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The in-flight tests and the operational sequences of the Superfluid Helium on-Orbit Transfer (SHOOT) experiment are outlined. These tests include the transfer of superfluid helium at a variety of rates, the transfer into cold and warm receivers, the operation of an extravehicular-activity coupling, and tests of a liquid acquisition device. A variety of different types of instrumentation will be required for these tests. These include pressure sensors and liquid flow meters that must operate in liquid helium, accurate thermometry, two types of quantity gauges, and liquid-vapor sensors.

Keywords: space cryogenics, helium, spacecraft operations

The Superfluid Helium On-Orbit Transfer (SHOOT) project is a demonstration of the components and operations that might be needed to resupply liquid helium in space. The SHOOT is not intended to act as a prototype of the tanker that will eventually service space-based instruments, rather it is only a demonstration of the critical components and operations for such a tanker. A description of the SHOOT system and its component parts has already been given.[1] This paper will emphasize the on-orbit operational aspects of the demonstration. These operations have been selected to test the system over a wide range of conditions to ensure that the components will work as designed. In addition, many of these operations will form the basis for the operations to be used on the future tanker.

The operations that will be undertaken during the flight are:

1) Cool down the transfer line;

2) Resupply a cold, partially full tank. This will be done at various rates from 0.1-0.8 m^3/hr at a variety of supply temperatures (1.3-1.8 K) and receiver temperatures (1.3-2.0 K)

3) Resupply a warm, empty tank. This will be done at two temperatures. One near 20 K and the other possibly as warm as 150 K.

4) Operate and verify a heat-pulse-type mass gauge. (The mass gauge is of the same type as the one used in the Superfluid Helium Experiment (SFHE), but has much greater accuracy; ref. 2.) This gauge will be compared to superconducting wire level gauges during periods of beneficial acceleration.

5) Verify that the liquid acquisition system can function during adverse accelerations; and if the accelerations are sufficiently strong to cause the liquid acquisition system to fail, then to verify that the system will recover and restart at the end of the acceleration.

6) Demonstrate the human factors of connecting and disconnecting the transfer line; and that these operations do not change the thermal performance and flow impedance of either the coupling or transfer line.

7) Demonstrate that the astronauts can do a complete transfer operation from a controller (AFDC) mounted on the aft flight deck of the Space Shuttle. (Most of the transfers will be controlled from the ground.)

8) Demonstrate the in-space conversion of normal helium to superfluid. This operation is not required for the tanker, which will be launched with superfluid. However, because of ground operational and weight constraints, SHOOT will probably be launched with normal fluid.

These operations will be described later in more detail after a brief description of the components of the system.

Hardware description

A more detailed description of the SHOOT hardware has been given in Ref. 1. It consists of two 0.21 m^3 helium Dewars. These will be mounted in the forward part of the Space Shuttle's cargo bay. Figure 1 shows an artists concept of the Dewars and associated hardware. A schematic representation of the interior of one Dewar is shown in fig. 2. The two Dewars are connected together by a flexible transfer line. At launch the transfer line will be connected to the Dewars. Part way through the mission an astronaut will go out to the cargo bay (as an extravehicular activity (EVA)) to disconnect and then reconnect the transfer line. Each Dewar has a fountain effect (thermomechanical) pump allowing the helium to be transferred back and forth between the two Dewars a number of times. The flow from the pump will be measured by a venturi flowmeter. To ensure that there is always liquid at the inlet of the pump, there is a gallery-type liquid-acquisition device. This device has four arms made of a U-shaped channel with a fine mesh screen across the open side. The arms are mounted close to the inner tank wall so as to always be at least partially wetted. The arms meet in a sump at the pump inlet. Twenty liquid-vapor sensors/tank[a] are distributed within the arms and main part of the tank. The majority will be placed inside one of the arms. A few are placed in the pump sump and in the main body of the tank. In the main volume of each tank there are four superconducting level sensors. These are for use during ground operations and on-orbit during periods of acceleration. Each tank is vented through two phase separators; one for venting vapor from either normal fluid or superfluid, the other will only be used when large quantities of heat are being dissipated in the superfluid. The fill line incorporates a heat exchanger to the inner tank wall to help precool a warm tank. The two tanks are identical, except that only one of them has a coupler that can be operated on-orbit by an astronaut. Distributed throughout the system there will be numerous temperature and pressure gauges

