Chapter 4
The Superfluid Helium On-Orbit Transfer (SHOOT) Flight Demonstration

Michael DiPirro

Abstract Cryostats for space applications have unique requirements including significant weight and volume limits as well as the need to take into account zero gravity when designing fluid systems. This chapter describes the design, testing and space operations of the Superfluid Helium On-Orbit Transfer (SHOOT) flight demonstration. Topics covered in the design of the SHOOT cryostats include: structural and thermal insulation design, phase separation and liquid acquisition systems, the use of thermomechanical pumps, instrumentation and safety. Operations on both the ground and on orbit are also discussed.

4.1 Introduction

In the 1980s NASA recognized that there would be an increasing demand for cryogenic instruments in space. In particular, cooling to below 4 K would become routinely required for advanced astronomical instruments. In that period cryocoolers for this temperature range were in their infancy; none provided long life, high reliability, and low input power required for space flight. This left stored cryogens, uniquely liquid helium, to be required for many future missions. Refueling helium dewars in orbit was being studied to extend these instrument's lifetimes in the early days of the space shuttle and in the concept phase of the International Space Station [1]. The Superfluid Helium On-Orbit Transfer (SHOOT) Flight Demonstration was proposed in 1984 to carry out a series of tests of the technology and physics required to store and move liquid helium from a large depot into individual dewars aboard various satellites.

The experimental components for SHOOT, which drove the requirement for an on-orbit test, were the liquid acquisition devices (LADs). These LADs could only be thoroughly tested in the proper acceleration conditions, i.e., in a very low acceleration for an extended period of time, in orbit. Of course one must demon-

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M. DiPirro (✉)
Code 552, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
e-mail: mike.dipirro@nasa.gov

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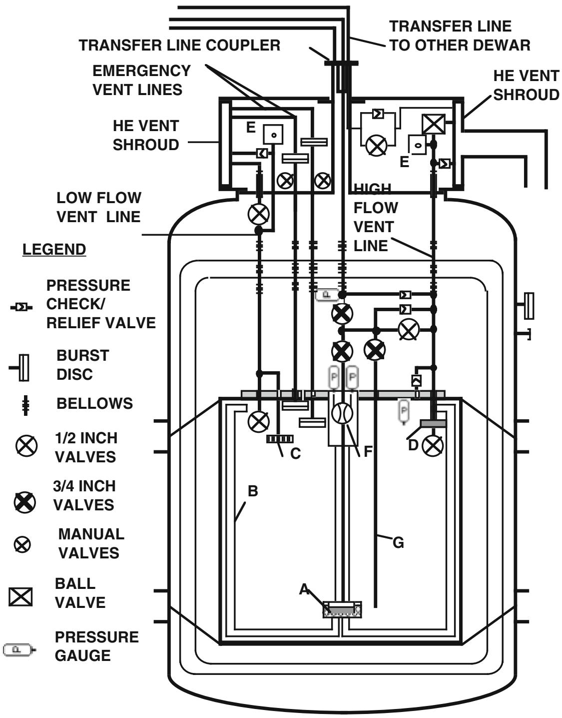


Fig. 4.1 Schematic of one of the SHOOT dewars. *A* TM pump; *B* liquid acquisition device; *C* HeI/HeII phase separator (also known as the low-flow phase separator); *D* high-flow phase separator; *E* anti-thermoacoustic oscillation volumes; *F* venturi; *G* fill line

strate the ability to control the fluid position during a number of different states of the system: precooling a tank, filling or draining a tank, and during adverse accelerations. To provide these conditions it is therefore necessary to implement an entire system demonstration in orbit. In the design of the space demonstration consideration was given to scaling of the system to larger sizes, hold times of the liquid helium tank before launch, and many other practical limitations. There were also several opportunities that presented themselves in a technology-only mission, namely obtaining engineering data as a primary goal. SHOOT also served as a test bed for intelligent machine control of a complex process in orbit.

The SHOOT payload consisted of two dewars connected by a flexible transfer line. The two dewars, labeled "port" and "starboard", contained removable cryostat inserts ("cryostats") on which the experiments' components, the valves and plumbing were mounted. See Fig. 4.1 for the schematic of one of the SHOOT dewars. The two dewars were identical, but the cryostats contained different LADs (Fig. 4.2) and liquid/vapor detectors to measure the liquid position on orbit. Superfluid helium was pumped between the two dewars using the thermomechanical, or fountain, effect that allowed heat to be directly converted to a pressure differential across a material with fine pores.

During the SHOOT design phase the shuttle Challenger suffered a catastrophic failure during launch. This led to a fundamental rethinking of the way the remaining

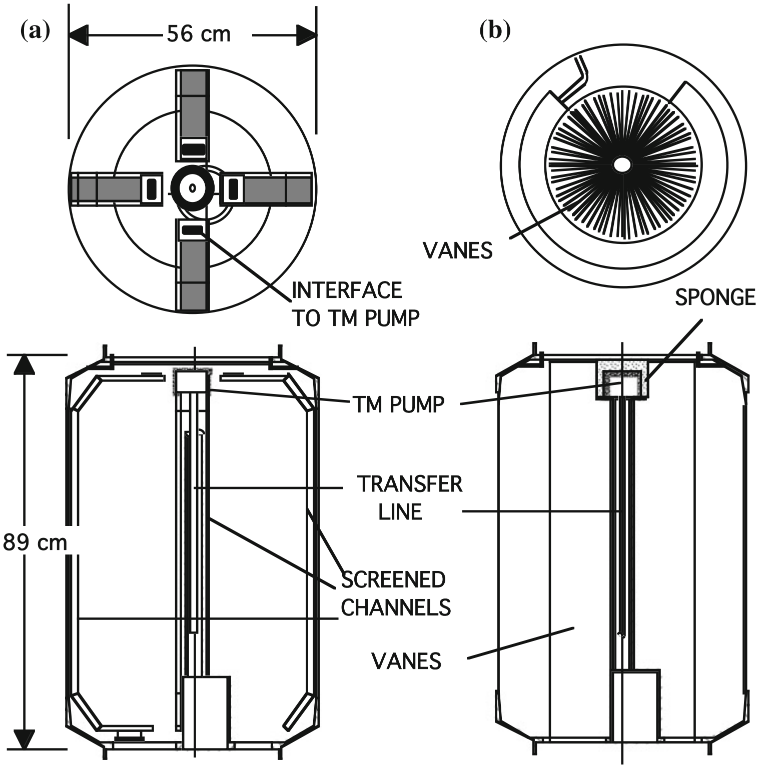


Fig. 4.2 Arrangement of **a** the screen channels in the starboard helium tank and **b** the vanes and sponge reservoir in the port helium tank. The vanes are fewer in number and extend out to the wall of the helium tank contrary to the schematic illustration

shuttles would be used and to an emphasis on safety. Up until this point the plan was to use SHOOT on two missions: the first to explore the fundamental aspects of helium management in orbit, and the second (SHOOT-II) to explore the human interfaces in a real dewar-to-dewar helium refill. When the shuttle manifest contracted, some of SHOOT-II's goals were folded into SHOOT. A manual, astronaut-Extra Vehicular Activity (EVA) compatible connector that astronauts would exercise during an EVA on SHOOT-II was dropped due to cost and schedule, but an expert system computer program was planned along with an astronaut operated helium transfer from within the shuttle cabin.

