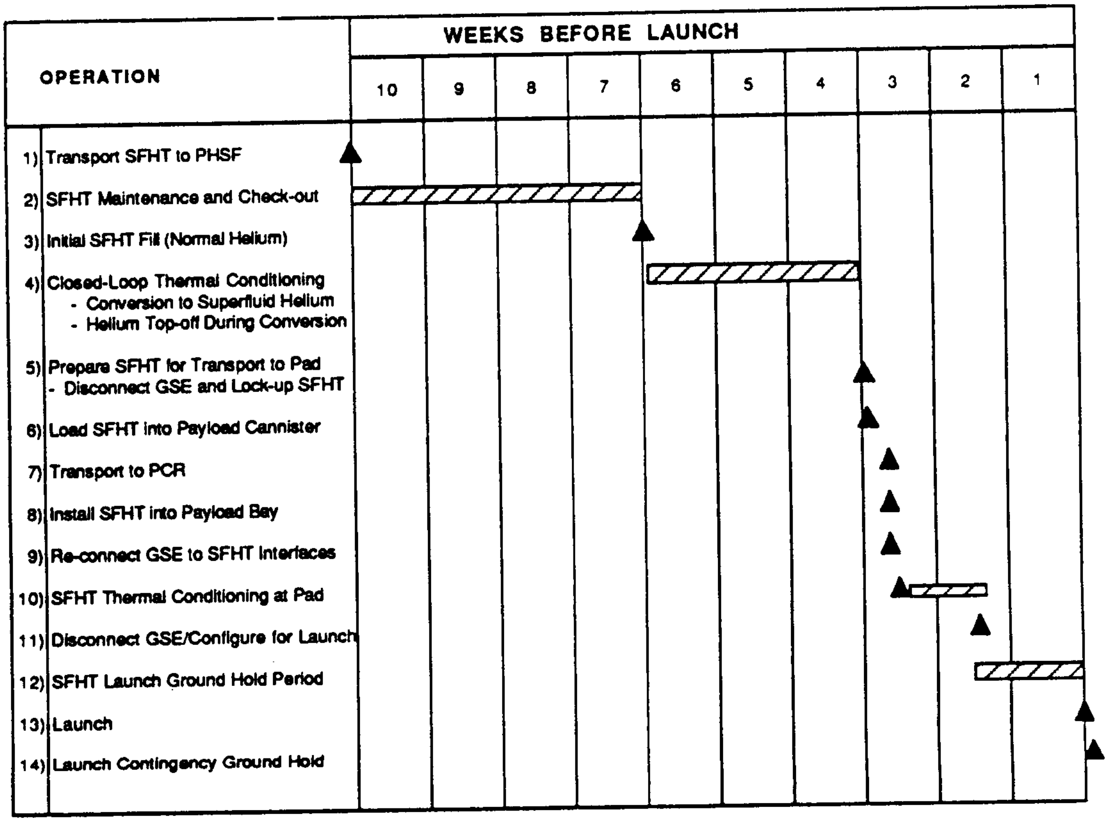
6.3.1.1 SFHT Ground Servicing for STS Launch - The preliminary timeline developed for an STS launch of the SFHT is presented in Table 6.15. The operations begin with the delivery of the SFHT to the Payload Hazardous Servicing Facility (PHSF). Any required maintenance and check-out of the SFHT will be performed in this facility. Four weeks are provided in the timeline for this activity but much more time would be required if components inside the vacuum jacket required replacement.

The initial chilldown and fill of the SFHT would occur approximately six weeks before launch. Thermal conditioning and stablization of the Dewar and conversion to superfluid would require about three weeks. The SFHT would then be prepared for transport to the pad in the payload cannister by disconnecting the GSE, locking up the Dewar, and attaching the portable GSE monitoring system (described in Section 6.2.2.2). The SFHT would be placed in the payload cannister and transported to the Payload Changeout Room (PCR) three to four weeks before launch.

Once at the pad, the SFHT/PCR interfaces, consisting of vent lines to the outside, would be connected. These lines are required in the event of an emergency vent should the SFHT be damaged during the process of installing it into the Orbiter. Once installed in the Orbiter cargo bay, the SFHT/Orbiter interfaces, discussed in Section 6.1.2.1, would be mated, the GSE reconnected and thermal conditioning of the SFHT resumed via the internal heat exchanger. Pad thermal conditioning operations would occur during the next eleven days to subcool the superfluid helium, insulation and vapor cooled shields. Ten days prior to launch, the GSE would be disconnected and the SFHT Dewar locked-up and prepared for launch.

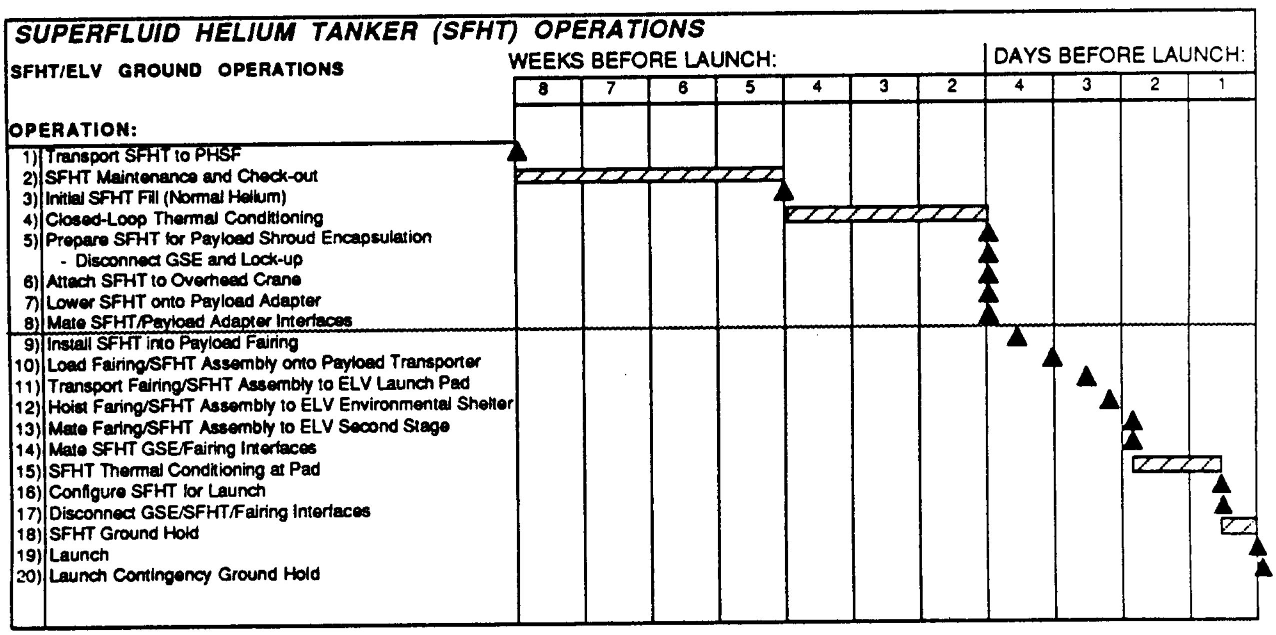
A contingency hold time of 24 hours for a launch scrub is required in addition to the ten day hold. KSC personnel have indicated that the second launch attempt usually occurs 24 hours after the inital launch attempt. The third launch attempt would then occur seven to ten days later due to vehicle recycling procedures. The payload bay doors are normally re-opened during this time allowing access to the SFHT. The GSE would be reconnected and thermal conditioning to subcool the insulation, shields and the superfluid helium would begin, lasting as long as the schedule would allow. The SFHT would be locked up and prepared for the third launch attempt. This procedure would be repeated for subsequent launch attempts.