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[a] The liquid-vapor sensors are purely resistive devices as opposed to the normal-superconducting device of the SFHE. Operationally they are similar to the SFHE devices (ref. 2), but dissipate less than 0.2 mW/sensor.

(Table 1) for monitoring the performance of the system and its components. In addition there are a number of valves and heaters for controlling the system.

Operations

Operations will normally be controlled from a ground operations center (Program Operations and Control Center; POCC). Here the operators will be able to send commands (or pregenerated groups of commands) using a computer. The commands will select which sensors are to be monitored and will individually actuate the various valves and heaters. The computer will store a record of all commands sent to and all data received from SHOOT. Also, this computer will display, on several graphical and alpha-numeric screens, the status of SHOOT. A second computer will be mounted on the aft flight deck of the Space Shuttle. This will display data for the astronauts during those operations they participate in, and will allow the astronauts to control one of the transfers.

Two operations are automatic (independent of the computers). The first is the activation of SHOOT during ascent, prior to communications being established. The second is the automatic shut down of the system if communication is broken for longer than a predetermined period of time. This time delay is set to any length by a command from the operator.

A highly simplified diagram of the sequence of the operator-controlled operations is shown in fig. 3. This figure shows the principal operations, which are discussed below.

The flight operations begin with the launch of the Space Shuttle. Prior to launch the power to SHOOT is off. Both Dewars will have been topped off 2-3 days before launch. The liquid helium starts subatmospheric but may be above atmospheric pressure at launch, venting through relief valves. There is no communication between the POCC and SHOOT until sometime after SpaceShuttle has reached orbit. During the ascent, power is turned on and valves F (fig. 2) in the normal vent lines are opened. These events are triggered by barometric pressure. Opening the valves increases the pump down rate of the liquid helium and sets a pressure gradient across the phase separator necessary in the event of launch with superfluid in the tanks. Turning on the power starts the data system which will start reading all the sensors in a continuous sequence. The ascent data is stored on board for later retrieval.

After reaching orbit, communications will be established between the POCC and SHOOT. At this time the automatic data taking sequence is halted and the status of the hardware is established. All the sensors will be read and intercompared to determine which, if any, have failed. Failed sensors will be deleted from subsequent lists of sensors to be monitored. In some cases, back up sensors will have to be used for the monitoring of critical operations. From this time on the operators can select which of the many sensors will be read and in what order they are read. A list of desired sensors will be transmitted to SHOOT. This list will be endlessly cycled through until a new list is sent. All data will be transmitted to the ground for processing and storage. None of the data will be stored on board (except during brief periods when the communication link is broken). With the opening of the communication link, the operators will be able to control the various valves and heaters in SHOOT. Valves E, G, and H are opened. Opening G opens the high flow vent line and E vents the transfer line (valve J was open at launch). H vents the nose seal of the coupler. This vent is used to verify the performance of the coupler's nose seal and to vent any residual leakage past the nose seal. Valves F, G, and H remain open for the rest of the mission. They will only be closed just prior to reentering the atmosphere. The system is now in the standby mode. At a convenient time the operators can command the ascent data to be transmitted to the ground.

After the system has been checked out, the helium may still be above the superfluid transition temperature. Allowing the pump down and conversion to superfluid to be monitored. This will establish the effectiveness of the normal phase separator. While this information is not needed for large helium systems, such as the the helium tanker, it may be useful to future uses of small helium Dewars. If helium can be launched as normal fluid and converted to superfluid in space, then small systems can be launched without the need to carry on-board vacuum pumps for pre-launch operations, as the Superfluid Helium Experiment (SFHE) did.[2] This would simplify prelaunch ground operations.

