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EXPERIMENTAL RESULTS OF TESTS PERFORMED ON SUPERFLUID HELIUM PHASE SEPARATORS FOR THE RELATIVITY MISSION

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ABSTRACT

Tests were performed to select a Phase Separator (porous plug) material to be used with the NASA/Stanford University Relativity Mission. The porous plug is used to retain superfluid helium (SFHe) in the 2400 liter tank of the Dewar. Operation of this plug is unique in that it is used to control SFHe temperature, operate over a wide range of flowrate, and provide gas for spacecraft attitude control.

This paper summarizes data taken during evaluation of various materials made of sintered stainless. Data was taken during normal and choked flow conditions. Tests were performed on increasing the flowrate capability by using a heater on the downstream side of the plug. Critical breakthrough parameters were determined. These tests led to the selection of a material for use in the Dewar.

INTRODUCTION

The primary requirements that affected the design of the porous plug were: 1) the SFHe tank temperature has to be controlled to +/- 0.010K, 2) operate over a range of 4-16 mg/s without choking, and 3) operate with a sufficient back pressure so that the vented gas can be used for the spacecraft attitude control system. The predicted nominal flowrate during science phase of the mission is 6.5 mg/s. The higher flowrates are required during the early phase for orbit trim.

These requirements make it unique in that the downstream flow conductance of the plumbing is not constant such as other space borne Dewars. The Relativity Mission utilizes a heater in the tank and a variable flow conductance valve in the vent line to provide the temperature control and flowrates required for attitude control. Increases in venting are achieved by decreasing the downstream temperature of the porous plug and maintaining the bath temperature by turning on a heater. The vent line provides flow to 16 thrusters. The SFHe is to operate at 1.8 K.

A number of different materials were tested. Most of the data presented in this paper reflect the material that was selected. The intention of this paper is not to deal with the theory of phase separators but to present some interesting data that is available for the theorists to use in evaluating modeling techniques. A good review of the theory can be found in references 1-3.

MATERIAL CHARACTERISTICS

The materials tested were all porous 316L sintered stainless steel porous media purchased from Mott Metallurgical Corp. The first two plugs had a thickness of 1.27 cm. This thickness was picked due to early concerns of breakthrough while operating at the lower end of a wide range of flowrates. Plug #1 was fabricated in disc form. After preliminary results showed that this plug was very susceptible to breakthrough, a second plug, Plug #2, was assembled with some available 0.318 cm sheet material. Discs were fabricated from the sheet and four discs were stacked to get the 1.27 cm thickness. Results of this plug showed that breakthrough was no longer a concern and subsequent plug thicknesses were reduced to 0.635 cm and fabricated in disc form. The first two materials were purchased by specifying a filtration grade of 0.5 micron. Mott's manufacturing criteria to determine if a material has been fabricated to the correct micron grade is to perform a bubble point test.

Since the two first materials had large difference in permeability for the same filtration grade, subsequent materials were purchased by specifying a permeability. Microscpopic examination showed much different surface characterisitcs between the two materials which are probably due to fabrication differences between discs and sheets. Material for Plug #3 was ordered with the specification of having a permeability comparable to plug #2. The material received had a permeability much lower than that specified and therefore, the diameter was too small. Tests proceeded with this material and once it was well characterized, new material for the final Plug #4 was ordered with the same permeability as #3. Table 1 is a summary of the characteristics of these materials.

Figure 1 is a summary of a number of Mott stainless porous materials that were tested at Lockheed for permeability and bubble point with 2-propanol. It can be seen that materials with comparable permeability can have much different bubble point pressures. Based on Mott's criteria, the material of plug #3 is 0.3 micron and #4 is 0.1 micron. The higher bubble point of #4 would indicate a lower distribution of pore sizes then #3 which had the same permeability.