Table 6.15 SFHT Ground Operations at KSC - STS Launch



6.3.1.2 SFHT/ELV Ground Operations - A preliminary ground operations flow for launch of the SFHT on an ELV was developed and is shown in Table 6.16. The PHSF could again be utilized for SFHT maintenance, check-out, and fill as in the STS launch flow. The major difference, however, is that the SFHT can be transported to the ELV launch site approximately 3 to 4 days before launch rather than the 3 to 4 weeks required for an STS launch. SFHT transport operations would begin by bringing either the ELV payload fairing (Atlas and Titan launches) or

Table 6.16 SFHT Ground Operations - ELV Launch



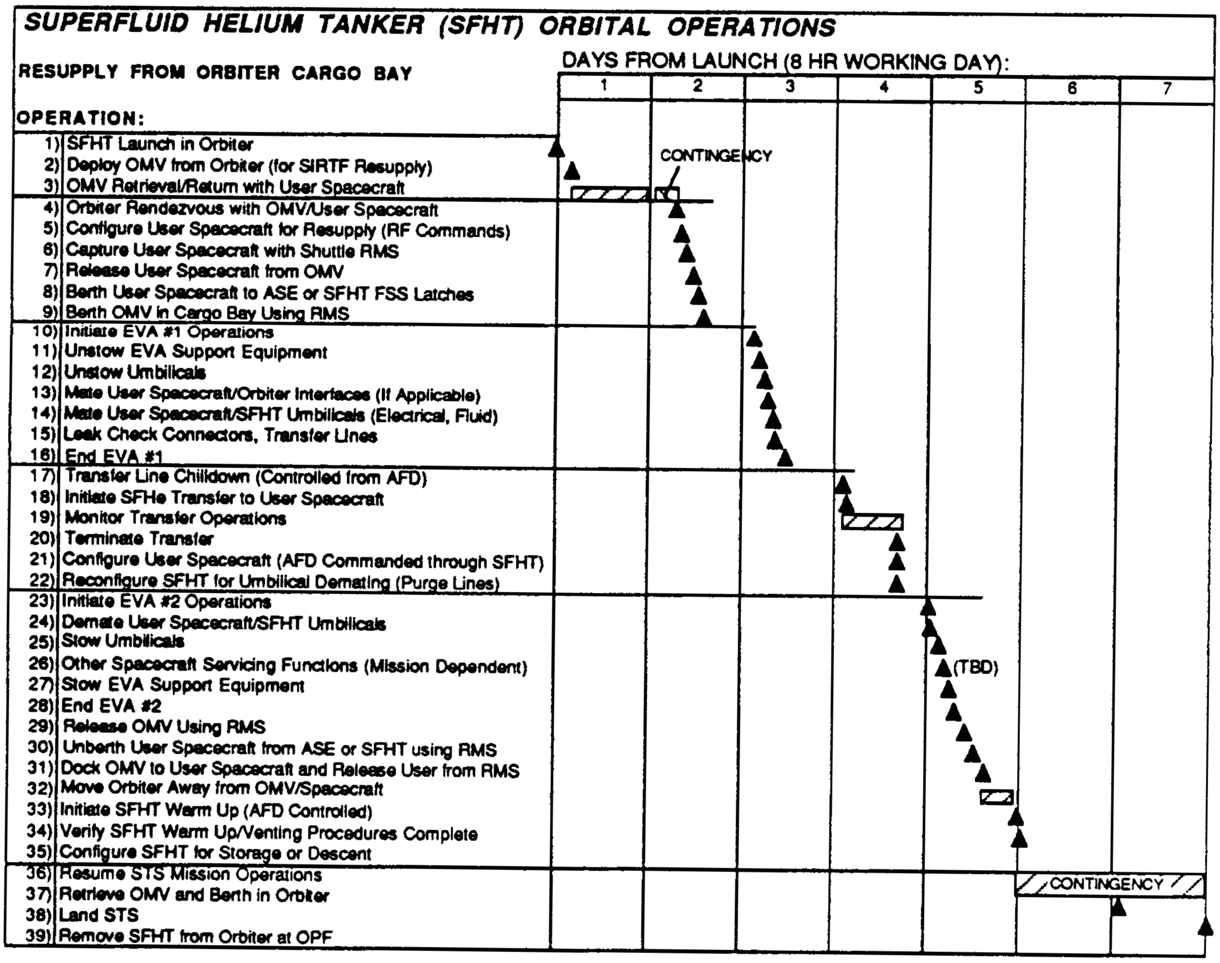
a transport cannister (Delta launch) to the PHSF. The SFHT would be installed and the interfaces with the fairing mated. The SFHT assembly would be loaded onto the ELV payload transporter and taken to the pad. The SFHT transport configuration is shown in Figure 6.50 for both the cannister and fairing installation options. Regardless of the particular ELV, a nitrogen purge and limited power is provided to the payload to maintain conditions during the transport process.

Once at the pad, the fairing or cannister is hoisted to the environmental shelter area surrounding the launch vehicle where work platforms and other equipment for mating the payload to the launch vehicle are provided. The SFHT is then mated to the ELV second stage and all utility connections are mated. The benefit of the ELV launch flow is that, since the SFHT is taken to the pad only 3 to 4 days before launch, no thermal conditioning should be required as the Dewar can remain locked-up during this time. However, in the event of extended launch scrubs, GSE would be required to thermally condition the insulation, shields, and superfluid helium via the closed-loop heat exchanger. This requires appropriate interfaces in the payload fairing to allow the GSE to connect to the SFHT ground service panel.

6.3.2 Ascent and On-Orbit Operations

6.3.2.1 SFHT/STS Operations - An operational flow for SFHT helium on-orbit replenishment operations from the Orbiter cargo bay was developed to identify EVA requirements and timelines. The timeline is presented in Table 6.17 with the operations listed sequentially with their corresponding time intervals based on 8 hour working days. The timeline was generated around a SIRTF type resupply mission where the OMV and the SFHT are launched simultaneously along with a berthing mechanism such as the A' cradle.