Once the conversion process is finished, the mass in both tanks will be measured using the heat-pulse technique. From this time on, a running estimate of the quantity of helium in each tank will be kept. This estimate is maintained by estimating the mass vented (estimated from the tank pressure, vent line impedance, and whether valve D is open or closed) and by estimating the mass transferred from one tank to the other (estimated by integrating the flowmeter readings). The estimated masses will by corrected each time the heat pulse mass gauge is used. The mass gauging will be repeated before, after and twice during each transfer. While this may seen to be a large number, many of the measurements can do double duty. A post transfer measurement on one transfer can also serve as a pretransfer measurement for the next transfer.

To compare our heat-pulse mass gauging technique with a more standard technique of level measurement used on the ground, a beneficial acceleration will be applied by the Space Shuttle to settle the liquid in the aft end of the dewar. An acceleration of a few milligravities will provide a relatively flat liquid/gas interface in the dewar. The depth of the liquid will then be measured using commercially available superconducting wire level sensor. At the same time the liquid/vapor detectors will be calibrated by applying various currents to the sensors during the low level acceleration. This data will be used to determine the optimum value for liquid/vapor discrimination while using the lowest power. The astronauts will determine the acceleration needed to settle the liquid while also watching the interface motion through a graphical display on the aft flight deck of the level sensors and liquid/vapor detectors.

The first of nine cold transfers can now begin. The object of these operations is to demonstrate the ability to refill cold tanks at different rates and temperatures and to establish the effectiveness of such refill operations. A cold transfer starts by closing valve E in the supply Dewar and precooling the transfer line by pumping through supply valves B and J . During this precooling operation the line is vented to space through receiver valves E, G, and J. During the several transfer line cooldowns, the transient behavior of the two phase flow in the transfer line will be observed. This will be done by measuring (on sequential cooldowns) the time history of the flow or alternately the pressure drop in the line. These measurements can be made at a 4-Hz data rate. At other times the various thermometers will be scanned at a 1-Hz data rate and the liquid-vapor detectors at a 5-Hz data rate.

Once the line is cold, the flow will be diverted into the receiver through valve C. When the receiver is full or the supply tank is nearly empty, the transfer will be stopped. If time permits the next cold transfer will start immediately without again precooling the transfer line. These transfers will proceed in alternate directions at a variety of flow rates (0.1-0.8 m^3/hr) and tank temperatures (1.3-2.0 K). While only nine cold transfers are shown in fig. 3, more will added at the end if there is sufficient helium. The flow rate is controlled by the power dissipated in the pump heater. The amount of heat required is given by a combination of the thermomechanical effect:

$$\Delta P = \int_T^{T+\Delta T} \rho S_T \, dT \tag{1}$$

and of the mechanocaloric effect:

$$\dot{Q} = \dot{m} S_T T \tag{2}$$

where ΔP and ΔT are, respectively, the pressure and temperature increases across the pump, T is the inlet temperature, ρ is the density, S_T is the entropy (at T), $\dot{Q}$ is the heat input and m is the mass flow. Equation 2 gives the effective heat load on the supply tank. The heat that is applied to the heater on the down stream side of the pump is given by

$$\dot{Q} = \dot{m} S_{T+\Delta T} (T+\Delta T) \tag{3}$$

This power could be as high as 40 W. The temperature, T, is controlled by opening or closing the high-rate vent lines (valve D). The downstream temperature, $T+\Delta T$, is determined by the pressure, ΔP, required for the flow to overcome the transfer line impedance.