Table 1. Characteristics of porous plugs

Plug #	Thickness (cm)	Dia. (cm)	Bubble Point (cm Hg)	Permeability (cm2)
1	1.27	3.3	7.8	3.55×10^{-9}
2	1.27	3.3	7.9	1.7×10^{-9}
3	0.635	4.06	10.9	3.8×10^{-10}
4	0.635	6.86	19.3	3.8×10^{-10}

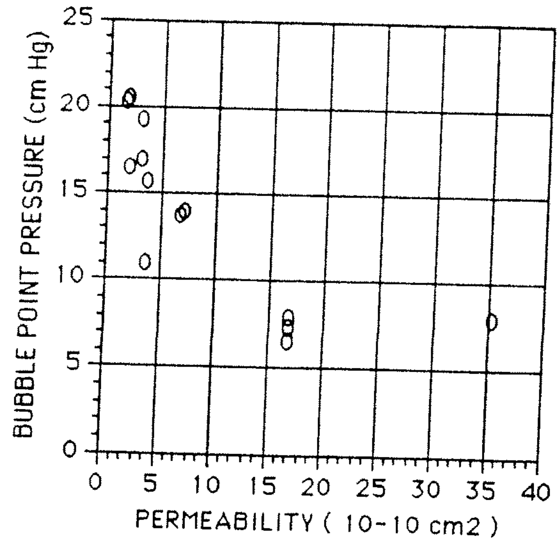


Figure 1: Permeability vs bubble point of sintered stainless material

TEST APPARATUS AND POROUS PLUG DESIGN

In the test apparatus, the porous plug assembly is installed at the bottom of a helium tank such that the inlet of the plug is submerged until the liquid level drops to the inlet of the plug. The downstream side of the plug is facing down. A 100 torr baratron type warm pressure transducer is installed in the warm section of the plumbing. No attempt was made to measure the pressure just downstream of the plug. The transducer was put in the warm section to simulate the location in the actual Dewar vent plumbing. The pressure reading taken at this point is referred to as the "back pressure". The tank contains a superconducting liquid level sensor, to measure the amount of liquid remaining in the tank, and a heater to vary the heat load. During most of the tests, the vent line of the porous plug was hooked up to a spacecraft thruster whose flow capacity was enlarged in order to handle the full flow of all the thrusters. A pump was installed on the outlet of the thruster.

The plug assembly consisted of the porous media with two thermometers on both the upstream and downstream side, a liquid point sensor (LPS) and a 0.28 watt heater on the downstream side. The LPS generates a substantial amount of heat (0.018 W) when activated and therefore was only pulsed on when a set of data points was taken. Thermometers are GR-200B-1500 germanium resistance (GRT) sensors by Lake Shore Cryotronics calibrated by the vendor. The lead wires of the GRTs are epoxied to the surface of the media in order to get a good reading of the surface temperature. In addition to the LPS on the downstream side of the plug, one is installed in the plumbing line a few inches downstream. These point sensors were purchased from American Magnetics. The heater heats a coarse mesh copper screen that covers the downstream side of the media.

NORMAL OPERATION

During normal operation of the plug, the liquid/vapor interface resides on the downstream surface. Figure 2 shows the data taken for plugs #2 and 3. There were thermometry problems with plug #1 and therefore the temperature gradients are not reported. It is reminded that plug #2 was twice as thick as #3. The interesting result is that the slope of the data does not appear to be directly proportional to permeability as some of the theories suggest[4].

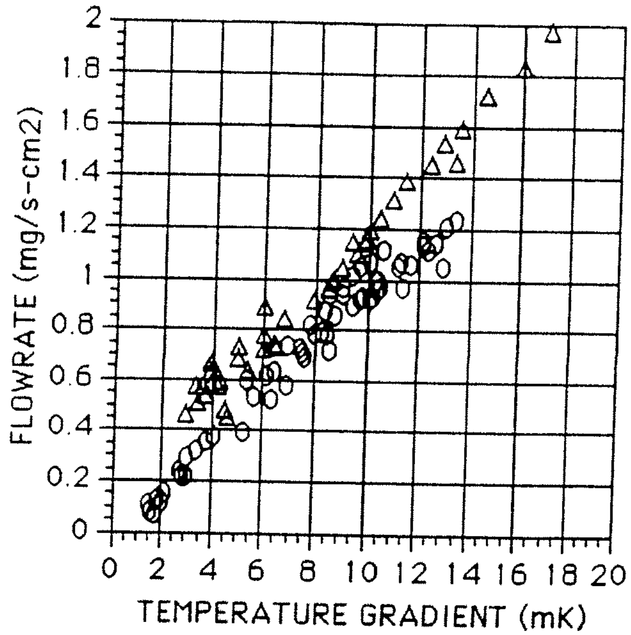


Figure 2: Effect of permeability on the normal operating characteristics at 1.8 K (Δ - K_p=1.7 x 10^{-9} cm^2, 0 - K_p=3.8 x 10^{-10} cm^2).