Table 6.17 SFHT Orbital Operations from Orbital Cargo Bay



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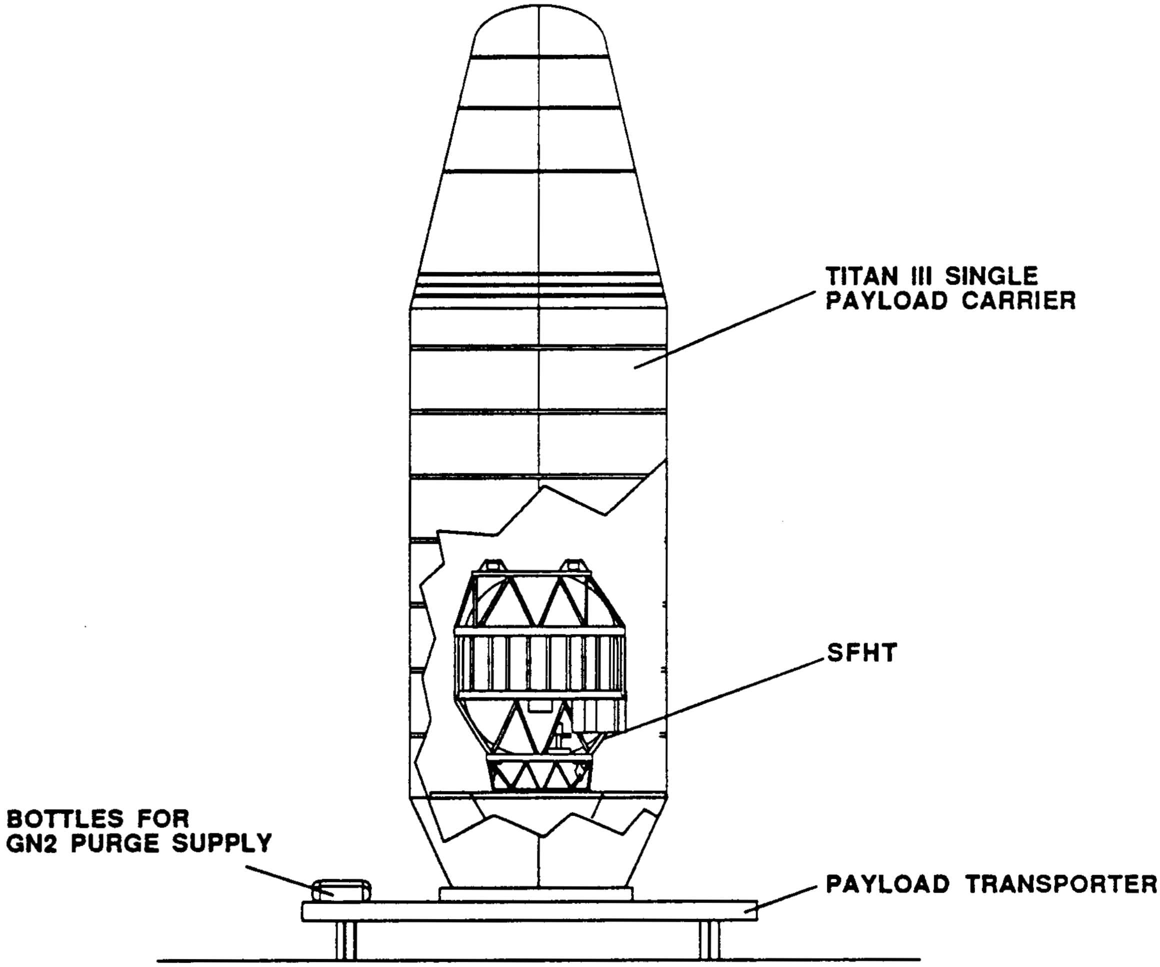
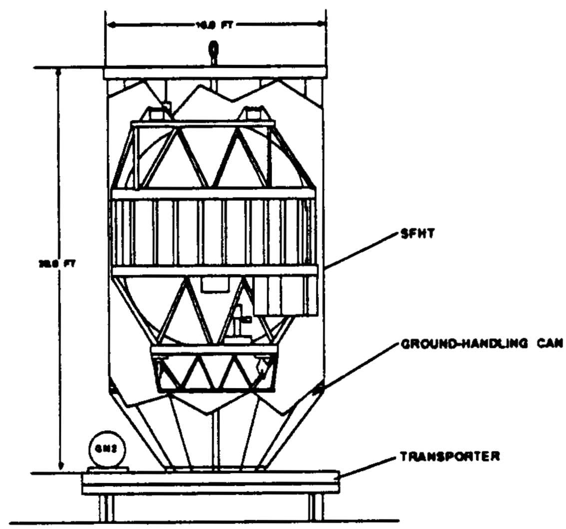


a) SFHT in Titan III Payload Shroud/Transporter



b) SFHT in Delta Payload Ground-Handling Canister/Transporter

Figure 6.50 SFHT Transport Options for ELV Launch Mode

After reaching orbit, the OMV is deployed on the first day of the mission to retrieve the SIRTF from its operating orbit. Various studies including the STICCR studies have estimated the time for the OMV to retrieve and return with the SIRTF to the Shuttle orbit as 16 hours. OMV rendezvous with the Orbiter occurs on the second day, and capturing and berthing of the user spacecraft and the OMV is performed using the Shuttle RMS. Any reconfiguring of the user spacecraft subsystems could also be performed at this time. Contingency was included in the second day's timeline to account for problems in the OMV retrieval phase. An EVA would be initiated on day 3 after the OMV and the user spacecraft are berthed in the Orbiter to unstow and mate the fluid and electrical couplers. The helium couplers would then be leak checked to ensure a proper connection. Any other spacecraft servicing functions could be performed after this during the remainder of the six hour EVA.

Helium transfer operations would be initiated on day 4 via the Aft Flight Deck control station. The fourth day would also be used as a rest day for the EVA crewmembers. When transfer operations are complete, both the SFHT and user spacecraft would be configured for umbilical demating. This involves venting of the transfer lines to space to remove the helium. Due to helium's low vapor pressure and the long length of the lines, this venting operation would take place during the sleep period. Also, adequate time is needed for line warm-up prior to EVA disconnections and stowage.

On the second EVA on day 5, the couplers would be demated and the transfer lines stowed. Any other EVA tasks required to prepare the user spacecraft for deberthing would be performed and the EVA ended. The RMS would then deploy the OMV and deberth the user spacecraft. The user spacecraft would remain attached to the RMS for OMV docking and then released. The OMV would begin the transport of the user spacecraft to its operating orbit. The SFHT would then be configured for storage and descent from the aft flight deck control station. Two days would remain for contingency and OMV retrieval assuming a normal seven day mission.

6.3.2.2 <u>SFHT/Space Station Operations</u> - Operations of the SFHT at the Space Station will involve long orbital stay times. Resupply of small laboratory experiments will take place frequently, but replenishment of large users such as Astromag and SIRTF will be done at approximately two year intervals. The SFHT can be launched to the Station on either the Shuttle or ELV. If launched on an ELV, retrieval of the SFHT by the OMV will be required. For a Shuttle launch, the SFHT will be removed from the payload bay sometime during the 5 to 7 day stay time at the Station. The SFHT/Orbiter interfaces would be demated and the Station MRMS would then grapple the SFHT and transport it to its storage location, either on the truss or in or near the Servicing Facility when it is in place. The SFHT storage period before performing a large user resupply such as SIRTF, could be 90 days. The user spacecraft would be transported to the SFHT (or visa versa) and the fluid and electrical interfaces mated. From this point, the helium transfer operations are the same as an STS-based operation. After completion of the transfer operations, the SFHT would be demated from the user and returned to its storage location on the truss. A representative resupply timeline when servicing at the Space Station is shown in Table 6.18.

6.3.2.3 <u>SFHT/ELV Orbital Operations</u> - Launch of the SFHT on an ELV requires that the ELV place the SFHT in a stable orbit within reach of either the OMV or the Orbiter for retrieval. The operational flow for these orbital operations is presented in Table 6.19. The SFHT would remain attached to the ELV second stage after the desired parking orbit is reached. Second stages of the Delta II and Titan III provide limited three-axis stablization capability as does the Centaur upper stage. The Titan IV currently does not have any capability to stablize payloads for deployment in low earth orbit. The OMV would then rendezvous with the ELV second stage and dock with the front face of the SFHT which would be equipped with FSS "towel" bars to mate with the OMV's TPDM, as shown in Figure 6.51. The explosive bolts on the SFHT's adapter structure would then be fired to separate the SFHT from the ELV. The OMV would subsequently transport the SFHT to the Space Station or to the user orbital location for in-situ resupply operations.