During the sixth and seventh cold transfers a series of adverse accelerations of different magnitudes are applied. This settles the liquid at the "top" end, the end away from the pump. The object of this operation is to try to cause the liquid acquisition device to fail; and if it fails to see if it will spontaneously recover when the acceleration ends. The failure and recovery will be detected by the liquid/vapor sensors in the galleries and by the flow meter. Rapid readout of the flow meter and liquid/vapor detectors (approximately 5 times/sec) will show when and where the liquid acquisition device cavitates and how it restarts. The astronauts controlling the adverse accelerations will have real time feedback on the Aft Flight Deck Controller (AFDC) which will allow them to remove the acceleration immediately after the liquid acquisition breaks down to permit immediate recovery simulating the momentary accelerations which might be present in an actual tanker refill operation.

During both the beneficial and adverse accelerations the astronauts will be able to monitor SHOOT from the Aft Flight Deck Controller (AFDC). During the eighth cold transfer the astronauts will control the transfer from the AFDC. This is the transfer prior to the EVA and prior to the second warm transfer. At the end of the eighth cold transfer the starboard tank will be left empty. One of the purposes of these operations that involve astronaut participation is to demonstrate the human factors of the AFDC. The helium tanker will be controlled by operators in space through something like the AFDC.

There are two warm transfers planned. The purpose of these is to demonstrate servicing a tank that ran dry before servicing could be scheduled. After the fifth cold transfer the starboard tank will be emptied and allowed to warm to approximately 20 K. The second warm transfer occurs after the EVA. For this one, the starboard tank will be emptied before the EVA and allowed to warm to a higher temperature. If necessary, a heater can be used to speed the warming. The temperature for the second warm transfer could be as high as 150 K. The temperature will be chosen to ensure that there is enough helium left to recool and partially fill the tank. During a warm transfer, the transfer line is not precooled; rather, the flow through the transfer line is directed directly through the receiver (via valves J and C). This makes the maximum use of the enthalpy of the cold gas in cooling the warm tank. The heat exchanger in the fill line helps ensure that the maximum use is made of the latent heat of the liquid by helping vaporize the liquid before it enters the tank. This reduces the chances that liquid will be blown out the vent lines unvaporized. While the tank is warm, the phase separators are bypassed by opening valve A. Once the tank is cold enough to collect liquid, the bypass valve is closed and the transfer proceeds as during a cold transfer.

The last operation is the manipulation of the transfer line and coupler by the astronauts to demonstrate attaching and detaching a transfer line. There are two reasons for this operation. One is to demonstrate the human factors of operating a transfer line in 0 g. The other is to verify that the coupler and line can withstand being manipulated. This operation is left until late in the mission so that most of the data on transfers can be collected beforehand, in case the transfer line cannot be reconnected or is otherwise damaged by the EVA. This operation begins by the astronauts verifying that the valves are in the proper condition (A, B, C, D, and J closed; and E, F, G, and H open). The astronauts then turn off the power to the valve drivers, preventing the valves from changing position, even if commanded to do so. An astronaut goes out to the cargo bay (an EVA), disconnects the coupler in the transfer line, and then later reconnects the coupler. Next, the thermal performance of the transfer line and coupler, and their flow impedance are compared to their pre-EVA behavior. This is done by comparing the pressure drop and temperature rise during post-EVA transfers to that during pre-EVA transfers.

At times when no operations are taking place the system will be put into a standby mode. In this mode the transfer line is vented (valves J and E are open); the Dewars are vented through the normal vent lines; Valves A, B, and C are closed; and valve D will normally be closed unless there is a need to rapidly cool the Dewar. At these times all the sensors will be read sequence. From time to time communications between the POCC and SHOOT will be lost for various reasons. If this loss of signal (LOS) is expected SHOOT can be commanded to continue the current operation for a predetermined time period. At the end of this timed period SHOOT will revert to the standby mode unless it receives a further command from either the POCC or the AFDC. During an LOS's, 30 to 120 min of data may be temporarily stored for later transmission as it was during ascent.