CHOKING CHARACTERISTICS

The performance of plugs #3 and #4 are very typical. As the flowrate is increased by decreasing the back pressure, the temperature gradient increases until the plug achieves a choked condition. The flowrate at this point is referred as the critical flowrate. Above this point, as the flowrate is increased and subsequently decreased, the temperature gradient would go through a hysterisis loop. Figure 3 shows typical temperature gradient and back pressure profiles for various bath temperatures. As expected, the slope of flowrate verses temperature gradient in the normal mode and the critical flowrate increase with bath temperature

The most interesting observations are the difference in gradients across the plug before and after going through a hysterisis loop and readings of the LPS on the downstream surface. Upon returning to normal mode, while decreasing the flowrate, the gradients would be larger than those observed while increasing the flowrate at beginning of the loop. This is indicated by larger temperature gradients and lower back pressures.

While operating in the normal mode, the LPS would indicate liquid. This confirms that the liquid/vapor interface resides on the surface of the plug. The LPS is in contact with the copper mesh screen that covers the surface. As the plug was subjected to a hysterisis loop, this sensor would continue to indicate liquid until the plug went into the choked mode. The temperature gradients at the point when the LPS would begin to indicate vapor were 13.0, 31.5, and 27.4 mK for temperatures of 1.7, 1.8, and 1.9K respectively in the three cases shown. The hydrostatic heads were 21, 30, and 24 cm respectively. The sensor would indicate vapor until the plug returned to the normal mode and then sense liquid. The LPS in the plumbing would always indicate vapor. In Plug #4, the LPS was set slightly off the copper mesh and it did not indicate liquid in the normal mode.

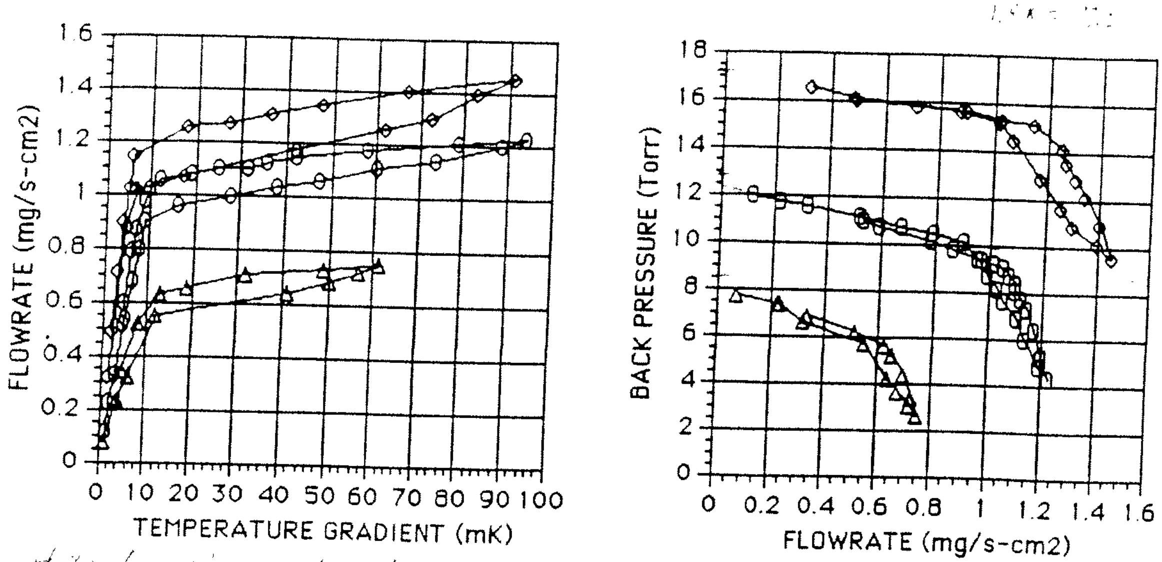


Figure 3. Effect of bath temperature on temperature gradient and back pressure of material with $K_p=3.8 \times 10^{-10}$ cm² (Δ 1.7K, O 1.8K, ∇ 1.9K).

Figure 4 shows the effect of hydrostatic head on the critical flowrate of plugs #3 and #4. The interesting observation is the difference which is most likely due to the different bubble point pressures of the two plugs. Based on the results of this test, the 1.8 K critical flowrate at zero hydrostatic head for the material of plug #3 is 0.47 mg/s-cm² and 0.57 mg/s-cm² for #4.