Table 6.18 SFHT Orbital Operations When Servicing From Space Station

SUPERFLUID HELIUM TANKER (SFHT) ORBITAL OPERATIONS

RESUPPLY FROM SPACE STATION:

DAYS: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

	OPERATION:
1)	SFHT Launch in Orbiter
2)	Orbiter Rendezvous/Dock with Space Station
3)	Demate SFHT/Orbiter Umbilicals (Electrical, Emergency Vent, etc.)
4)	Unberth SFHT from Orbiter Using STS RMS or Station MRMS*
5)	Transport SFHT to Station Storage Location
6)	Berth SFHT to Station Truss Assembly
7)	Mate SFHT/Station Umbilicals (Electrical)
8)	SFHT Storage**
9)	Transport User Spacecraft to SFHT or Visa Versa
10)	Mate User Spacecraft/SFHT Umbilicals
11)	Leak Check Connectors, Transfer Lines
12)	Transfer Line Chilldown (Monitored from Station Control Console)
13)	Initiate SFHe Transfer
14)	Monitor Transfer Operations
15)	Terminate Transfer
16)	Configure User Spacecraft
17)	Reconfigure SFHT for Umbilical Demating
18)	Demate User Spacecraft/SFHT Interfaces
19)	Unberth SFHT from Spacecraft or Truss using MRMS
20)	Transport SFHT to Storage Location
21)	Berth SFHT to Station Truss Assembly
22)	Mate SFHT/Station Interfaces (Electrical)

* COULD BE 5 DAYS UNTIL SFHT IS UNLOADED FROM ORBITER CARGO BAY
** UP TO 90 DAYS

Table 6.19 SFHT Orbital Operations for ELV Launch

SUPERFLUID HELIUM TANKER (SFHT) OPERATIONS

SFHT/ELV ORBITAL OPERATIONS

HOURS AFTER LAUNCH: 1 2 3 4 5 6 7 8

	OPERATION:
1)	Parking Orbit Insertion and Trim Burn
2)	Establish Three Axis Stabilized Mode
3)	OMV Rendesvous with ELV 2nd Stage
4)	Dock OMV to SFHT
5)	Deploy SFHT from ELV 2nd Stage
6)	ELV Stage 2 Separation Manuever
7)	SFHT Transport to User/Space Station by OMV

6.3.3 Descent and Post-Landing Operations

SFHT on-orbit operations, under normal conditions, will result in the SFHT being returned to the ground empty. For the case where the SFHT is used as a supply depot at the Space Station, the SFHT will likely be empty upon being returned to the ground since it is being changed-out with a full SFHT. For STS-based resupply, the SFHT should be empty or nearly empty if SIRTF is the user spacecraft. Upon completing the final helium transfer operation on-orbit, the SFHT will besafed by venting the Dewar to space and allowing it to warm-up. Therefore, under normal conditions, the SFHT post-landing operations would be relatively simple, involving only removal of the SFHT at the Orbiter Processing Facility (OPF) and transporting it to the PHSF. Contingency situations, however, where the SFHT returns to the ground with helium remaining could result in involved post landing operations, as discussed in the next section.

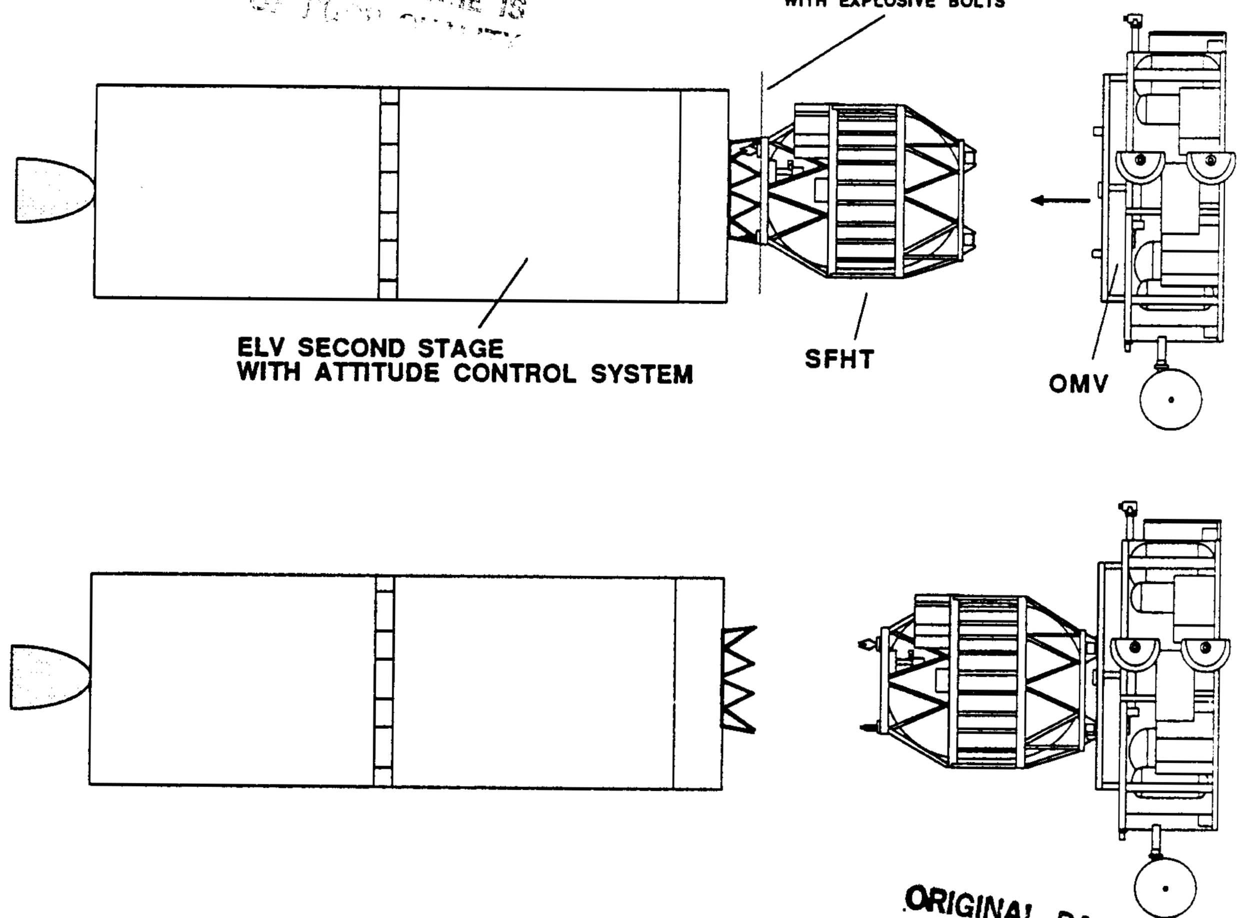


Figure 6.51 Transfer of SFHT From the ELV to the OMV

6.3.4 Contingency and Abort Operations

The SFHT can either be partially full of helium or completely empty upon completion of a helum resupply operation, depending on the user being serviced. In all cases, however, it is desirable to return the SFHT to the ground empty to avoid creating a situtation where the burst disks need to rupture to relieve pressure. Apart from the potential hazards resulting from such a vent, extended maintenance operations would be necesassry to replace the burst disks since some are located inside the vacuum jacket of the SFHT Dewar.

The SFHT could return to the ground with a full or partial load of helium due to several contingenies. A Return to Launch Site (RTLS) abort results in the SFHT landing with a full load of helium while still in the Orbiter cargo bay. In this case, access to the SFHT is not possible and the emergency vent system with the redundant burst disks ensures that the SFHT will be able to relieve any excessive pressure buildup. Personnel and equipment would have to avoid the vent discharge, however, to prevent a hazardous situation. The Orbiter would then be towed to the OPF and the SFHT removed after a relatively short period.

Once removed from the Orbiter, it is desirable to drain the SFHT as quickly as possible to avoid an emergency venting case. After connecting the SFHT and determining the temperature and pressure conditions inside the Dewar, the SFHT would be drained by connecting to the ground fill port and pressurizing the tank to above atmospheric pressure using gaseous helium if required. The helium would then be drained through the fill line. Depending on the conditions inside the Dewar, this drain process could take place either in the OPF or the PHSF.

The RTLS abort returns the Orbiter to KSC relatively quickly and therefore the SFHT could be removed from the bay in a fairly short time period. However, an abort to a contingency landing site, either from a transatlantic abort or an emergency return from orbit, would mean that no access to the SFHT would be possible for as long as several weeks until the Orbiter is returned to the OPF, since the payload bay doors cannot be opened and supported without external equipment. The SFHT could be full of helium in the bay for this time and the emergency vent system would ensure a safe condition. The only alternative would be to provide an SFHT/Orbiter fill/drain interface to allow the SFHT to be drained with the Orbiter horizontal and the payload bay doors closed or to provide relief valves to vent directly into the payload bay. This requirement needs further examination since it would be major impact to the SFHT fluid subsystem and the GSE.