The preceding operations were developed to accomplish the goals of the SHOOT mission, Which is to demonstrate the critical technologies and operations required for a future helium resupply tanker. In particular, to verify components and techniques that have not been demonstrated in space before and cannot be demonstrated on the ground.

Acknowledgements

We wish to thank the help and support of the people (too numerous to list here) within NASA and from industry and universities who have and are continuing to contribute to this project.

REFERENCES

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2. Mason, P., Petrac, D., Elleman, D.D., Wang, T., Jackson, H.W., Collins, D.J., Cowgill, P., and Gatewood, J.R., Advances in Cryogenic Engineering, 31 (1986) 869.

Table 1 Sensor and heater list for one SHOOT Dewar

Type	Location	Type	Location
GRT	Coupler-transfer line side	PRT	Transfer line exterior
	Coupler-dewar side		Normal vent exit
	Normal vent at OVCS		Coupler vent exit
	High flow vent at OVCS		High flow vent exit
	Between B and flowmeter		Outer vapor cooled shield (OVCS)
	Top of normal phase separator (2)		Tank bottom (2)
	Bottom of normal phase separator		
	Top of high flow phase separator (2)	APT	Above J
	Bottom of high flow phase separator		Cold plate
	Tank wall (3)		
	Inner vapor cooled shield (IVCS)	DPT	Flowmeter high
	Top of TM pump (2)		Flowmeter low
	Bottom of TM pump		
	Heat exchanger outlet	Heaters	Transfer line primary
	Pump housing (sponge)		Transfer line secondary
	Pump housing (gallery arm)		Operate TM pump (2)
	Spare (4)		Mass gauge (2)

Table 1 Concluded

Notes: Each Dewar has an identical set of sensors and heaters

GRT = germanium resistance thermometer

PRT = platinum resistance thermometer

APT = absolute pressure gauge

DPT = differential pressure gauge

(n) indicates the number of devices

FIGURES

Figure 1	An artist's concept of SHOOT mounted on it is supporting structure with an astronaut disconnecting the transfer line.
Figure 2	Schematic of the interior of a SHOOT Dewar showing the principal components including the plumbing lines (except emergency vent lines), valves, pressures sensors, flowmeter, mass and level sensors, and phase separators. Not shown, because they are too numerous, are the temperature sensors and the liquid-vapor detectors. The two Dewars are identical, except only the starboard one has an EVA coupling.
Figure 3	Sequence of operations for SHOOT. The sequence has been greatly simplified for clarity. Conversion refers to the on-orbit conversion of normal fluid to superfluid. Xfer is an abbreviation for transfer. Beneficial g refers to an acceleration of the shuttle in the forward direction. Adverse g is an acceleration in the opposite direction. EVA refers to the astronaut operations in the cargo bay.

