Orbital Resupply of Liquid Helium

Peter Kittel*
NASA Ames Research Center, Moffett Field, California

The ability to resupply scientific instruments in orbit with liquid helium would greatly enhance several planned missions. These missions include the Space Infrared Telescope Facility, the Large Deployable Reflector (LDR), and Gravity Probe-B and individual instruments on the Hubble Space Telescope and Advanced X-Ray Astrophysics Facility. Resupply in orbit would extend the lifetimes of these missions without the difficulties, delays, and costs associated with retrieving the system, resupplying these systems on the ground, and relaunching. This is especially true of systems, such as the LDR, that are assembled in space and thus would be difficult to return to Earth. This paper presents a conceptual design of a helium resupply system and a discussion of the transfer efficiency.

Nomenclature

C = effective heat capacity
C_P = heat capacity at constant pressure
d = diameter
k = thermal conductance
$\dot{m}$ = mass flow rate
P = pressure
Q = total heat
Q_C = heat conducted to supply tank
Q_M = heat converted into the mechanocaloric effect
Q_T = heat absorbed by fluid
Q_{KE} = heat converted to kinetic energy
S = entropy
S_o = entropy at pump outlet
T = temperature
T_o = temperature at pump outlet
v = velocity
v_c = critical velocity
V = volume per unit mass
W = fluid power
Δ = difference
ϵ = efficiency
ρ = density

Introduction

THE resupply of liquids, particularly cryogenic liquids, in space is made difficult by the absence of gravity. On Earth, gravity separates the liquid and vapor phases. The denser liquid phase sits on the bottom of a tank while the less dense vapor phase fills the rest of the tank. This allows pure liquid to be withdrawn from the bottom of the supply tank while the vapor can be vented from the top of the receiver tank. In space, this is not possible. The liquid will not, on its own, remain at the outflow pipe, nor will it be kept away from the vent tube.

Over the years, considerable effort has been devoted to devising means of transferring cryogens in space.[1] Most of these studies have focused on the resupply of liquid hydrogen, where the preferred approach is to use capillary devices to separate the phases in the supply tank and to use a no-vent fill technique in the receiver. Unfortunately, the properties of hydrogen and helium are sufficiently different so that the techniques developed for hydrogen are not directly applicable to helium. The properties of hydrogen and helium are summarized in Table 1. In this table the properties of superfluid helium are emphasized because this is the state of helium most useful for instrument cooling.

The Cryogenic Fluid Management Facility (CFMF), a planned Shuttle-based liquid hydrogen transfer demonstration, will use a capillary device to separate the phases of liquid hydrogen. These devices work by using screens with pores so small that surface tension forces dominate the expected acceleration forces. This process prevents the vapor from passing through the screen. Such capillary control is characterized by the Bond number, a dimensionless quantity that depends on the peak acceleration, on the ratio of the liquid density to the surface tension, and on a geometry factor. The CFMF proposes to use 2300-mesh screens (approximately 10 μm pores) to ensure a low enough Bond number.[2] To achieve the same level of control in superfluid helium, the pores would need to be a factor of 33 smaller in size; this level of control would require 0.3-μm pores. This presents a problem in the fabrication of a control device with a surface area large enough to prevent an excessive pressure drop at the desired flow rates.

The receiver tank presents another problem. In the CFMF, there is a proposal for the use of a no-vent fill technique.[1] In this technique the receiver is first evacuated and then capped off with a valve. The receiver tank is then cooled by injecting liquid cryogen into it until the maximum supply pressure is reached. Then the supply is shut off, the receiver is again vented, and the cycle is repeated. With each cycle the receiver is cooled further until it is cold enough for the liquid to collect in it. This technique will not work as well for helium because the latent heat of evaporation is a factor of 20 smaller (so that less heat can be removed by evaporating a given quantity of liquid) and less pressure can be used without exceeding the critical pressure (so that less liquid can be injected per cycle); thus a greater number of cycles are required for this process. For these reasons we are taking a fresh look at cryogen transfer to find a method that will work for superfluid helium.