6.3.5 Ferry Flight Operations

Ferry flight operations for a normal SFHT mission would not require any significant preparation procedures since the SFHT would be empty or nearly empty. However, the contingency situations, described in the previous section, would require the SFHT to be transported while still full of helium. Again, the emergency vent system is in place should an excessive pressure build-up occur. It would be desirable, however, to monitor the SFHT Dewar conditions during the ferry flight to determine if the pressure and temperature within the Dewar are staying within non-vented condition limits. Power to the on-board avionics would be required, or the battery-powered portable GSE monitoring system could be left attached to the SFHT, to provide a limited monitoring capability without the need for vehicle power.

6.4 SYSTEM SAFETY

The Superfluid Helium Tanker (SFHT) is being designed to meet the requirements of both manned and unmanned launch systems. The requirements for design are stipulated in NHB 1700.7B for manned systems and ESMC 127-1 for unmanned ELVs. The design requirements, specifically as they address the degree of fault tolerance, for manned systems are the primary driver except for ordnance and pyrotechnics systems. In the area of range safety and launch operations, the ESMC 127-1 document is the primary driver because these requirements are more stringent.

The following paragraphs discuss the requirements of NHB 1700.7B which are considered to be the most critical to the design of the SFHT. It must be indicated that these requirements are not firm requirements since the NHB 1700.7B document is not an approved document and that some changes to the text may be forth coming. However, it is a good indication of the direction safety requirements and design implementation is heading and allows us to make preliminary safety assessments of our design concepts. The safety provisions for our baseline design have been factored into the various subsystem designs and are discussed in their respective sections. The flight and ground safety discussions below highlight several of the major safety drivers for both the ELV and STS launch options.

6.4.1 Flight Safety

There is one design issue that is being driven by ELV launch. ESMC Range Safety is requiring destruct capabilities in the event of an aborted mission for payloads which contain large Dewars. There is at this point no distinction between Dewars which contain liquids such as LO2/LH2 versus Dewars which contain liquids such as LN2 or LHe. Some ELVs are providing the destruct capabilities as a service to the payload organization. This service is desirable to prevent destruct hardware from being placed on the SFHT itself. This requirement could greatly increase the complexity for redundancy and safing verification, especially for mission scenarios in which the SFHT is to be launched by an ELV and retrieved by the Space Shuttle.

In the evaluation of the SFHT to NHB 1700.7B requirements, there is only one SFHT design element that has been identified as being safety critical. This design element is the electrical shutdown of the superfluid helium pump. The identification of the helium pump as safety critical necessitates the requirement that the pump electrical system be two-fault tolerant to terminating the electrical power to the pump unit. The identification of the pump electrical power circuit as being safety critical is to provide sufficient fault tolerances to prevent superfluid helium from being flowed into its associated transfer line in the event of an emergency with the Orbiter or the receiving satellite vehicle.

Since we cannot assume we can use Orbiter power in the event of an Orbiter emergency requiring that we separate the user spacecraft from the SFHT, we have added a battery to provide power for firing the pyrotechnics used to operate the emergency disconnect. We will need to monitor the status of valves and pump heater power prior to activating the emergency disconnect so that we don't dump a large quantity of liquid helium in the cargo bay. The monitoring of these critical components will be done through use of the Orbiter GPC.

6.4.2 Ground Safety

In the evaluation of the SFHT ground processing flow to the requirements of ESMC 127-1 and KHB 1700.7A, three ground processing safety concerns were identified: 1) emergency venting in the PHSF during SFHT fill operations, 2) emergency venting while the SFHT is being transported to the pad, and 3) emergency venting in the PCR. Special vent lines and procedures will be provided to assure that during the entire ground processing, once the Dewar is loaded with liquid helium, safe Dewar venting could occur.

7.0 TASK 4 - COMMONALITY ASSESSMENT AND TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

The initial subtask of Task 4 was to assess SFHT design and operational commonality with other subcritical/supercritical cryogen tankers. This task was de-emphasized at the beginning of the program, so we only did a quick review of the SFHT design to identify those elements that might be usable as part of a non-helium cryogenic tanker. Some of the concepts and modeling tools for Dewar thermal optimization might be usable but must be used with the appropriate databases for the fluids under consideration. The vent system (e.g., porous plugs) for SFHe is of course unique to liquid helium and the flow analysis involves two-fluid models and identification of flow regimes where the fluid behaves as a "Quantum" fluid or a "Newtonian" fluid. Design of components, such as valves and the transfer line coupler, suggest approaches for low heat leak but would need a thorough review of the safety aspects, particularly for cryogens such as liquid hydrogen and liquid oxygen. For example, the liquid helium valve being designed by Utah State for SHOOT would not be acceptable in its current configuration for hydrogen usage on the ground since hydrogen in and around the stepper motor could lead to fire and explosion.

Our overall assessment of commonality potential is that there is little that is directly transferable to other cryogenic tankers, particularly in the fluid subsystem. The OSCRS avionics subsystem might have a fair amount of commonality; due to the safety issues with liquid hydrogen and liquid oxygen, however, the avionics redundancy and fault-tolerance would be closer to OSCRS than to the avionics for the SFHT, which is not as safety critical.

In evaluating technology needs for the superfluid helium tanker, we looked at both those items being developed on the SHOOT program, and those tanker-specific items not being developed on SHOOT. In some cases, those items being developed on SHOOT require additional testing for 50 missions usage or to design limits beyond those used for the experiment test bed. Table 7.1 is a brief summary of the technology development being pursued for SHOOT. Table 7.2 contains our listing of development needs not being addressed by SHOOT. These items are listed in their order of prioritization. Under each item we have listed specific development issues or concerns pertaining to technology development of the specific item. It should be noted that some issues are marked "post-SHOOT". These are tasks that would be done following

Table 7.1 SHOOT Mission Technology Development

Demonstrate:

- Liquid Helium Transfer Using TM Pump
  - 500 L/Hr (Goal of 800 L/Hr)
- Fluid Containment Techniques
  - During Normal Storage and Cooldown of Receiver
  - During High Flow Rate Transfer
- Fluid Acquisition System
  - 500 L/Hr (Goal of 800 L/Hr)
- Mass Gauging and Flow Measurement Techniques
  - Heat Pulse
  - Superconducting Wire (With Settling)
  - Venturi Flowmeter
- EVA Transfer Line Coupler On-Orbit Operation
  - (Use of GRiD Computer; Interface with Orbiter GPC)