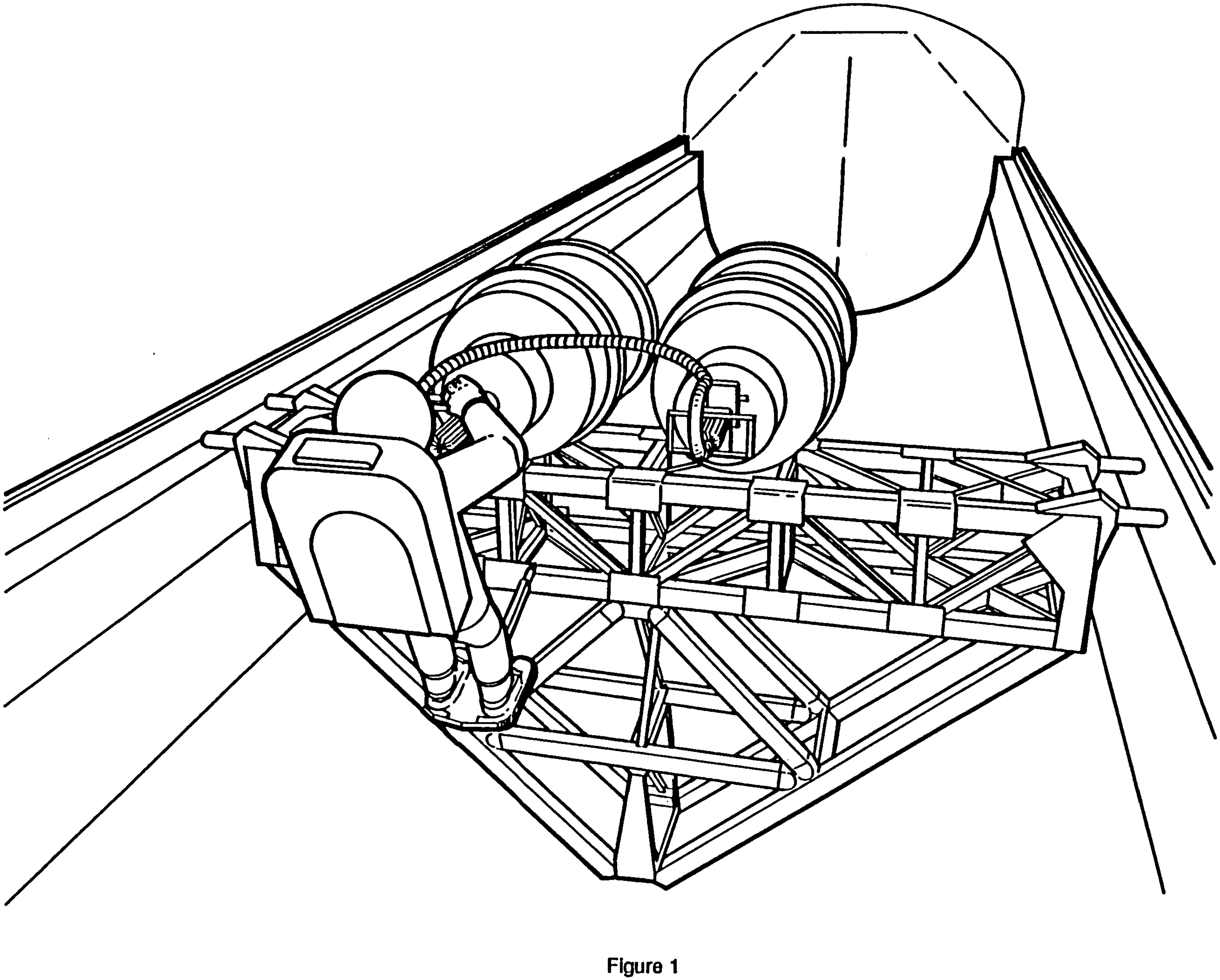