Table 1 Properties of hydrogen and helium

Property	Hydrogen	Helium	Units
Critical point	33	5.2	K
	13	2.3	10^5 Pa
Lambda point[a]	NA	2.2	K
	NA	0.049	10^5 Pa
Surface tension[b]	1.8	0.1	10^{-3}N·m^{-1}
Latent heat[b]	439	21	10^3J·$^{-3}$
Density[b]	70	145	kg·m^{-3}

[a]Lambda point—the highest point on the saturated vapor pressure line for which superfluid helium exists. [b]For normal boiling point (21 K, 10^5 Pa), hydrogen and, for 2 K, saturated superfluid helium.

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*Research Scientist, Space Technology and Systems Branch. Member AIAA.

Potential Applications

A number of future space missions would benefit if they could be resupplied with superfluid helium while in orbit. Superfluid helium has been picked for these missions because of its low temperature (<2.2 K), its high thermal conductivity, and the fountain effect that makes it easy to vent the vapor while containing the liquid in a zero-gravity environment. Containment by the fountain effect was used successfully on IRAS (Infrared Astronomical Satellite).[3] The planned missions that could benefit include the Space Infrared Telescope Facility, Large Deployable Reflector, and Gravity Probe-B. Individual helium-cooled instruments have also been proposed for the Hubble Space Telescope and Advanced X-Ray Astrophysics Facility. In the future, other helium-cooled instruments may be proposed for the space station.

These applications range in size from about 100 to 10,000 liters. To refill these dewars in a reasonable length of time, flow rates up to 1000 liter/h will be required. Because it may not be possible to schedule on-demand servicing, the receivers may have run dry and may have begun to warm up before the helium can be replenished. If this happened, both the quantity of helium required and the length of time needed for servicing would increase.

The servicing of the above systems could take place on the Shuttle, on the space station, or at a remote location. These locations involve a variety of different environments. This makes it possible to develop a servicing system that will operate at only one or two locations. We are interested in a system that can be easily adapted to all the likely locations. Such an approach necessarily eliminates some options but should result in a more versatile system.

Transfer Techniques

Among the variety of liquid replenishment methods that have been suggested are: 1) capillary devices; 2) artificial gravity, produced either by spin or thrust; 3) bladders; 4) tank replacement; 5) cryogen transfer as a cold gas followed by conversion into liquid; and 6) pumps, either mechanical or thermomechanical.

Each of these methods needs to be analyzed to find the one most suitable for liquid helium transfer. The first one, capillary control, was discussed above and is probably suitable only for small tanks or for situations where the residual accelerations are considerably smaller than the typical Shuttle environment.

There are several cases for which artificial gravity could be used. It appears that the Shuttle could be spun fast enough to separate the liquid and vapor phases adequately both in the supply and receiver tanks. The liquid could then be driven through the transfer line by applying a slight overpressure to the supply tank. Unfortunately, this technique will be difficult to implement on the space station. A second case would make use of the artificial gravity available at a tethered platform. A tether on the order of 1 km would be needed for adequate fluid control.[4] A third case would use thrust to provide the artificial gravity. This could be achieved by attaching the supply tank to the front of the receiver tank and by transferring the liquid while the receiver is being reboosted to a higher orbit. At the end of the transfer, the supply tank would have to be returned to Earth or jettisoned.

The third replenishment method utilizes bladders to expel the liquid from the supply tank. This method has been used in space for liquids that can be stored at ambient temperatures. The difficulty in applying this technique to cryogens is finding a suitable bladder material and a suitable means of compressing the bladder. The bladder needs to be both flexible and leaktight. The latter requirement is particularly difficult because superfluid helium is more likely to leak through very small holes than any other substance. Only thin metal membranes will meet these requirements. A common means of compressing bladders is to pressurize one side with a noncondensible gas. This is not possible for liquid helium systems because no suitable gases are available. All gases, even the isotopes of helium, would condense before sufficient pressure could be reached. The bladder could be compressed mechanically by a solenoid, motor-driven, or remote piston-driven shaft. Such methods require the use of cryogenic mechanisms and large forces, e.g., $>2\times10^6$N($>5\times10^5$ lb) for a 10^4-liter spherical tank.