Table 7.2 Technology Development Needs Not Being Addressed by SHOOT

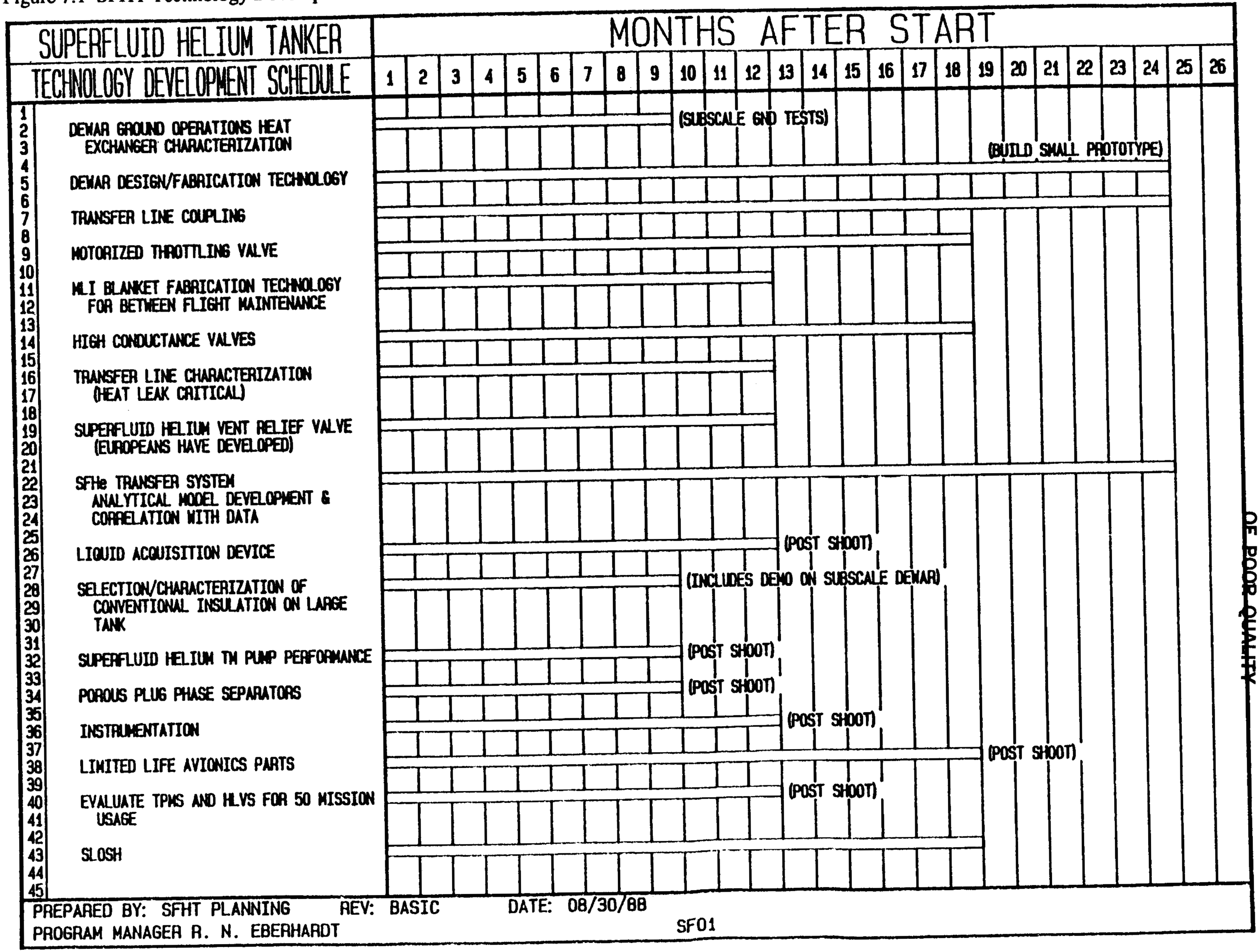
- Dewar Ground Operations Heat Exchanger Characterization
  - Internal Heat Exchanger Sizing and Design to Condition and Maintain Stored SFHe at Desired State Without Topping
- Dewar Design/Fabrication Technology
  - Structural Design Approach (Supports Piercing Into Inner Vessel)
  - Stiffness of Telescoped Tank Support
  - Effective Thermal Conductance of Telescoped Tank Support System; Thermal Cross-Coupling
  - VCS/Heat Exchanger Fabrication and Thermal Optimization
  - Alumina-Epoxy Straps for Large Dewars
    - Cycle Life To Meet 50 Mission Requirement
    - Thermal Performance
- Transfer Line Coupling
  - Qualifying for 50 Missions
  - Automatic Operation Carrier Interface
  - Heat Leak
- Motorized Throttling Valve
  - LHe Temperatures
  - Use as Thermal Conditioning (JT Valve)
  - Use for High Rate Venting During Transfer
- MLI Blanket Fabrication Technology for Between Flight Maintenance
  - Dewar Component Changeout Considerations
  - Blanket Edge Fabrication and Performance
- High Conductance Valves
  - Handle Fluid Transfer Rates to 1000 L/Hr
  - Reduced Weight
  - Good for 50 Mission Life
  - Low Heat Transfer (Valves Outside)
  - Total Shut-Off (Valves Inside)
- Transfer Line Characterization (Heat Leak Critical)
  - Flex Lines
  - Line Lengths to 12 Feet
  - EVA Compatibility (Including Couplings)
  - Emergency Disconnect Compatibility
  - Two Phase Flow During Transfer (How to Suppress, if Needed)
- Superfluid Helium Vent Relief Valve
- SFHe Transfer System Analytical Model Development and Correlation with Data (Assume One-g Transfer System Tests are Being Done by NASA and/or Industry)
- Liquid Acquisition Device (Post SHOOT)
  - Two-Fluid Flow
  - Pumping to Refill
- Selection/Characterization of Conventional Insulation on Large Tank
  - K vs T
  - Outgassing
  - Ability to Withstand Thermal Shock
  - Use of Reflective Surface (e.g. Tape) or Other Options Such as Direct Aluminum Layer Application
- Superfluid Helium TM Pump Performance (post SHOOT)
  - 500 to 1000 L/Hr Range
- Porous Plug Phase Separators (Post SHOOT)
  - High Capacity Porous Plug Phase Separators for Venting During Transfer
  - Characterization of Normal Vent Porous Plug Phase Separator (Controllability, Flooding, Efficiency as Thermodynamic Vent Element)
  - System Level Ground Demo - Separate Supply and Receiver Vessels
- Instrumentation (Post SHOOT)
  Level Sensors, Mass Quantity Sensors, Flow Meters
- Limited Life Avionics Parts (Post SHOOT)
  - Identification of Piece Parts That May Not Withstand 50 Missions (Examples: Switches, Relays, Motors, Solenoids)
  - Conduct Qual Tests To S Level to Impove Life
- Evaluate TPMS and HLVS for 50 Mission Usage (Post SHOOT)
  - Evaluate Reliability of Piece Parts
  - Examine Repackaging to Increase Reliability
  - Examine Maintainability (Parts Replacement
- Slosh
  - Design Concern? Impact to Liquid Acquisition Device?

completion of the SHOOT flight to address issues or performance ranges not being addressed by SHOOT. For all items in this category at least one issue is design/certification for 50-mission usage of the tanker; SHOOT is designed for one flight. Two items in the list were identified as potential candidates for zero-g investigation, liquid acquisition device performance and low-g slosh impacts.

A technology development program schedule of these items is provided in Figure 7.1. All items are scheduled as months from authority to proceed. Relative time phasing was not addressed, except that the post-SHOOT activities would start following the 1991 flight of SHOOT.

We prepared a rough order of magnitude cost estimate for each of these development items. This estimate is contained in Section 6.0 of our program cost estimate document submitted to NASA-JSC (Reference 7.1).

Figure 7.1 SFHT Technology Development Schedule



8.0 TASK 5 - PROGRAM PLAN FOR SFHT DEVELOPMENT

We prepared a program plan for the SFHT development which addressed our approach to the detailed design and development, fabrication and test of the superfluid helium tanker conceptually designed during this study. The phase C/D program as outlined runs through post-flight analysis of the first mission and is 6 years in length, ending with a launch in October 1997. The program plan, master program schedule and work breakdown structure are addressed in the following paragraphs. The groundrules associated with our program cost estimate will be presented in this section although the actual cost data is being submitted to NASA-JSC as a separate document.

8.1 PROGRAM PLAN

The program plan addresses detailed design, fabrication and test of the conceptual superfluid helium tanker design prepared during Task 3. The SFHT is designed to meet the requirements of the Systems Requirements Document, Attachment A to the contract SOW. The program consists of detailed design of both the flight equipment and GSE, fabrication and test of a dedicated Dewar Qual article to verify the multimission life capability, fabrication of one flight unit and one set of GSE, testing, delivery to NASA-KSC and support of the mission. We believe that eventually, a second superfluid helium tanker would be procured as a backup capability or to permit one tanker to be used as a depot at Space Station while the second one is used for servicing from the Orbiter, and in-situ servicing of a payload when carried to the user spacecraft with the OMV.