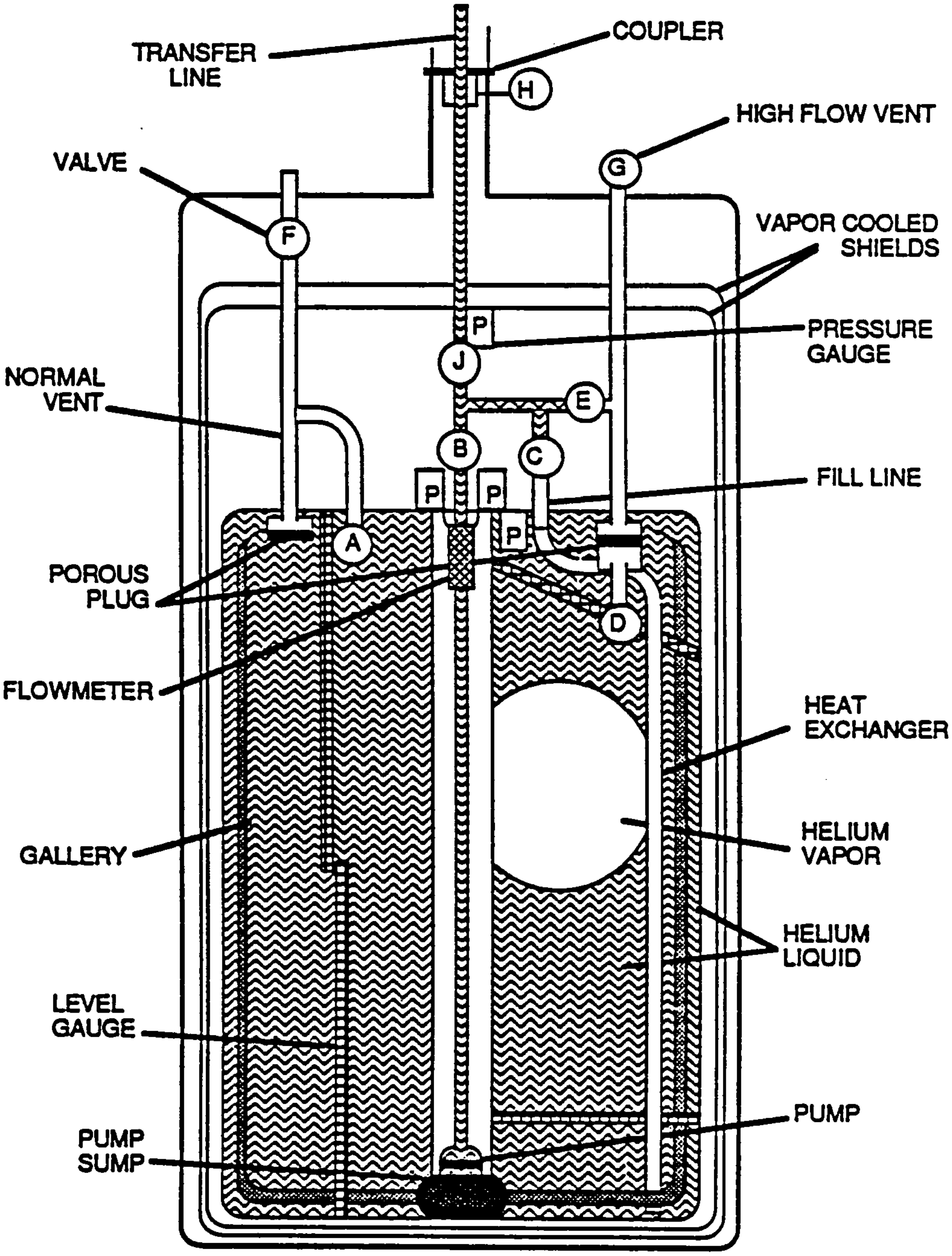