The fourth method would be to replace the cryogen tanks. This would be easiest if the tanks were external to the instrument being cooled. This configuration presents two drawbacks: 1) the increased parasitic heat load (decreased cryogen lifetime) because of the coupling, and 2) the difficulty in providing adequate cooling to the instrument. Many instruments need intimate contact with the cryogen for adequate cooling. This is easier to arrange with internal tanks. Tank replacement is also possible with internal tanks, that is, with tanks inside the same insulation as the instrument. This approach is probably far too difficult to be practical. It would involve using not only demountable joints in the insulation but also a high-thermal-conductance demountable connection to the instrument. The latter joint would probably have to be remotely actuated. In addition, a specially insulated chamber would be needed to protect the cryogen tank from contamination and from thermal loads during transportation and replacement.

The fifth option is to convert the cryogen from a high-pressure cold gas to a liquid, either during or after the transfer. This is a very inefficient process as only a fraction of the supply gas can be converted; the rest is exhausted as low-pressure gas. And there remains the difficulty of venting the large quantity of gas without letting any of the liquid escape.

We have chosen to pursue the last option: pumping the cryogen from the supply dewar to the receiver dewar. Either a mechanical or a thermomechanical pump may be used. Both types are currently undergoing development and testing. The National Bureau of Standards at Boulder, Colorado, is developing a centrifugal pump that is driven by a submersible three-phase motor.[5] Goddard Space Flight Center is working on the thermomechanical pump[6] that uses one of the unique properties of superfluid helium, namely, the thermomechanical, or fountain, effect. In this effect a temperature gradient across a porous plug produces a mass flow through the plug. The liquid flows from the cold to the warm side of the plug. This same effect was successfully used on the IRAS to contain superfluid helium.[3]

Conceptual Design

A liquid helium resupply system is shown schematically in Fig. 1. (This figure is intended to show the type of features that might be included in a resupply system. All the features shown may not be required in the final system but are included here to show the various options.) The system has two tanks: a supply tank and a receiver tank. The receiver tank is located within the instrument being serviced. The tanks have an inner liquid reservoir supported from an outer vacuum shell. The supports are low-conductance, high-strength supports such as passive orbital disconnect struts.[7,8] The outer shell and inner vessel are separated by layers of insulation and vapor-cooled shields. The tanks also have lines to vent the vapor, porous plugs to contain the liquid, and lines for filling the tanks prior to launch.

During servicing, the two tanks are connected by a flexible transfer line. This line is part of the supply tank. It is connected to the receiver by a coupling, either astronaut-operated or automatic. The liquid lines used in the resupply could be the same lines used for filling the tanks on the ground. The transfer line shown is vapor-cooled. Such vapor cooling will probably not be necessary unless very long lines are used. Some means of precooling the line is required to prevent warm gas from boiling off the remaining liquid in the receiver. This can be accomplished by initially venting the liquid line through its vapor cooling line or through the receiver's vent line, which bypasses the receiver.