STS integration is considered an element of the SFHT program. The approach during Phase C/D will be to develop generic documentation (PIPS and annexes) for SFHT usage in the Orbiter bay. The generic documentation package will be an SFHT-specific boilerplate set of plans and annexes that can be tailored for each payload/user desiring superfluid helium resupply.

8.2 MASTER PROGRAM SCHEDULE

The phase C/D master program schedule for the SFHT program is shown in Figure 8.1. Time phasing is based on completion dates for defining requirements, performing design tasks, procuring required components and materials, accomplishing fabrication and assembly, and conducting validation and verification testing. The initial emphasis has been placed on the systems engineering activities necessary to define requirements and firm up the interfaces. Following concurrence with the requirements and specifications reviewed at the Program Requirements Review (PRR) by NASA-JSC, we will authorize major procurements necessary to support the fabrication and assembly activities, particularly for the Dewar qualification test article. Our plan is to fabricate all components and piece parts for both the Qual Dewar and the flight article. We will then assemble the Qual Dewar and conduct the qualification tests. While this is occurring, we will be fabricating the other (non Dewar) subsystems, which are to be tested and then flown, in a protoflight approach. Once Dewar qualification is complete, the flight Dewar will be assembled and integrated with the rest of the tanker subsystems. System level tests will then be performed for flight certification and the tanker delivered to NASA-KSC.

For those elements of the SFHT which are to be protoflight, special care must be taken in their validation and the combination of testing and analysis which shows they're good for the 50 mission design life. For both procured and Martin Marietta-manufactured hardware, our verification test program will be initiated at the component level. These component prototype tests are expected to drive out any problems early and are prerequisite to assembly-level prototype testing. This test approach ensures a systematic validation of performance, personnel, and procedures that minimizes risk and establishes high confidence in the system verification activities.

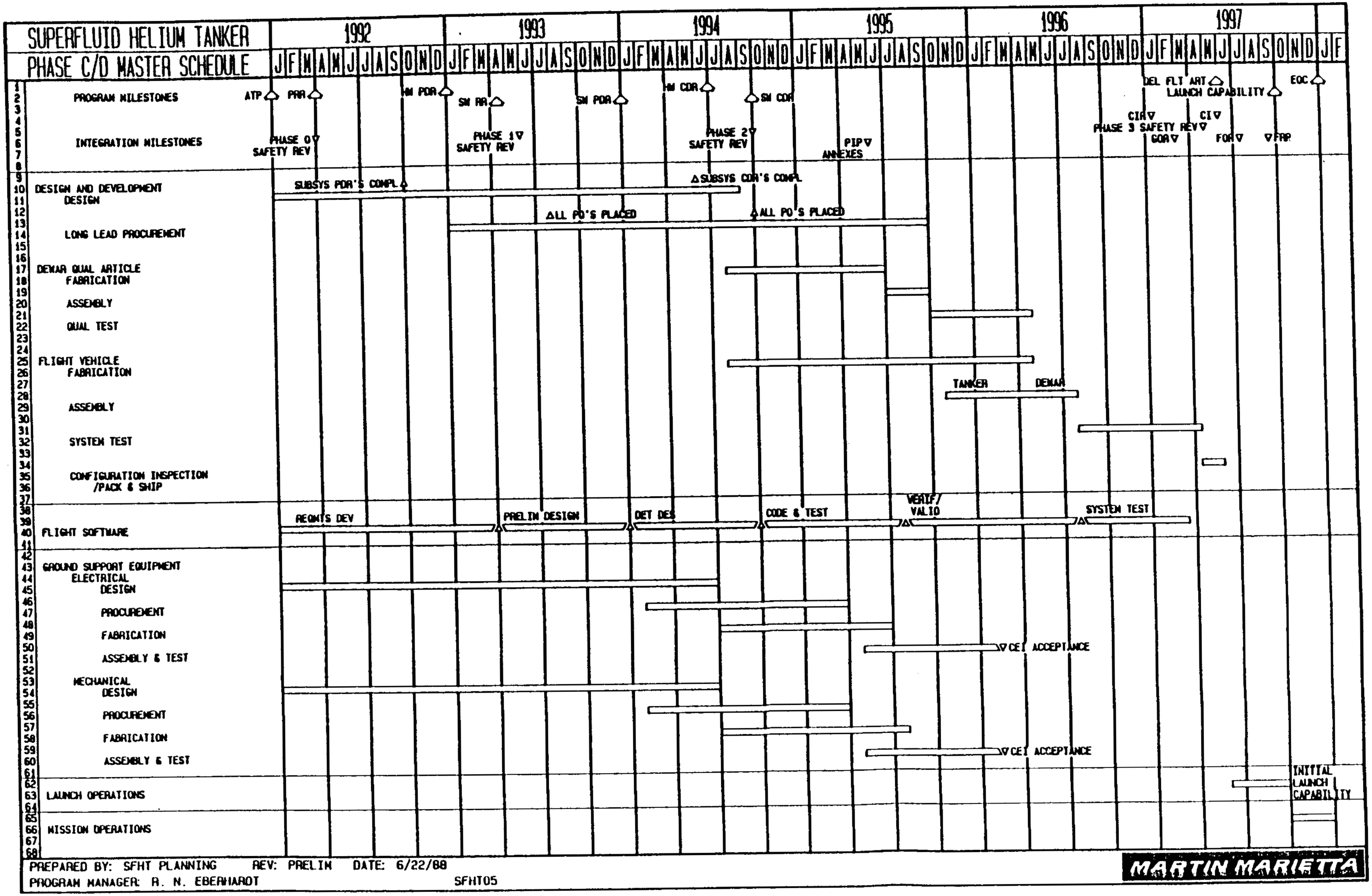


Figure 8.1 Superfluid Helium Tanker Phase C/D Master Schedule

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The tanker system test schedule, which is approximately 9 months in duration, is protected by preplanned schedule reserve and will support delivery to NASA-KSC 65 months from ATP. Launch operations also contains preplanned schedule reserve and supports the first flight of the SFHT. As indicated in the schedule, approximately 2 years at the beginning of the program is allocated for design and development.

8.3 WORK BREAKDOWN STRUCTURE

A Work Breakdown Structure (WBS) was developed which provides the framework upon which the programmatic technical, schedule and cost control is established. The WBS is broken down into six levels, as shown in Figure 8.2. The major categories in the WBS at the third level are:

- Program Management
- Systems Engineering
- Design and Development
- Hardware Fabrication, Assembly and Checkout
- Testing
- Software Design, Development and Test
- STS Integration
- Mission Operations

A total of 55 fourth level and fifty level subelements were identified.

8.4 PROGRAM COST ESTIMATE METHODOLOGY

A Program Cost Estimate was prepared and submitted to NASA-JSC (Reference 8.1) as a separate document, MCR-88-1403. All costs are reported in constant Government Fiscal Year 1988 dollars. The cost estimates reflect that the design of the SFHT incorporates components of like or similar design to those flying in the SHOOT orbital test. One major area of cost difference from the SHOOT system is the Dewar inner storage vessel, outer vacuum jacket, and alumina/epoxy support straps. We've also costed a dedicated Dewar test article for conducting qualification tests. Our structures, thermal, and avionics subsystem costs have been compared to those of the OSCRS design, with appropriate cost deltas generated per differences in the design. A set of the costing groundrules and methodology we used to prepare the phase C/D cost estimate is contained in Table 8.1.