In the ensuing years the reality of the cost of space flight and liquid-helium servicing also became apparent—science missions would not be able to afford to resupply on orbit. In most cases the bill was higher than the original science spacecraft cost. The raison d'etre for SHOOT would now be flight-proving the cryogenic components already developed or under development and demonstrating the technology of management of a cryogenic liquid on orbit.

4.2 Design Considerations

The SHOOT system was designed for ground testing as well as to function in space. The dewars had to be able to vent while horizontal or vertical. This involved careful positioning of the pumps and liquid/vapor detectors, and adequately sized ground support equipment vacuum pumps. The emergency vent system had to work when surrounded by air or in vacuum, and as far as possible, the operation of the system had to be demonstrated on the ground as well as on orbit.

SHOOT was a short duration space mission (days rather than months or years), which allowed some compromises on heat leaks compared to the extreme thermal isolation required for long life missions. The SHOOT tank was structurally supported from the outer vacuum shell by S-glass composite straps that were sized for infinite fatigue life rather than for the short duration required for testing and launch. This permitted a relatively simple suspension of the two vapor-cooled shields (VCSs) by attaching clamps to the straps. In fact, two VCSs were all that were required rather than the more standard three VCSs, which, again sacrificed thermal performance in favor of simplicity and size of the helium tank. In this configuration with a room temperature outer vacuum shell, the heat leak to the liquid helium was about 180 mW.

4.2.1 Structural Requirements

The dewar structural requirements for inertial, thermal and pressure loads are shown in Table 4.1. The largest inertial load requirement was to survive a very hard landing! (Fig. 4.3).

In addition the dewars were designed as fracture critical hardware, with a fracture control plan and provisions for non-destructive testing. The non-destructive testing included ultrasonic inspection of the raw material per MIL-STD-2154, special dye penetrant inspection per MIL-STD-6866 Type I, Method C or D, and radiography of welds per MIL-STD-453.

The dewars were designed for two launches and landing and a complete qualification test program with a safe-life safety factor of 4.

Bolted hardware was lock-wired to assure that a positive torque was maintained.

Table 4.1 Inertial loads used in the SHOOT design

Axis	Preliminary coupled load (Gravity, G)	Updated coupled load (G)	Verification load (G)
X	±15.7	±12.0	±5.7
Y	±4.7	±3.8	±3.1
Z	±8.4	±6.0	±5.5

Fig. 4.3 The space shuttle Endeavor landing a Kennedy space center. The "slapdown" of the nose wheel in a worst case landing is the most severe inertial load for the design

4.3 Dewar and Cryostat Details

4.3.1 Dewar Fabrication Details

The SHOOT Payload was mounted to a cross-bay carrier on the space shuttle (see Fig. 4.4).

Each dewar consisted of five main components (Fig. 4.1): the cryostat (which is discussed in the next section), fiberglass support straps, helium tank, inner and outer vapor cooled shields (IVCS/OVCS), and main shell. The dewars were designed to meet the shuttle safety requirements and the cryostats were readily serviceable. The dewar design loads were based on a combination of inertial and thermal loads, the maximum internal pressure of 410 kPa, and the support strap preload. Each load (Table 4.1) was multiplied by an appropriate factor of safety and then applied to a payload model in a NASTRAN finite element structural analysis. In general, highest element loads were extracted for each component so that the component was designed based on those loads.

An uncertainty factor of 1.25 was applied to these loads. The SHOOT dewars and components were designed to the preliminary loads. The SHOOT support structure was designed to the updated loads. The verification load was applied during vibration testing.

Each dewar had three straps on each end that were located 120° apart. The angle of the straps to the tank was chosen to minimize the tank to vacuum shell differential contraction effect on the straps' tension. The straps were fabricated by Structural Composites Industries from Owens-Corning Fiberglass Type S-2 high

Fig. 4.4 SHOOT at Kennedy space center. *Upper left* SHOOT on the cross bay bridge. *Upper right* SHOOT mounted in STS-57. *Lower center* SHOOT is mounted near the top of the payload bay just behind the Spacehab module

strength roving, bonded with SCI REZ 081 epoxy resin. The fiberglass was wound around two bobbins with a center-to-center length of 133 mm. The width of each strap was 20 mm and the thickness of each leg was 1.3 mm. The straps could only carry tensile loads, thus a preload of 11,000 N, based on inertial, thermal, and pressure loads, was applied to ensure that the straps were always in tension. The straps were instrumented with two strain gages to accurately measure the applied preload. The straps underwent a maximum of 12,000 cycles during ground test and flight, with a maximum load of 20,000 N. Several straps were tested from the production lot and showed an ultimate strength of greater than 90,000 N and a fatigue life (to the maximum load) of greater than 250,000 cycles. Additional testing showed that there was only a 10 % reduction in ultimate strength after 12,000 cycles [2].

The helium tanks had a 206 L helium capacity. The cold plate of the cryostat was mounted to the helium tank on the forward end with an indium seal and a closeout cover was mounted on the aft end also with an indium seal. The barrel of the helium tank was formed from a rolled cylinder of 3.18 mm thick 2219 T37 aluminum sheet. The two heads were machined from a 15 cm thick plate of 2219 T37 aluminum and welded to each end of the cylinder. The tank then was heat treated to the T87 condition, machined to final dimensions, and qualified by pressurizing to 735 kPa. The stresses that developed from this pressure, envelope the maximum stress due to inertial, thermal, internal pressure, and strap preload which would be seen during flight. Additional units were proof-tested to 575 kPa. During dewar assembly each tank was covered by a five layer multilayer insulation (MLI) blanket, consisting of double aluminized Mylar with Dacron net spacers.