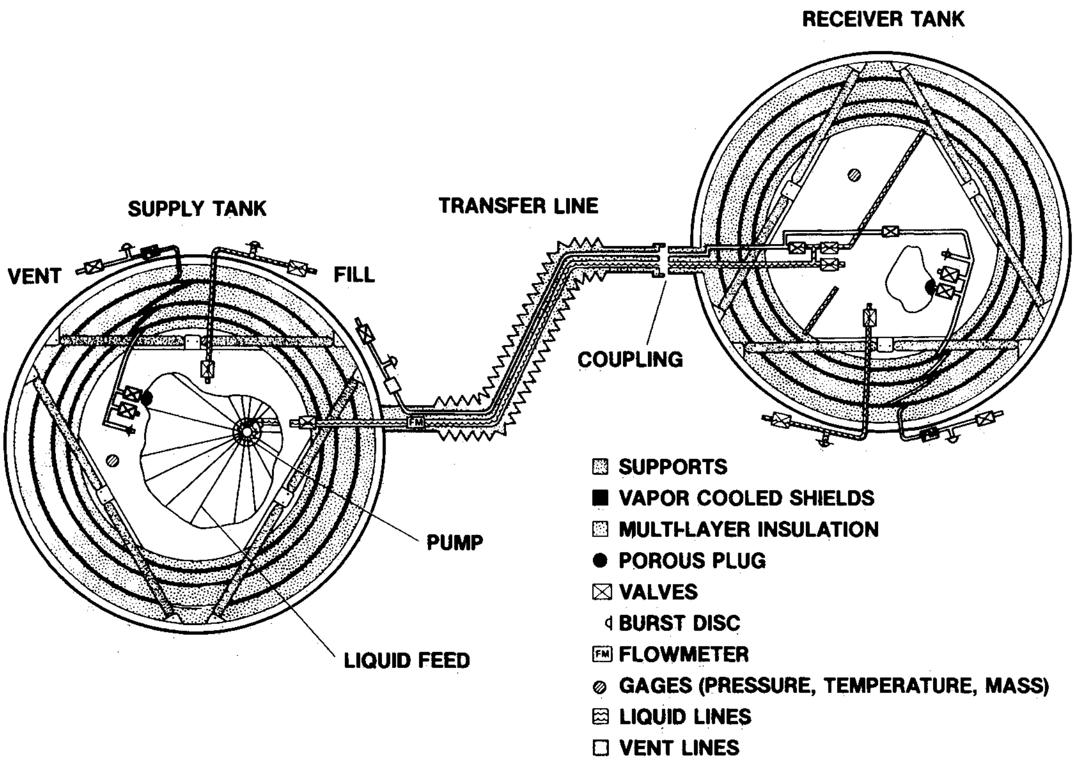

Fig. 1 The helium resupply concept.

One difficulty in resupplying a cryogen occurs if the receiver has run dry and has begun to warm up before a service can be scheduled. Some efficient means of precooling the receiver must be arranged. Otherwise some of the liquid might go directly from the inlet to the outlet without cooling the tank. To make full use of the latent heat and enthalpy of the helium, a heat exchanger is wrapped around the inner tank. This is not the only way to cool the tank. Another possibility is to inject the liquid into the tank circumferentially, thus using centrifugal force to separate the liquid and the vapor phases.

All configurations require the use of several remotely actuated cryogenic valves. These valves must be able to operate reliably many times during the life of the equipment. Many of the valves need to be superfluid leaktight. This is a difficult requirement in view of the propensity of the superfluid to leak through small holes.

A variety of different types of instrumentation will be needed to monitor the transfer. Both tanks will need temperature, pressure, and mass gages to keep track of the condition of the tanks and lines and of the amount of fluid in them. Other gages will be used for monitoring the transfer. These include flowmeters (cold ones in the transfer line to measure liquid flow rates and "warm" ones in the vent lines to measure the effluent vapors) and possibly liquid-vapor ratio meters or liquid-vapor sensors (in the transfer line and vent lines to monitor the efficiency of the transfer).

Finally there is the pump which, as mentioned above, could be either a mechanical or thermomechanical pump. In either case, some means of supplying liquid to the pump must be provided. On the ground this is done by placing the pump in the bottom of the tank. Such a solution is not available in space. The only way that appears feasible is to use capillary devices. Fortunately, in this application the requirement for the level of liquid control is not as high as it would need to be for the CFMF type of application. In the CFMF, the screens must be small enough to prevent any vapor from penetrating them. Otherwise the devices will fail and will be difficult to restart. In our application closely spaced channels (rather than screens) extend throughout the volume of the tank. The spacing of the channels becomes narrower at the pump inlet. These channels are not required to control the liquid under all expected accelerations but only under most accelerations. If the pump runs dry under peak accelerations, it can be easily stopped and restarted after the peak has subsided. Thus the spacing requirement can be reduced by two to three orders of magnitude. Another alternative is to use some of the outflow to swirl the liquid in the supply tank.