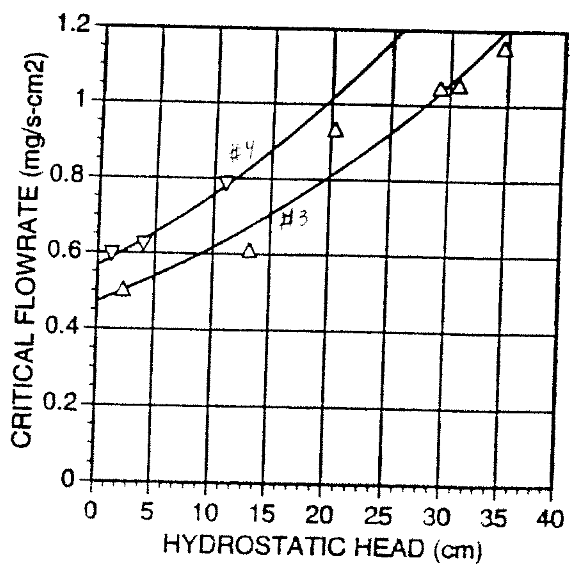


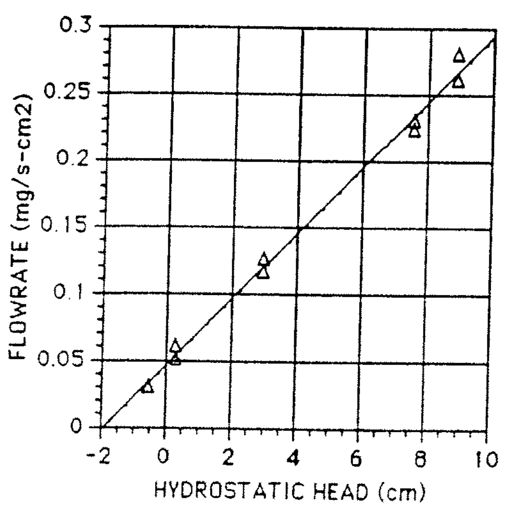
Figure 4: Effect of hydrostatic head and bubble point (Δ 10.9 cm Hg, ∇ 19.3 cm Hg) on critical flowrate of material with $K_p=3.8 \times 10^{-10}$ cm² operating at 1.8K.

The behavior of plug #2 in the choked mode did not follow a typical hysterisis loop. While the plug was choked, the temperature gradient would increase, then suddenly decrease and then further increase as the flowrate was increasing. It is speculated that this behavior was due to the fact that the plug was made of four discs stacked on each other and the location of the liquid/vapor interface was effected by this. This behavior was very repeatable. Even though it is intended to only operate in a normal mode, it was decided not to build a unit with a stack of discs because of this behavior while choked.

BREAKTHROUGH CHARACTERISTICS

Plug #1 was very susceptible to liquid breakthrough. This was evident in runs where temperature control of the bath was progressing smoothly for a few hours when suddenly breakthrough would occur. During these operations, the back pressure was staying constant within a few hundredths of a torr. The next plugs were not susceptible to breakthrough.

A number of tests were performed with Plugs #3 and #4 to characterize breakthrough. The test sequence was such that the flowrate was decreased in small increments and the LPS in the vent line was monitored. As soon as it indicated liquid, the flowrate would be increased, setting the plug in a choked condition and heater in tank turned up to maintain bath temperature. Once the LPS showed vapor, the plug would be unchoked and the test repeated at a lower hydrostatic head. The results are shown in figure 5 which indicate that operation below a flowrate of 0.05 mg/s-cm^2 would cause breakthrough. It is possible that indications of liquid by the LPS was not actual breakthrough but rather a build-up of a large film of SFHe. In either case this would not be desirable due to the possibility of the film conducting heat back to the tank. The hydrostatic head is measured from the inlet surface of the porous media. Both plugs #3 and #4 showed the same characteristics which would indicate that the difference in bubble point does not effect breakthrough.