The VCS used the cold, vented gas from the helium tank to intercept heat coming into the dewar. Each SHOOT dewar had two VCSs made from 0.5 mm sheets of 1100 series H14 aluminum. Each VCS was anchored at each strap through an aluminum block that was clamped between the legs of the strap. Epoxy bonding was attempted at first, but peeling of the outer fiberglass layer occurred at the bond edge. The forward anchors allowed flexibility in the axial direction of the tank to prevent buckling of the shields during cooldown. The forward and aft cones of the VCS's were removable to allow access to the cryostat and helium tank. During dewar assembly the inner VCS was covered by a 15 layer MLI blanket, and the outer VCS was covered with a 35 layer MLI blanket.

The main shell contained the cryostat, helium tank, and VCSs and provided attachment points between the dewar and the flight support structure. The barrel of the main shell was a rolled cylinder of 3.18 mm thick 2219 T37 aluminum sheet. The hard points of the main shell, which served as the interface to the flight support structure and the anchor for the support straps were two girth rings. The girth rings were machined from a 15 cm thick plate of 2219 T37 aluminum and welded to each end of the cylinder. The main shell was then heat treated to the T87 condition and machined to final dimensions. The forward and aft heads were spun domes from aluminum 2219 and 6061 respectively. After spinning they were heat treated to the T6 condition and then machined to final dimensions.

4.3.2 Cryostat Details

The dewar/cryostat system was designed for the easy removal of various components. The majority of these components were in the cryostat. The port and starboard cryostats were nearly identical to allow easy-change out of parts or even the entire assembly. To facilitate the removal of the cryostat, the dewar plumbing and valves were located in a small volume. Thermal attachment of the gas vent lines to the vapor cooled shields was made over a relatively short distance at the top of the dewar. Thermal conduction in the vapor-cooled shield material provided a nearly isothermal environment. For relatively small dewars, as in SHOOT, this scheme led to an acceptable temperature difference along the shields of about 13 K in the outer shield and 2 K in the inner shield.

In the jargon of space helium dewar design, SHOOT had an “instrument dominated” heat load as opposed to a “parasitic dominated” heat load. That is, the heat generated within the helium tank was large enough, on average, that optimization of vapor cooling to reduce parasitic heat did not much increase its lifetime. Coupled with the mission duration of about one week, this allowed the plumbing design to be optimized for the transfer of helium, rather than configured as a long-term storage dewar.

The cryostat plumbing lines consisted of a low-flow vent, high-flow vent, transfer line, and two emergency vents (refer to the schematic in Fig. 4.1). The low-flow vent led from the liquid/gas phase separator within the cryogen tank through a warm valve and out of the dewar. This was the normal vent path out of the dewar and was the primary means of cooling the VCSs. It was made of 12.7 mm diameter stainless steel tubing with 0.5 mm thick walls. The tube was interrupted by thin-walled bellows between the cold plate, IVCS, OVCS, and warm plate to allow for some misalignment and provide structural isolation between dewar components. The total length of the vent was approximately 1.2 m.

A cold valve could be used to bypass the phase separator for chill down of the dewar. The high-flow vent was a much shorter (0.6 m), straighter, and wider (18 mm i.d.) tube which led from the high-flow phase separator out of the warm plate to a large diameter Ball valve. It provided a low impedance vent path at the expense of vapor cooling efficiency for those times when large amounts of heat were being dissipated in the liquid such as during a transfer. The high-flow vent line was only weakly coupled thermally to the VCSs to minimize warming of the gas vented and thus decrease the pressure drop in the line. This, however, also led to an increased heat input to the cryogen tank of about 50 mW in the standby mode. The transfer line left the cryogen tank through two valves, running through the shields to the external coupler and external transfer line. This was similar tubing to the low-flow vent, and was thermally isolated from the shields as was the high-flow vent. The dual emergency vents provided the means of releasing fluid within the cryogen tank in a controlled, safe way following a catastrophic loss of the dewar guard vacuum. See the section on safety for more details.

Over 300 electrical leads traveled from hermetic connectors on the warm plate to the cold region of the cryostat. 90 % of the leads were made of manganin wire, with the remainder of 0.13 mm diameter copper. The leads were heat stationed at each VCS through a connector potted in Stycast 2850. This has proved to be an effective heat sinking method. Approximately 180 leads were fed into the liquid helium tank through 32 pin hermetic connectors. In our experience, these are the largest commercial connectors that can continue to be hermetic at low temperatures.

The main attachment of the cryostat to the cryogen tank was the cold plate at the top of the tank. The cold plate was machined from an explosion welded aluminum-stainless steel sheet [3].

4.4 Components

4.4.1 Development Notes

Each individual component developed for or used in SHOOT went through a thorough process of testing and qualification before integration into the flight dewar/cryostat system. Several of the components' performance could be visually observed by using glass dewars. We were able to see the phase separation performance of the high-flow phase separator, the low-flow phase separator, the liquid/vapor detectors, and part of the screen channel liquid acquisition system.

4.4.2 Phase Separation

The "natural state" of liquid helium in a dewar on the ground is 4.2 K at one atmosphere (4 K at the reduced pressure in Boulder, CO!). By the same token, in orbit where the pressure is practically zero the equilibrium temperature will be less than 2 K (i.e., superfluid). The equilibrium temperature of the liquid will result from a balance between the pressure drop in the vent line plus the phase separator and the boil off rate.

Without a significant acceleration aiding liquid settling, a method to allow boiling to maintain a low temperature and pressure while not exhausting liquid directly must be employed. For superfluid helium, the fountain effect can be used for this purpose. The fountain effect directly converts a temperature gradient into a pressure gradient in the same direction. In the two-fluid model, superfluid ^{4}He is composed of two interpenetrating components: a "super" component that flows without viscosity and a "normal" component that has viscosity and behaves as a normal Newtonian fluid. The fountain effect is realized in a porous material whose pores are small enough to significantly restrict the flow of the normal component while allowing the super component to flow freely. A temperature gradient across the porous medium then leads to a gradient in the proportion of normal and super component which gives rise to an osmostic-like pressure gradient. This pressure gradient is in the same direction as the temperature gradient and is about 12 times larger than the vapor pressure gradient in the opposite direction.

The device typically used is called a porous plug which consists of a disk of porous material (usually stainless steel) with small pores ($\sim$a few microns in diameter) through which a temperature and pressure gradient can be developed while venting out one side. Bulk superfluid helium is prevented from passing out of the plug by the fountain effect across the pores. The pores are sized at about 4 microns in effective diameter; large enough to allow some heat conduction out of the tank to maintain a relatively small temperature drop, while small enough to obtain a relatively large fountain effect (up to about 14 kPa). Trade-offs between ultimate temperature in the tank and large-enough fountain pressures usually end

Fig. 4.5 Picture of two high-flow phase separators. The cylinders are made of porous sintered stainless steel in a reentrant geometry to maximize the flow area and minimize pressure drop across this device

with a porous plug impedance that is on the same order as the impedance of the vent line downstream of the porous plug.