Operation

Two modes of operation are foreseen. The first is the refilling of a partially full dewar. The process starts with the mating of the transfer line to the receiver. The line is then precooled by pumping liquid through it. The resulting effluent vapor is either vented through a specially provided vent or through a line that bypasses the receiver tank and vents directly into the receiver's vent line. If the latter option is used, the receiver will have to be valved off from its vent line during this operation. Once the transfer line is cold enough to carry superfluid, the liquid is injected directly into the receiver and the receiver is once again vented through its porous plug. During the transfer the receiver's vent line will probably have to carry a higher flow rate than it would during its normal operation (i.e., between resupplies). To allow for this, a second and larger porous plug may be required. The higher flow rate is a result of having to reject additional heat, the parasitic heat load in the transfer line, the heat of condensation of the vapor bubble in the receiver, and the heat that is removed in cooling the liquid from the supplied temperature to the desired operating temperature. During the transfer the pumping rate will have to be controlled to prevent the pump from running dry, to keep the fluid in the receiver as superfluid, and to minimize liquid losses. Once the receiver is full (except for a small ullage), the transfer is stopped, the valving is returned to the normal configuration, and the transfer line can be disconnected.

The second mode of operation occurs when the receiver has run dry and has warmed up. In this case both the receiver and the transfer line must be precooled. One method of doing this is to route the flow from the transfer line through a heat exchanger that is wrapped around the receiver and then through the tank and out through a vent that does not have a porous plug. The purpose of this approach is to ensure that the helium is completely vaporized before it reaches the vent and to provide a means of venting the receiver while it is too warm for the porous plug to operate as a phase separator. Once the tank has been cooled to about 2.1 K, the transfer can proceed as described above for the first mode.

Pump Comparison

The most critical component in the transfer system is the pump. For this reason, two types of pumps are being developed. One is the thermomechanical pump, which generates a pressure from a heat input. The pressure generated is shown in Fig. 2 and is given by[9]

$$\frac{dP}{dT} = \rho S \tag{1}$$

The total heat input Q includes components that increase the temperature of the fluid Q_T, are converted into kinetic energy of the fluid Q_{KE}, and are conducted to the supply Q_C and into the mechanocaloric effect (the result of the flow of superfluid through a porous plug) Q_M. Thus Q is given by

$$Q = Q_T + Q_{KE} + Q_C + Q_M \tag{2}$$

where

$$Q_C = k\Delta T \tag{3a}$$

$$Q_{KE} = (1/2)\dot{m}v^2 \tag{3b}$$

$$Q_T = \dot{m}C\Delta T \tag{3c}$$

$$C = \frac{TdS}{dT} \tag{3d}$$

$$Q_M = \dot{m}TS \tag{3e}$$

If ΔT is large, then Eqs. (3a) and (3c) must be replaced by the appropriate integrals. Furthermore, Eqs. (3c) and (3e) are both part of the mechanocaloric effect and can be combined as

$$Q_T + Q_M = \dot{m}T_oS_o \tag{3f}$$

where $T_o = T + \Delta T$ and S_o is S evaluated at T_o.

Equation (2) is the total power input for the thermomechanical pump. This power must be supplied by the heater and by the parasitic heat leaks through the transfer line and its insulations and accessories. For steady-state operation, the heat $Q_M + Q_C$ must be removed from the supply tank (along with other parasitic heat loads on that tank), while $Q_T + Q_{KE}$ are added to the transferred liquid. For purposes of discussion, it has been assumed that the porous plug acts as an ideal "superleak," allowing flow of the superfluid only. Thus, Q_M is given by the relation (3e) for an ideal superleak. An actual plug would allow normal fluid to flow as well, affecting Eq. (3e). We are assuming that this effect can be made small and thus be ignored by an appropriate choice of plug. [For a mechanical pump, Eq. (2) is also valid if Q_M is replaced by the joule heating and other losses within the pump.]