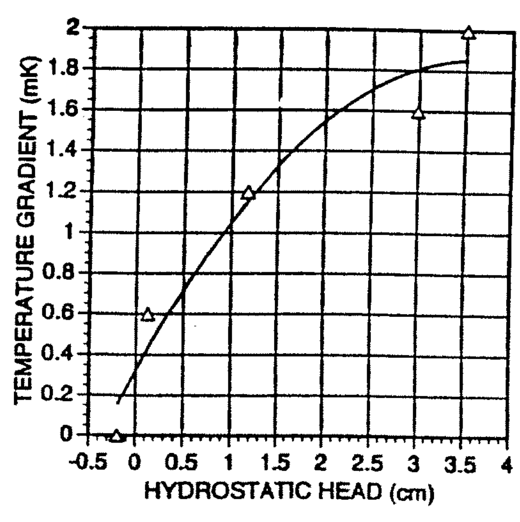


Figure 5: Effect of hydrostatic head on breakthrough of material with K_p=3.8 x 10^{-10} cm^2 operating at 1.8K.

DOWNSTREAM HEATER TESTS

Tests were performed with the heater on the downstream side of the porous media to determine if it can be used to achieve a flowrate above the critical flowrate without choking. Results of this test are shown in figure 6. The plug was first put through a hysterisis loop to show the critical point. The flowrate was then brought up the critical point at a flowrate of 0.94 mg/s-cm^2 with a temperature gradient of 7.2 mK (0 point in figure). The heater was then turned on and the flowrate increased to 1.18 mg/s-cm^2 while plug temperature gradient only increased to 8.6 mK (■ point-in figure). The plug operated at the higher flowrate (25 % above the critical point) while maintaining a normal mode of operation. The hydrostatic head on the plug during this test was 19 cm. All of the heater power went into vaporizing liquid.

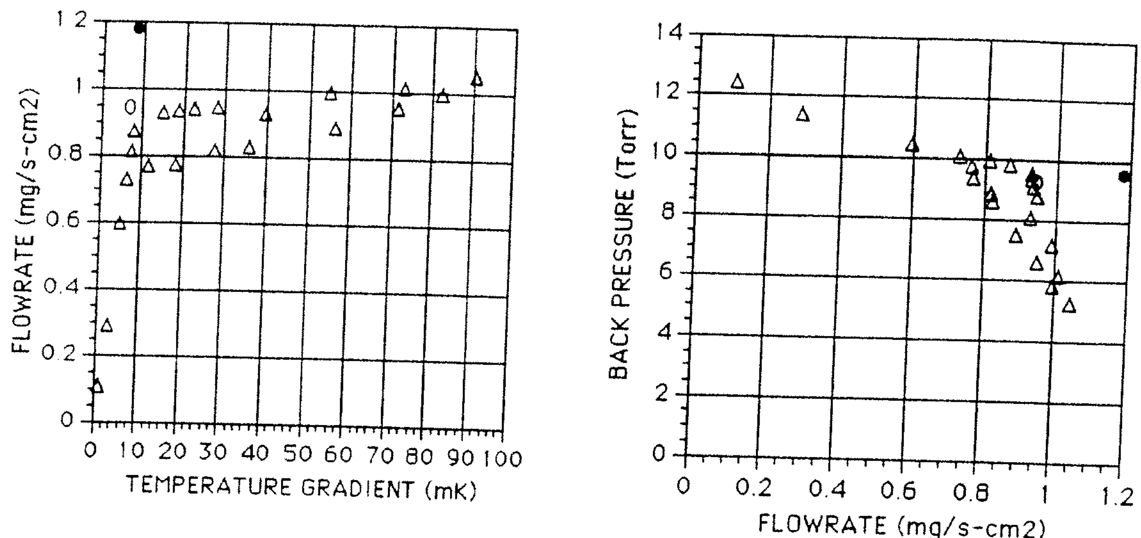


Figure 6: Operation of downstream heater to increase flowrate above critical point (0 start point-heater off, ■ end point-heater on).

SUMMARY

A porous material for phase separation of SFHe has been succesfully tested. Based on results of these tests, the flight plug (#4) was selected to be 0.635 cm thick with a diameter of 6.86 cm. The flight plug for the Relativity Mission has been assembled, gone through vibration testing, and performance testing. Based on the measured breakthrough point of 0.05 mg/s-cm^2 and a critical point of 0.57 mg/s-cm^2 at zero hydrostatic head, the flight plug operates in a normal mode over the range of 1.8 to 21 mg/s, meeting the requirements of 4-16 mg/s.

A downstream heater is available for increasing the flow beyond it's predicted critical point without choking, but is not planned to be used at this time. Data is presented showing the effect of hydrostatic head on the breakthrough and critical point of the material. In addition results show that the bubble point of the material appears to have an effect on the critical point.

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