SHOOT used two types of phase separators: a high- and a low-flow phase separator, schematically shown in Fig. 4.1 as D and C, respectively.

The high-flow phase separator had commonly-used porous stainless steel but in a large area and with pores of effective diameter of 8 microns rather than the standard 4 microns (see Fig. 4.5). The 8 microns and large area were necessary to maintain a low temperature in the dewars during superfluid transfer. When transfers were not taking place, SHOOT's temperature was 1.06 K—the coldest thing in space!

As a passenger on the space shuttle, SHOOT had to abide by the access restrictions common to attached payloads. One of those restrictions was that the last servicing needed to be performed about 65 h prior to launch. For superfluid helium payloads on expendable launch vehicles (IRAS, COBE, IRTS, etc.) the last servicing was 12 h before launch. Waiting this extra time on the launch pad and maintaining the liquid below the lambda point would require an on-board vacuum pump [4] or a normal liquid helium guard tank [5]. The former had proven unreliable on two previous shuttle missions and the latter required a large fraction of the space within the vacuum shell. For SHOOT a new approach was implemented: launch with normal liquid helium (He-I, $T > 2.17$ K) and convert to superfluid (He-II, $T < 2.17$ K) on orbit. The added benefit to this approach was that vapor-cooling could be used while on the launch pad even when the liquid was below 4.2 K due to stratification.

The low-flow phase separator was designed to phase separate He-I from its vapor in addition to He-II from its vapor. The flow of He-I out the vent was throttled by closely spaced ($\sim$6 microns), parallel, high conductivity, copper washers. The washers were hollow in the center and helium flowed radially through

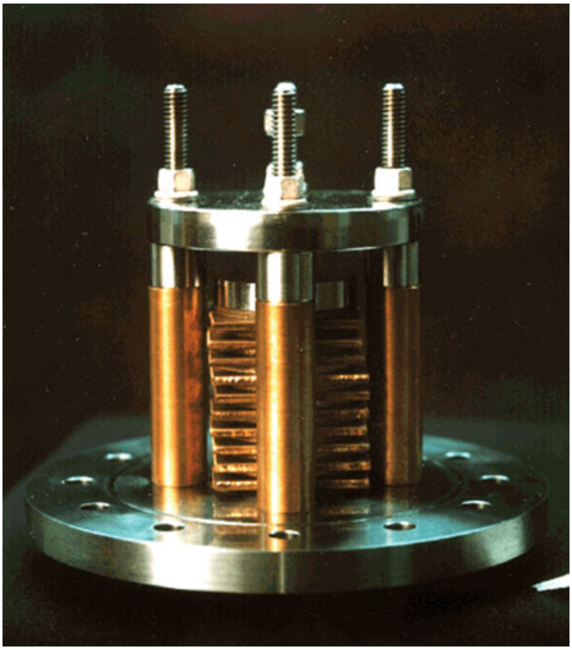


Fig. 4.6 The SHOOT low-flow phase separator. *Square* and *circular* disks alternate in the stack with tiny Kevlar fiber spacers. The bolt at the center top was sued to adjust the clearance between washers

the gaps to the vent line. The gap width in the stack of washers was controlled by an adjustable screw and pressure plate at the top of the device (see Fig. 4.6). The high conductivity copper carried the heat of vaporization of the helium back to the liquid in the center hole. We discovered that even at 2.17 K the Kapitza resistance at this inner boundary was significant. We then crenelated the inner surface to increase the surface area. This decreased the thermal boundary resistance to an acceptable value and this phase separator performed perfectly at pressures up to 110 kPa. As the dewar vented and temperature decreased the flow rate decreased, reaching a minimum at around the lambda point. During on-orbit operation the high-flow phase separator was used in parallel from slightly above the lambda point to continue lowering the temperature. For more details see Refs. [6, 7].

4.4.3 Liquid Acquisition

The LADs were the heart of the SHOOT demonstration. The screen channels (Fig. 4.7) could only be demonstrated on a small scale in one g and the vanes in the port dewar (Fig. 4.8) could not be demonstrated on the ground at all. Their function was to gather the liquid from various places within the tank and feed it to the pump by using surface tension. These are described elsewhere [8].

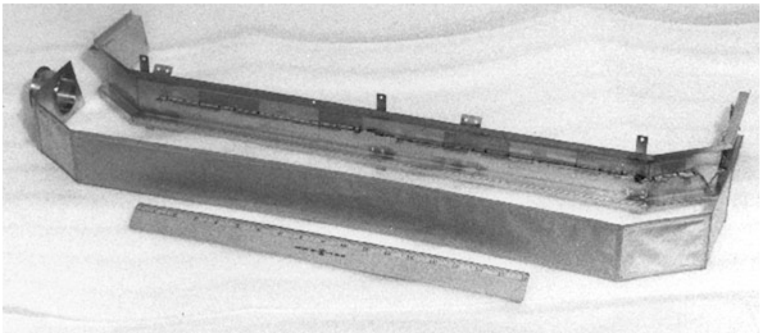
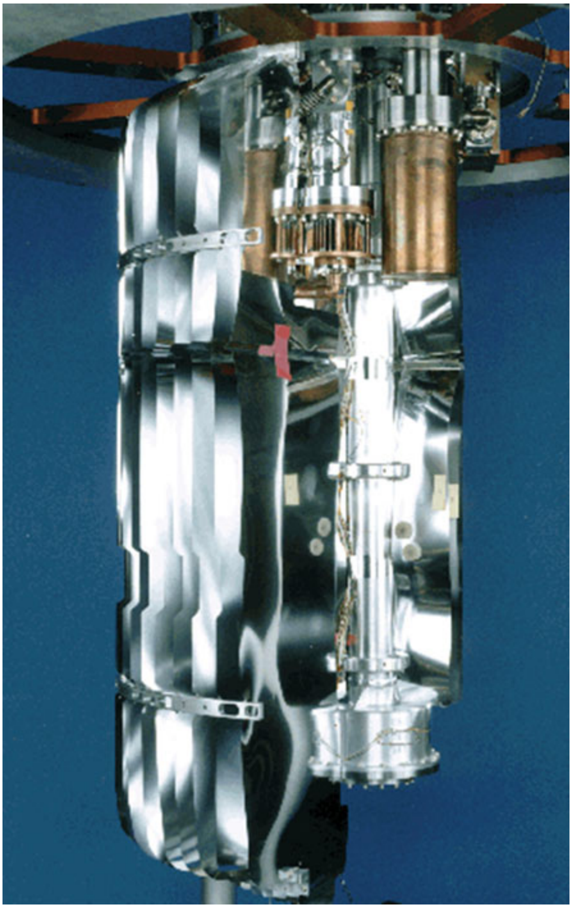