The efficiency ϵ of the pump is the ratio of the fluid power W to the heat input:

$$\epsilon = W/Q \tag{4}$$

where

$$W = \dot{m}\Delta P/\rho + (1/2)\dot{m}v^2 \tag{5}$$

Ignoring, for the moment, the contribution of Q_C, Eq. (4) becomes

$$\epsilon = \frac{\Delta P/\rho + v^2/2}{T_oS_o + v^2/2} \tag{6}$$

Making use of Eq. (1), Eq. (6) becomes

$$\epsilon = \frac{S\Delta T + v^2/2}{T_oS_o + v^2/2} \tag{7}$$

which can be readily evaluated for several cases.

$$\text{Case 1: } v^2/2 \gg S\Delta T, \quad \epsilon \simeq (1 + 2S_oT_ov^{-2})^{-1} \tag{8}$$

$$\text{Case 2: } v^2/2 \gg T_oS_o, \quad \epsilon \simeq 1 \tag{9}$$

$$\text{Case 3: } v^2/2 \ll S\Delta T, \quad \epsilon \simeq S\Delta T/S_oT_o \lesssim 0.19 \tag{10}$$

$$\text{Case 4: } v^2/2 \ll S\Delta T, \quad \Delta T \ll T, \quad \epsilon \simeq \Delta T/T \tag{11}$$

Clearly, high efficiency requires that v be kept large and ΔP small (cases 1 and 2). If v is small, the best efficiency is achieved for large ΔP (cases 3 and 4). The velocity at the pump outlet is related to the mass flow and the diameter of the outlet by

$$v = 4\dot{m}/\pi d^2\rho \tag{12}$$

This makes the efficiency very strongly dependent on d.

The pressure the pump needs to generate is the sum of contributions that are due to 1) flow through the porous plug, 2) flow through the transfer line, 3) pressure and temperature differences between the tanks, and 4) flows induced by heat fluxes into the transfer line. We will consider the flow-induced losses first. For superfluid helium there is no flow-induced pressure drop if the velocity is kept below the critical velocity; i.e., superfluid helium displays no viscosity for low flow rates. For large tubes ($d > 0.1$ mm) the critical velocity is[9]

$$v_c = 6.4 \times 10^{-8} d^{-1} \ln(2.8 \times 10^9 d) \tag{13}$$

For small tubes, such as in the pump itself, the critical velocity depends on $d^{1/2}$. In this case, the critical velocity will be considerably higher than in the transfer line. For this discussion we will assume that the critical velocity is not exceeded in the porous plug. The transfer line's critical velocity [Eq. (13)] is so small that in any practical system it will be exceeded. For example, in a 0.1-m-diam tube the critical velocity corresponds to a 0.35-liter/h flow rate. To achieve a flow rate of 1000 liter/h in such a tube would require a pressure drop of $\ll 10^{-5}$ Pa (10^{-10} bar) to satisfy the case 1 requirement. This is impractical because the pressure fluctuations, let alone the

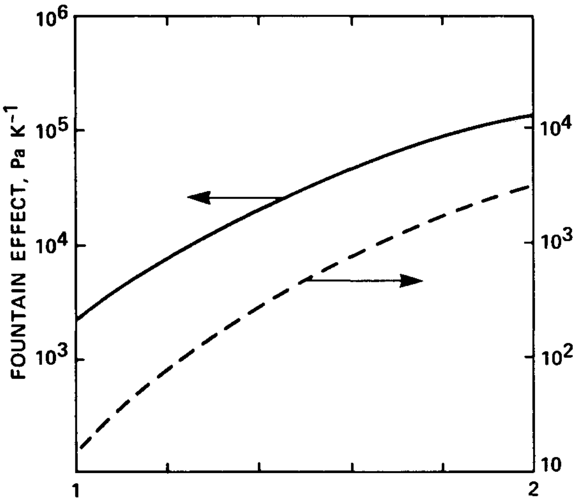

Fig. 2 The solid curve and the left-hand scale are the fountain effect [Eq. (1)]. For reference, the ambient tank pressure (the saturated vapor pressure) is shown by the dashed curve and the right-hand scale.

other pressure terms mentioned above, will exceed this requirement. (A critical flow of 1000 liter/h would require a 12-m-diam pipe.)