Table 8.1 SFHT Cost Estimating Groundrules and Methodology

- Estimate made in constant government fiscal year 1988 dollars
- A SFHT phase B preliminary design and technology development effort is not included in costs for phase C/D effort
- STS integration is included as a cost element
- Cost estimates do not include contractor fee, but include overhead, and general and administrative costs
- Normal GFP/GFE, such as launch site facilities, liquid helium and transportation, is assumed
- A protoflight testing approach is used at the superfluid helium component level and a full qualification at the Dewar level. The carrier and other support subsystems will use the protoflight approach
- Vendor data quotes are not used
- Cost estimating techniques used depend on amount and type of design data available
    - Parametric cost estimating relationships (CERs) (mathematical equations derived from historical data
    - Historical Analogy (Historical cost data of a point design used to establish a new item)
    - Industrial engineering estimates (production costs built up in terms of material usage and labor quotes)
    - Expert analysis (tops-down, bottoms-up or vendor quotes)
- Estimates were prepared for each program plan category. Costs were broken out for non-recurring, recurring (1st unit) and recurring (1st launch)
- Estimates were prepared for each subsystem for both design and development, and hardware fabrication, assembly and checkout

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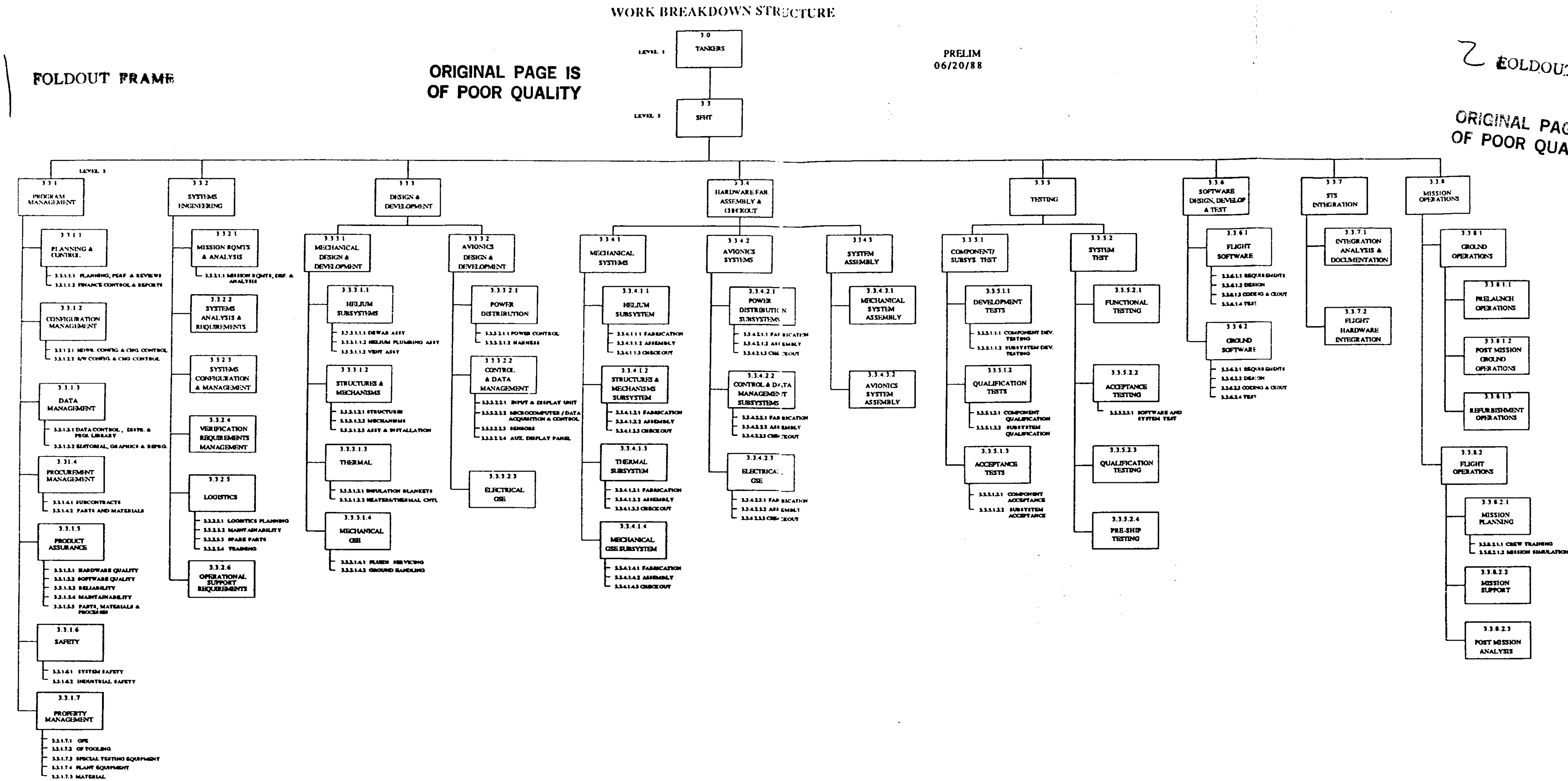

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Figure 8.2 Work Breakdown Structure (WBS)

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9.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were complied during the course of the SFHT study effort:

- A 6000 liter SFHT appears to be a reasonable size to handle the reduced user complement specified for SFHe resupply through the year 2006. We had selected the 6000 liter capacity during our Task 2 effort using this reduced user complement and found no reason to change that decision.

- We have selected a slightly cylindrical Dewar shape which fits within the fairings of the Delta, Atlas, Titan III and Titan IV launch vehicles, as well as the STS Orbiter. This results in a mixed fleet approach to minizing total mission launch costs. We recommend that the SFHT be designed for compatibility with only one ELV in addition to the Orbiter since interface hardware and ELV unique GSE, operations and integration can result in significant non-recurring and recurring costs to maintain flight compatibility with all ELVs.

- We have selected a ground servicing concept which utilizes a ground heat exchanger for establishing and maintaining the storage Dewar at the desired temperature without activating flight valves to conduct periodic topoffs. This technique allows us to "subcool" the Dewar thermal protection system and meet the eleven day ground hold period following cargo bay door closure. Either pressurized (subcooled) or saturated superfluid conditions in the Dewar are possible.

- Based on a worst case vent analysis for loss of guard vacuum (where we assumed some stratification could develop within the supercritical fluid at the 80 psi burst level), we selected a conventional insulation (non-MLI) to be applied to the inner storage vessel to reduce the heat flux and minimize the size of the vent line. We configured two totally redundant vent lines within the Dewar to handle loss of guard vacuum conditions.

- Our selected avionics approach ties into the Orbiter GPC for safety-related monitoring and utilizes a redundant computer system on the AFD for superfluid helium transfer monitoring. We baselined the use of the HLVS and TPMS boxes being developed on SHOOT to interface with tanker temperature and pressure sensors, valves, and TM pump heater elements.

- An overboard vent interface, such as a J-O umbilical interface or a "generic" orbiter vent interface, is required to handle nominal and emergency venting when the SFHT is launched in the STS. Automated decoupling is needed in the vent line, as well as the electrical SFHT/STS interface to allow the SFHT to be removed from the Orbiter for its use as a Space Station supply depot.

- We recommend that automatic refueling (transfer line coupling interface) be baselined as the primary method for SFHT with capability for EVA mating/demating as a backup.

- We can meet the design goal mass fraction of 0.25.

Several recommendations for additional study effort beyond the scope of work on the present contract resulted from our study effort:

- Some follow-on work should be performed to identify approaches for establishing SFHT stability once on-orbit when launched by an ELV. The overall ELV operating concept, including docking and transport scenarios with the OMV, should be more thoroughly investigated.

- Growth provisions for adding helium refrigeration/reliquefaction capability should be investigated as a means of minimizing the adverse boil-off and venting.

- Users desiring superfluid helium resupply should assess receiver Dewar design impacts early in their design process since the ability of the SFHT to adequately accomplish the servicing is coupled to the specific features of the user's design. Developing standardized interfaces is required to minimize the diversity and complexity of the SFHT interfaces to the potential users, but is difficult until user interface requirements are much better defined. User interface definition should also be an early priority in the user design process.

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