Fig. 4.7 One of 4 screen channels in the starboard dewar. The fine mesh screen (*lower half*) ran along the helium tank wall to scavenge as much helium out of the dewar as possible. A row of liquid-vapor detectors can be seen attached to the sheet metal top of the screen channel

Fig. 4.8 The SHOOT port dewar cryostat insert. The vanes extend to the outer edge of the inside of the tank and feed fluid to the center. At the top of the cryostat is the low flow phase separator housing (*center*) and the high flow phase separator housing (*right*)



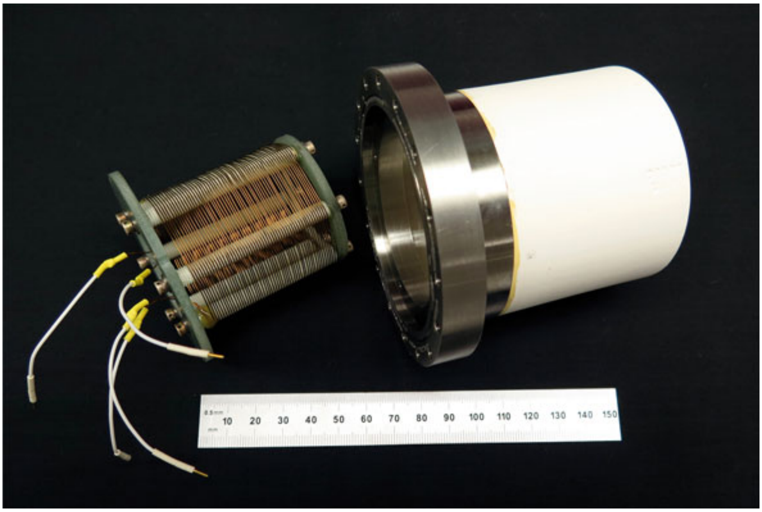


Fig. 4.9 The SHOOT thermomechanical pump. The item on the left is a manganin wire-wound 50 Ω heater which is inserted into the ceramic cup on the *right*. Together they comprise a pump capable of producing a flow of 1 m^3 per hour of superfluid helium

4.4.4 Thermomechanical (Fountain Effect) Pumps

SHOOT used the very simple and reliable fountain effect pumping method. The pumps were simply constructed from a mullite cup having pores with 0.4 micron effective diameter. These pumps were capable of flow of over one m^3 per hour and pressures up to 60 kPa [9] (see Fig. 4.9).

Motor driven mechanical pumps were tested with superfluid helium but had difficulty with cavitation at the inlet when a hydrostatic head was not present [10].

4.4.4.1 Instrumentation

Knowing roughly where the liquid was during the mission was a key requirement. To solve this problem discreet liquid/vapor detectors were developed. Implementation was very quick (concept to working model in 2 weeks, see Figs. 4.10 and 4.11) and effective [11]. LVDs could be read out by injecting a constant current through a string of Si chips and reading their individual voltages. The response to a change of state was milliseconds and their position accuracy in terms of the liquid-vapor interface was 10s of microns.

The key to understanding the performance of any cryogenic system is thermometry. SHOOT developed a state-of-the-art flight electronics system measured germanium resistance thermometers to 16 bit resolution and accuracy with a 17 Hz excitation. Thermometers were selected for relatively low resistance (<5000 Ω) to

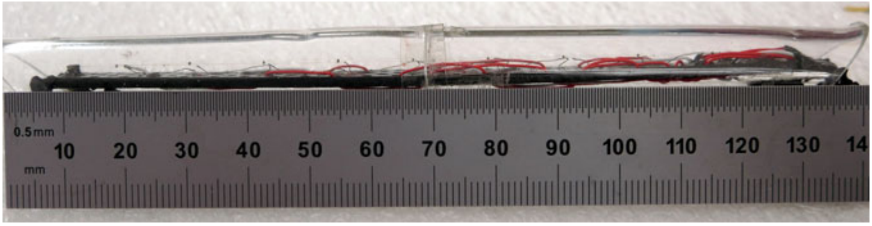


Fig. 4.10 Test model of the SHOOT liquid/vapor detectors. The *tiny dots* near the top of the picture space 10 mm apart are the 0.25 mm cube Si detectors mounted on a horizontal 0.05 mm diameter stainless steel wire

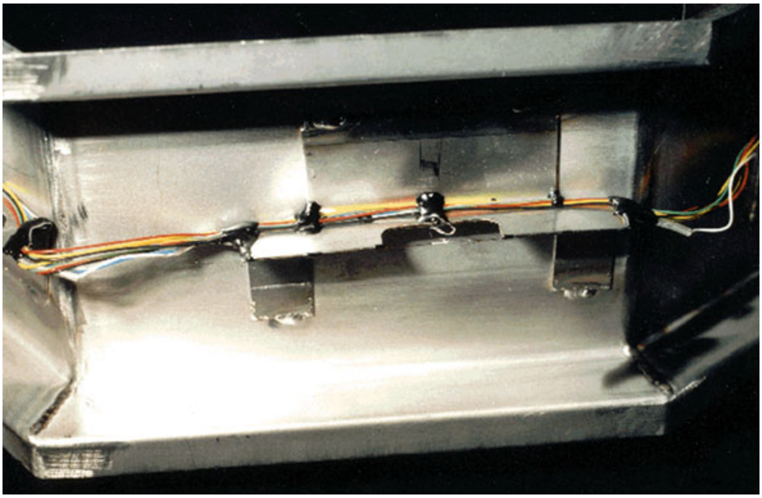


Fig. 4.11 Close-up picture of one of the liquid-vapor detectors inside the screen channel before the screen is welded in place

mitigate AC parasitic effects. This thermometry enabled high-resolution heat pulse mass gauging as described below.

In low gravity, where the liquid-vapor interface is not well known a priori, the amount of superfluid helium can be simply determined by applying a heat pulse and watching the temperature rise. This technique was used successfully on SHOOT to an accuracy of better than 2 %. It turns out that I learned a bit of forgotten thermodynamics at the same time because most of the 2 % error was due to calculating the fluid amount through enthalpy rather than properly using internal energy!

SHOOT measured the flow rate between the dewars in two ways: by the heating and upstream temperature of the TM pump [9] and by using a venturi flow meter. The venturi was read through variable reluctance pressure transducers and matched the TM pump inferred flow rate to better than 2 %. Integrating the two flow meters provided a check on the heat pulse mass gauging [12].