Since we must exceed v_c, we cannot have a high-velocity system. Once we exceed v_c, viscosity will appear, and thus a pressure head will be required. Figure 3 shows the pump efficiency at 1.8 K as a function of P and of the flow for a 1.13-cm outlet pipe. This shows that the pump is very inefficient and that the operation is in the case 3 [Eq. (10)] regime.

If the Q_C term is included, then the efficiency will drop even further. The size of the effect of Q_C on the efficiency will depend on the details of the application. However, a general statement can be made. Since Q_C depends on the conductivity of the helium through the pores in the plug, this contribution will be smaller if the critical velocity is exceeded in the plug. (In superfluid helium, the critical velocity marks not only the onset of viscosity but also a change in thermal conductivity. This is a consequence of convection dominating the thermal conductivity.) In any case, Q_M is expected to be $\gg Q_C$. Q_M as a function of temperature is shown in Fig. 4 for a flow of 1000 liter/h.

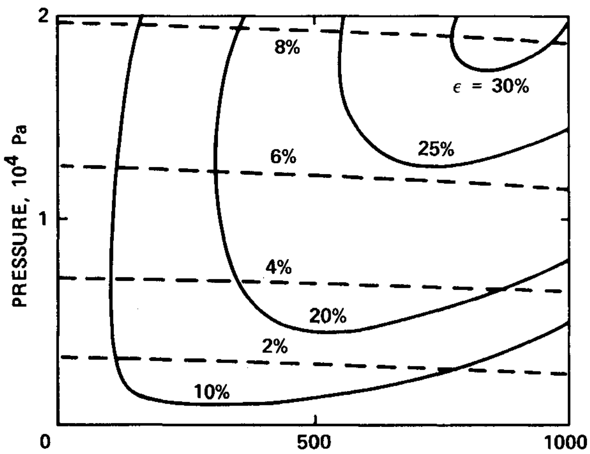

Fig. 3 The efficiency of liquid helium pumps with 1.13-cm-diam outlets as a function of flow rate. The dashed line is for a thermomechanical pump operating at 1.8 K. The solid line is for the mechanical pump described in Ref. 9. This efficiency includes both the pump and the motor contributions.

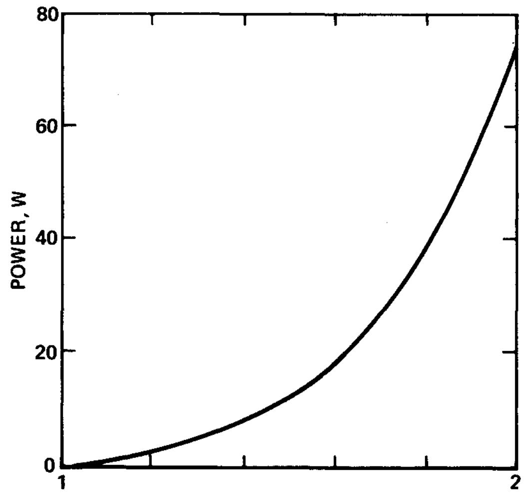

Fig. 4 The power Q_M required to move 1000 liters/h of superfluid through a porous plug. This is independent of pore size (ignoring the concomitant pressure drop) as long as the pores are small enough to clamp the normal fluid motion.[9]