Figure 1


TRANSFER LINE
COUPLER
H
HIGH FLOW VENT
G
VALVE
F
VAPOR COOLED SHIELDS
P
PRESSURE GAUGE
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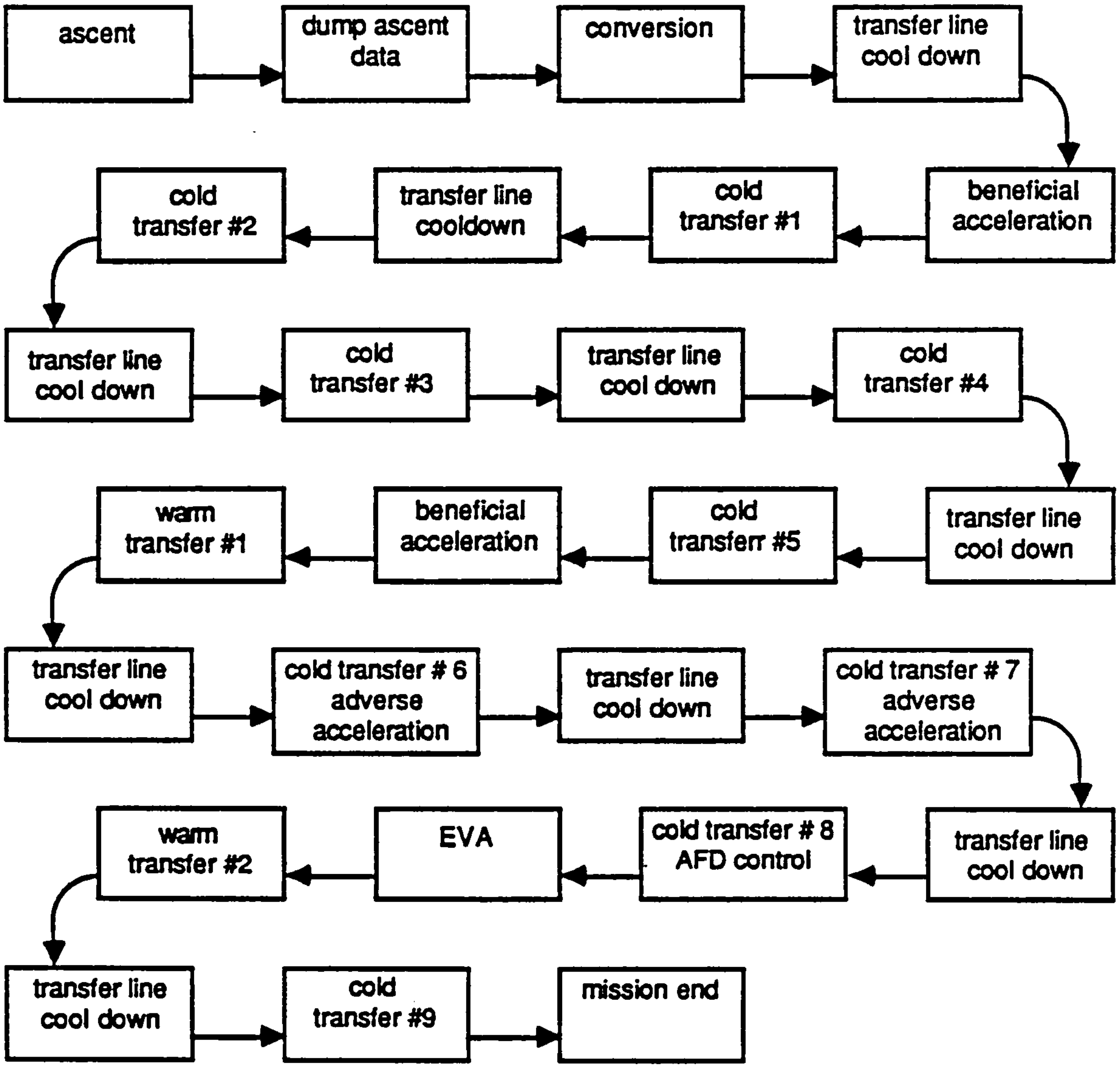
NORMAL VENT
E
B
C
FILL LINE
P
P
P
A
POROUS PLUG
D
FLOWMETER
HEAT EXCHANGER
HELIUM VAPOR
GALLERY
HELIUM LIQUID
LEVEL GAUGE
PUMP
PUMP SUMP

Figure 2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dump ascent data
conversion
transfer line cool down
beneficial acceleration
cold transfer #1
transfer line cooldown
cold transfer #2
transfer line cool down
cold transfer #3
transfer line cool down
cold transfer #4
transfer line cool down
cold transferr #5
beneficial acceleration
warm transfer #1
transfer line cool down
cold transfer # 6 adverse acceleration
transfer line cool down
cold transfer # 7 adverse acceleration
transfer line cool down
cold transfer # 8 AFD control
EVA
warm transfer #2
transfer line cool down
cold transfer #9
mission end

Figure 3

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16. Abstract
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