Strain gauge-based pressure transducers were also used to measure absolute pressure in each cryogen tank. These pressure transducers were bought from Teledyne Taber and used a Wheatstone bridge arrange for the strain gauges which eliminated temperature effects to first order.

4.4.5 Cryogenic Stepper-Motor Valves

Stepper-motor driven cryogenic valves for SHOOT were developed and qualified by Ralph Haycock at Utah State University [13]. Two valve sizes were developed, namely a nominal ½ inch valve and nominal ¾ inch valve. The finished valve assembly is shown in Fig. 4.12. The basic valve assembly consists of four major elements: a four-phase stepper motor, a recirculating ball screw assembly, a valve stem load cell, and the valve body. The stepper motor is a four-phase reluctance type motor. The ball bearings in the motors were replaced by dry-film lubricated bearings with increased dimensional tolerance to allow for thermally induced differential contraction. A redundant set of micro-switches at each end position provides positive indication of the valve status and control for the motor. The recirculating ball screw assembly consists of the transmission gears, the recirculating ball screw, and two rigid links that connect the recirculating ball nut to the valve stem through a load cell. The load cell assembly consists of the valve stem and an adjustable load cell consisting of Belleville spring washers stacked in

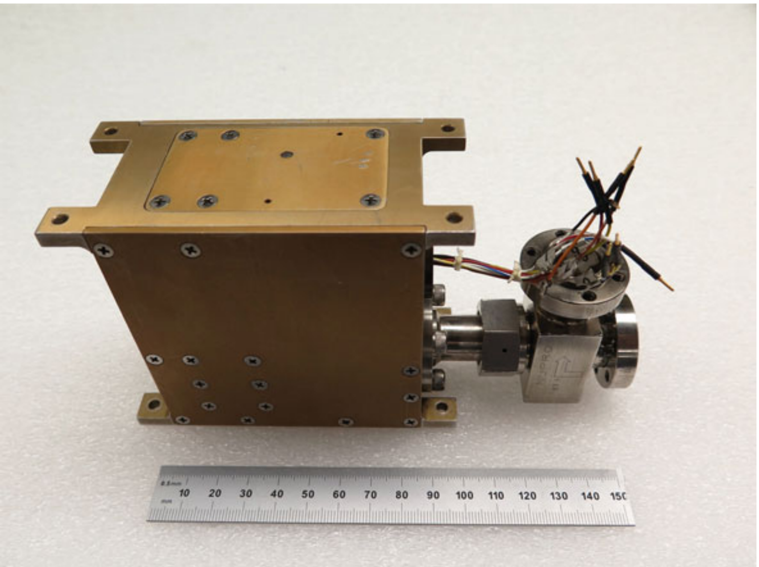


Fig. 4.12 The SHOOT stepper-motor-driven cryogenic valve

parallel. The spring washers maintained the stem tip force at cryogenic temperatures despite the differential thermal contraction of the valve elements.

The valves could be operated at any temperature from 300 K down. They required 1 A (1 W at low T) for 30 s generating a total heat input of about 30 J. Two valve sizes were developed, a ¾ inch throughput (based on a Nupro™ ¾ inch valve) and a ½ inch throughput. The larger valve generated a seating force of 202 N. This force caused micro-cracks in the original copper stem when pressed against the stainless steel seat. The copper was replaced with Torlon™ in the flight valves. When sealing against superfluid helium these valves were tested to be leak tight ($<10^{-10}$ Pa m^3/s) after more than 100 cycles. The micro-switch position sensors were somewhat unreliable at low temperature. Although they were adjustable at room temperature, they were very sensitive to small changes in position caused by differential contraction.

4.4.6 Cryogenic Relief Valves

Each SHOOT dewar had three volumes potentially where trapped liquid could exist between closed valves (Fig. 4.1). Pressure building up in these volumes could result in a vacuum failure. To prevent this, cold relief valves were used. A cold relief valve was developed for SHOOT. A spring held a stainless steel seat against a conical Vespel™ valve head until upstream pressure built in the bellows, moving the stem out. The spring provided a seating force of about 200 N on a seat of 3.8 mm diameter. The cracking pressure was approximately 150 kPa. Tests showed the pressure necessary to achieve full flow was 165 kPa. A number of open-close and thermal cycles were performed, both at room temperature and 4.2 K. In all cases the leak rate at 4.2 K in the closed position was less than 1×10^{-6} Pa m^3/s. at a pressure difference of 105 kPa, rising to 8×10^{-6} Pa m^3/s. at 140 kPa.

This valve was not designed to replace burst discs in an emergency venting situation. It had a low throughput designed to handle pressurization of liquid from a nominal heat input of a few watts.

4.5 Safety

In 1984, at the beginning of the SHOOT project, we were determined to comply with all of the space shuttle safety requirements to the letter, without asking for waivers. Two-fault tolerance for any failure with major cost or safety impacts was required. To that end, we designed dewars with two dedicated vent lines from the cryogen tank to the outside of the dewar. The dewar cryogen tank was also designed as a “leak-before-burst” vessel. Cold burst disks were located on the cryogen tank and were connected to two warm burst disks on the vacuum shell of each dewar. The outlet of the cold burst disk was hermetically connected to the inlet of the warm burst disk by 19 mm outer diameter (18 mm inner diameter) stainless steel tubes. Thus, there would be no worry about multilayer insulation restricting the flow path through the vacuum space. These dedicated emergency vent lines did add some extra parasitic heat, but since SHOOT's lifetime was to be short on orbit and dominated by heat generated in the transfers, it was an acceptable trade.

The burst disks used for SHOOT were similar to the ones used for COBE [14], but had indium sealed burst diaphragms rather than welded ones. This made it possible for the burst disk activation pressure to be measured and diaphragm punctured before being refurbished for flight.

The burst disks and vent lines were sized to prevent the dewar tank pressure from rising above 413 kPa. An emergency venting analysis was performed to show that the maximum design pressure of the dewar would not be exceeded in the event of a large rupture of the cryogen tank. See Figs. 4.13 and 4.14. Such a large rupture would only be possible if fork-lift tines were rammed through the main vacuum vessel of a dewar.