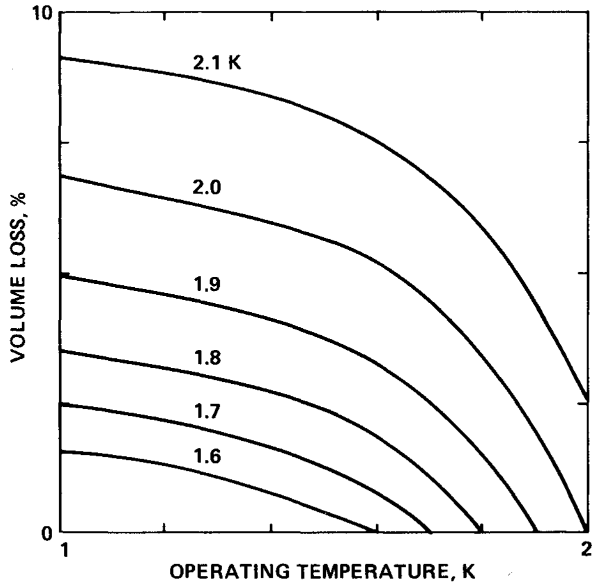

Fig. 5 Volume percent lost in evaporative cooling of liquid helium from various temperatures (labeled on curves) to a final operating temperature.

By comparison, a centrifugal pump can operate with a higher ,efficiency. For a flow of 900 liter/h, an overall efficiency of 30% has been achieved with a pressure increase of 5000 Pa.[10] As a point of reference, this is a greater pressure than the ambient pressure in the tanks. This efficiency includes both the pump and motor losses. At lower flow rates the efficiency of the same mechanical pump will drop. The performance of one such pump is shown in Fig. 3. This pump is considerably more efficient than the thermomechanical pump, and it also has a 1.13-cm outlet pipe.

In summary, the mechanical pump shows a clear efficiency advantage. This efficiency is not expected to be very temperature-dependent. The efficiency of the thermomechanical pump will improve with decreasing temperature because the entropy decreases. However, the thermomechanical pump also has the advantage of reliability. It has no moving parts, only a heater. While mechanical pumps have been operated for several thousand hours in liquid helium, there is only limited operating experience of their operating in superfluid. The principal failure mode is expected to be bearing failure. In either case, the efficiency of the pump is only part of the transfer efficiency. The goal of the transfer is to maximize the quantity of helium in the receiver when it has reached its normal operating temperature while minimizing the quantity of the helium transported to orbit. If the helium must be cooled after being transferred, some of it must be used to do the cooling. The change in volume in evaporative cooling from T_1 to T_2 can be shown to be

$$\frac{\Delta V}{V} = 1 - \frac{\rho(T_1)}{\rho(T_2)} \exp \int_{T_1}^{T_2} \frac{C_P}{L} \mathrm{d}T \tag{14}$$

This expression includes both the mass loss and the change in density. It is plotted in Fig. 5, where it has been assumed that only the liquid helium contributes to C_p. Since the dewar and instrument system need to be included, Fig. 3 gives a lower limit to the loss.

Concluding Remarks

The concepts discussed here represent a preliminary look at an orbital liquid helium resupply system. A variety of techniques have been considered: capillary devices, artificial gravity, bladders, tank replacement, gas-to-liquid conversion, and pumps. Of these, the most promising one for transferring superfluid helium is the pump. A conceptual design of a transfer system has been developed. In this design the most critical component is the pump. Two different types of pumps are being developed. The thermomechanical pump is the more reliable type, and the mechanical pump is the more efficient one. Of course, in any particular application a tradeoff between the various options would have to be made in light of the total system operation. In any case, a number of alternatives have been identified that appear to make the orbital transfer of liquid helium feasible. One might think that the ability to resupply cryogens would allow for simpler dewar design, i.e., the requirement for long cryogen hold times could be relaxed. I do not think this is a reasonable assertion. The cost and logistical problem of resupply will be great. I am confident that the lowest life cycle costs will be achieved by building the best instrument dewars possible and resupplying as infrequently as possible.

Acknowledgments

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