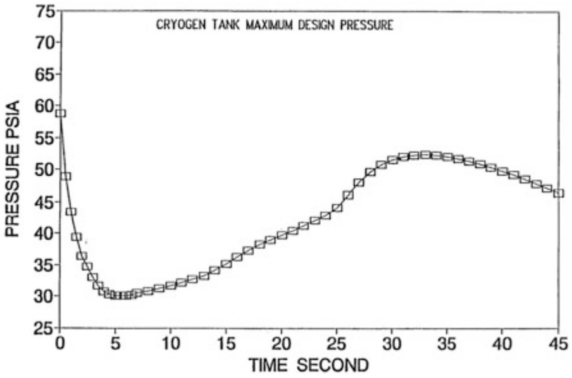


Fig. 4.13 The predicted blow down pressure in the event of a catastrophic loss of dewar guard vacuum. 60 psia is roughly 4 atmospheres, the pressure at which the cryogen tank burst disks rupture

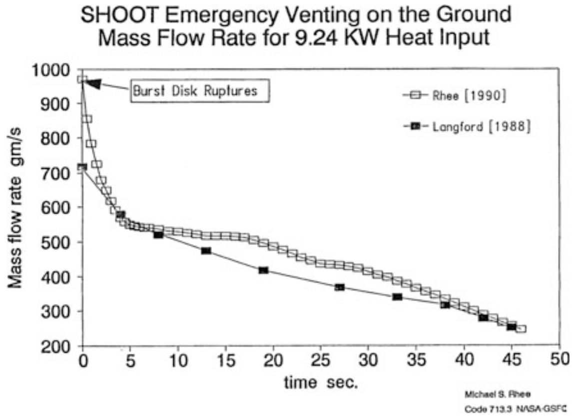


Fig. 4.14 Two predictions of the predicted helium flow rate versus time out of one emergency vent line after a burst disk rupture

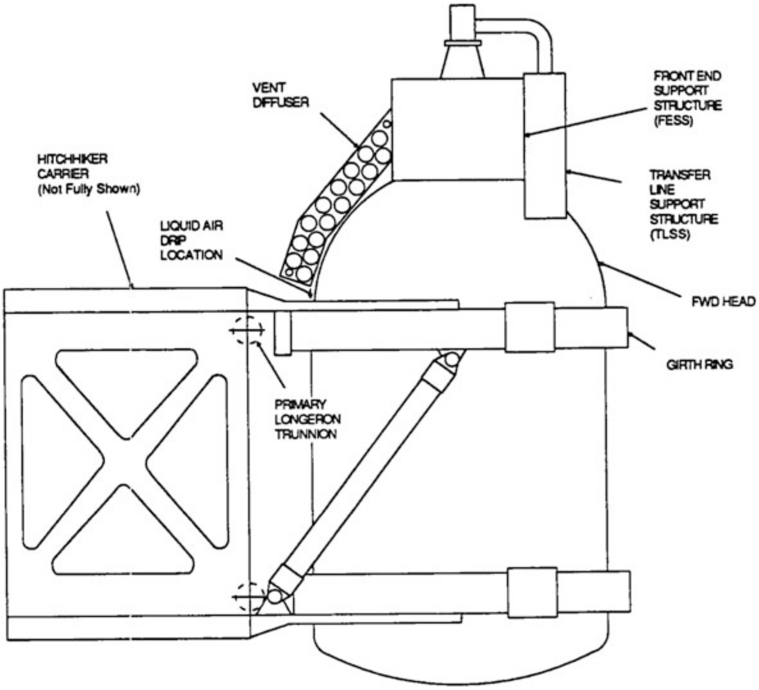


Fig. 4.15 Sketch of the SHOOT dewar in the orientation in the shuttle bay. The location of any liquid air formation is shown

Each dewar's exhaust helium, for both normal operations and for a sudden loss of vacuum, was channeled into a duct ending in a diffuser that would disperse the cold effluent. See Fig. 4.15. However, in the event of vacuum loss during ground operations, liquid air could form on the outside of the vent duct and diffuser. We tested this possibility by transferring liquid helium into the duct and diffuser at a rate of 400 L per hour for 30 min. Liquid air formation on the outside lower edge of the diffuser was collected and measured. A total of 0.4 L of liquid air was collected over 30 min. To prevent this liquid air from dropping to the floor or into the shuttle bay, a 1 L capacity drip pan was constructed from double aluminized Kapton, a material that is compatible with liquid air. This pan was fastened to the outside of the dewar immediately below the dripping area.

In the final review the Flight Safety panel at Johnson Space Center described our safety design and test effort as "a conspiracy to meet the requirements" with which we happily agreed!

4.6 Working with SHOOT on the Ground

The two dewars contained many fill and vent ports which led to an interesting effect that we noticed on the ground. 4.2 K gaseous helium has a density about 1/7th that of liquid so it is relatively heavy. When we had a dewar tipped on its side with one of the vents above the other, the lower vent had He gas outflow, while the upper vent, only a few cm higher was sucking in air!

Near the end of the ground test program one of the external burst disks on one of the dewars developed a small leak. Checking for leaks involved opening a valve that could potentially leak itself. Therefore a leak check cold was not done. After a couple of weeks the dewar was warm as planned and cool down before shipment to the launch site was planned. At this point the burst disks and emergency vent lines were checked. The one emergency vent line could not be evacuated because the cold burst disk on the tank had been ruptured. The rupture was not in the normal direction out of the tank, but in the opposite direction! That is, the leaking external burst disk had allowed enough air into the emergency vent line to freeze a solid ice plug into the line while the dewar was cold. The solid ice plug expanded upon warming, rupturing the burst diaphragm into (instead of out of) the helium tank. This was a very important lesson on the need to leak check thoroughly and as often as possible. This problem cost us 5 weeks of overtime for repairs before shipping to the launch site, but we still arrived in time for our original launch date.

The rubber o-rings that formed a seal into the vacuum space were used in areas of the dewar that were not cold. We did not consider the possibility of diffusion through these o-rings because we carefully ducted vented helium gas away from the dewars. However, given enough time even a few hundred ppm of helium gas in the surrounding atmosphere will contaminate the guard vacuum and lead to a higher heat load. We noticed that over several months without pumping the guard vacuum the heat load increased from 180 to 220 mW.

Another point of discovery was how our low temperature top-off procedure evolved over time. To achieve the maximum fill level on orbit the dewars needed to be topped-off with liquid helium near the superfluid transition. This required pumping down the SHOOT dewars and the supply dewar, well below atmospheric pressure. Similar procedures had been used by several other flight dewars; however SHOOT had differences. SHOOT used two vents on each dewar. We also filled the second SHOOT dewar from the first through the flight transfer line. This meant that we had several flow paths and several vent paths through the top-off. The procedure was rehearsed many times before flight, but each time it required a modification for a new issue: sometimes a vent would produce liquid air, sometimes a vent would be plugged by solid air, and so forth. This continued even on the last servicing on the launch pad. The final servicing concluded successfully, but only by making one final on-the-spot redline to the procedure.

4.7 On-Orbit Operations

This case study will not go into many of the details of the SHOOT on orbit results, but a sampling of the measurements made is given here. First, as an experiment, it was a huge advantage for SHOOT to be riding in the space shuttle. Beneficial and adverse accelerations were possible, the communication, power, and data storage were provided, and mission support from the Johnson Space Center and Kennedy Space Center contributed greatly to the success of this Goddard Space Flight Center-led mission.

Second, a lesson about unintended consequences was learned on orbit. SHOOT was launched containing He-I and needed to be pumped down over about 24 h to reach its operating temperature. The plan for this pump down was to use the low-flow phase separator to get close to the superfluid transition, then open the valve to the high-flow phase separator to complete the pump down. This had been tested on the ground to the extent possible, but the high-flow phase separator was difficult to test with a significant hydrostatic head. Thermometers on each phase separator indicated its proper operation: higher temperature on the upstream side of the separator and lower downstream. The port dewar containing the vane system pumped down more quickly than the starboard dewar. Everything appeared normal when the valve upstream of the port dewar's high-flow phase separator was opened, but when the valve on the starboard dewar was opened an alarm rang on the shuttle. The astronauts sleep with the shuttle's nose pointed toward Earth, a gravity-gradient, stable attitude because attitude control thrusters were noisy. The alarm woke the astronauts because the shuttle attitude had swung by 5° from vertical, then swung back to the other side 6°. We learned later that this was caused by a sudden venting of 10s of liters of liquid helium out the vent. Although the flow out the vent was diffuse, the gas impinged on an open shuttle bay that concentrated the momentum of the outflowing gas in the opposite direction. At the time we thought that the high flow phase separator on the starboard tank was broken allowing liquid to escape. What we found out later is that we had such a large pressure gradient and flow rate out of the high-flow phase separator that the upstream liquid was sub-cooled significantly from the liquid in the remainder of the tank [15]. This was the result of a late change to the design that thickened the thin-walled copper heat exchanger around the high-flow phase separator so that the heat flow was restricted. Even superfluid helium can have significant gradients! Discovery of this was hampered by the thermometer wiring being switched on the starboard phase separator, and the different behavior of the port LAD (vanes) which prevented most of the liquid from leaving the port dewar.

After this loss of helium event we had a little over half the amount of liquid we expected to have, but still managed to complete all of the types of transfers planned for the mission. These transfers were: port to starboard high and low rate, starboard to port high and low rate, transfer during adverse accelerations, chill down and transfer into an empty and cold and empty and warm tank, intelligent system controlled transfer, etc.

One of the more interesting side benefits to the expected data were some indications of how slosh in superfluid helium behaved [16]. After a fluid settling acceleration the superfluid motion damped out very quickly with only a couple of large amplitude oscillations.

SHOOT also obtained interesting results on stratification of He-I [17, 18].

4.8 Summary

Many components demonstrated for the first time in space, or anywhere for some, came to be used for other projects:

- Stepper-motor valves (XRS, XRS2, SXS and other liquid helium missions)
- Venturi flow meter (to be used on RRM3)
- Mass gauging (ISO and to be used on SXS)
- Fountain pumps (balloon payloads ARCADE and Super-ARCADE)
- Liquid/vapor detectors (shown to also work for other cryogens including liquid nitrogen)
- Cryogenic/ambient burst disks (XRS, XRS2, and SXS)

The SHOOT mission was fully successful in satisfying the original objectives. Along the way several interesting observations were made and lessons learned. The original purpose of helium resupply had disappeared but SHOOT became a demonstration platform for many useful cryogenic components and techniques. SHOOT is still the most extensive cryogenic fluid management experiment conducted in space.

References

1. P. Kittel, Orbital resupply of liquid helium. J. Spacecraft Rockets, **23**, 391 (1986)
2. K.F. Weintz, M.I. Basci, J.M. Uber, SHOOT Dewar support strap design and performance. Cryogenics **34**, 357–360 (1994)
3. Explosive Fabricators, Incorporated, Louisville, Colorado
4. D. Petrac, U.E. Israelsson, T.S. Luchik, The lambda point experiment: helium cryostat, cryo-servicing, functions, and performance. Adv. Cry. Eng. **39**, 137–144 (1994)
5. R.T. Parmley, J. Goodman, M. Regelbrugge, S. Yuan, Gravity Probe B dewar/probe concept. Proc. of the SPIE **619**, 126 (1986)
6. P.J. Shirron, J.L. Zahniser, M. J. DiPirro (eds.), A liquid/gas phase separator for He-I and He-II. Adv. Cryog. Eng. **37**, 105 (1992)
7. J.G. Tuttle, M.J. DiPirro, P.J. Shirron, Liquid/gas phase separators for the superfluid helium On-orbit transfer (SHOOT) project. Adv. Cryog. Eng. **39**, 121 (1994)
8. P.J. Shirron, M.J. DiPirro, J.G. Tuttle, Flight performance of the SHOOT liquid acquisition devices. Cryogenics **34**, 361 (1994)

9. M.J. DiPirro, E.R. Quinn and R.F. Boyle, Tests of a nearly ideal, high rate thermomechanical pump, in *Proceedings of 12th International Cryogenic Engineering Conference* (Butterworths, London, 1988), p. 646
10. P.R. Ludtke, D.R. Daney, Cavitation characteristics of a small centrifugal pump in He I and He II. Cryogenics **28**, 96 (1988)
11. P.J. Shirron, J.G. Tuttle, M.J. DiPirro, Performance of discrete liquid helium/vapor and He-I/He-II discriminators. Adv. Cryog. Eng. **39**, 1105 (1994)
12. M.J. DiPirro, P.J. Shirron and J.G. Tuttle, Mass gauging and thermometry on the superfluid helium on-orbit transfer flight demonstration. Adv. Cryo. Eng. **39**, 129 (1994)
13. These are now a commercial product of ATK/Mission Research
14. The COBE burst disks were built by Ametek Straza which became Katema. Currently a version is marketed by Hydrodyne
15. M.J. DiPirro, P.J. Shirron, J.G. Tuttle, Superfluid helium transfer in space. Cryogenics **34** (ICEC Supplement), 267 (1994)
16. M.J. DiPirro, P.J. Shirron, J.G. Tuttle, On orbit superfluid transfer: preliminary results of the SHOOT Flight Demonstration. Cryogenics **34**, 349 (1994)
17. P.J. Shirron, M.J. DiPirro, Low gravity thermal stratification of liquid helium on SHOOT. Cryogenics **32**, 159 (1992)
18. J.G. Tuttle, M.J. DiPirro, P.J. Shirron, Thermal stratification of liquid helium in the SHOOT dewars. Cryogenics **34**, 369 (1994)