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JT CRYOSTAT WITH LIQUID-SOLID CRYOGEN RESERVOIR

RALPH C. LONGSWORTH
APD CRYOGENICS INC
ALLENTOWN, PA 18103-4783

INTRODUCTION

Joule-Thomson cryostats with reservoirs that fill with liquid cryogen have been under development for applications where extended cooling is needed after gas flow has been stopped and for applications in space where the pressure in the reservoir can be reduced to provide temperatures below the triple point temperature of the cryogen. Two methods have been used to fill the reservoir. First is to cool the outside of the reservoir with the JT flow stream and condense gas from a separate supply bottle. Second is to have the JT flow fill the reservoir directly. In order to retain the cryogen in the reservoir and then transfer heat to it with minimum temperature rise, it is necessary to have a special packing in the reservoir.

This paper describes an experimental cryostat which was designed for use with Ar and N_2 that collects liquid directly from the heat exchanger. The packing in the reservoir separates the liquid from the gas as it emerges from the JT nozzle, retains the liquid in wicking material as it is rapidly depressurized, and transfers heat to the liquid or solid cryogen during the hold period with a small temperature rise. Tests were run to simulate its use in a sounding rocket.

PROCESS

Two basic means have been tried for filling the reservoir with cryogen as shown in Figure 1. The first, Fig. 1a, is to have two separate gas supply bottles, one which supplies gas to the JT heat exchanger at a high pressure, e.g. N_2 or Ar at 40 MPa, and a second which contains the gas that fills the reservoir at a lower pressure, e.g. N_2 at 1 MPa. Cold gas from the JT heat exchanger flows through another heat exchanger on the outside of the reservoir which cools the reservoir and causes the gas in the reservoir to condense until the reservoir is either full or the reservoir bottle pressure has dropped to the saturation pressure corresponding to the reservoir temperature. For example, a JT heat exchanger operating with Ar might cool the reservoir to 95 K corresponding to the Ar pressure in the evaporator being .21 MPa. Thus, if N_2 is condensing in the reservoir, the supply bottle pressure would not drop below .54 MPa. After filling the reservoir with cryogen the JT flow can be stopped and the vent valve on the reservoir opened to a low pressure corresponding to the saturation temperature that is desired in the reservoir. It is important that residual gas in the JT heat exchanger also be vented so that residual gas does not condense and freeze in the evaporator when the reservoir temperature is reduced.

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ABSTRACT

JT Cryostats have been developed which cooldown quickly and collect liquid in a reservoir which can then be vented to vacuum to solidify the cryogen and provide refrigeration at temperatures below the triple point. This paper describes an experimental unit which was designed for use with Ar and N_2 which has a packing in the reservoir that separates the liquid from the gas as it emerges from the JT nozzle, retains the liquid in a wick material as it is rapidly depressurized, and transfers heat to the solid cryogen during the hold period with a small temperature difference.

Examples are given of experiments that simulate a sounding rocket test in which the cryostat is cooled down on the ground and vented to a vacuum pump for pre-launch calibrations, flown into space with liquid maintained by a small on-board tank of gas, then solid cryogen is formed by stopping the JT flow and venting to vacuum.

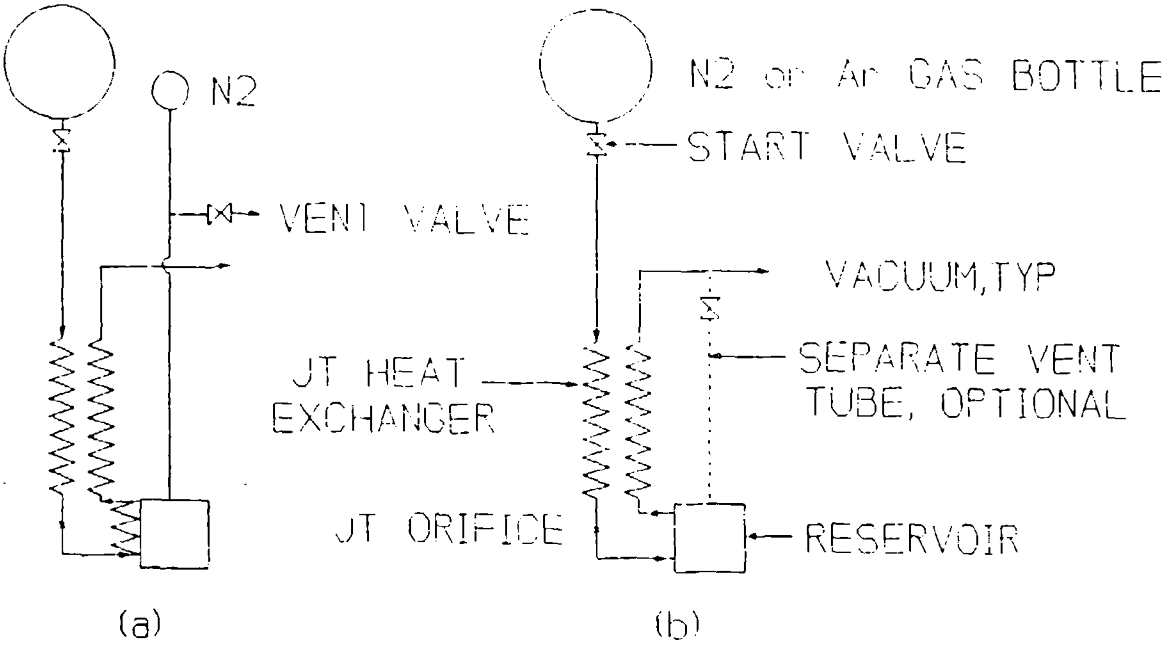

FIGURE 1 Process Schematics for Two Methods of Filling A Reservoir With a Cryogen Using a JT Cooler.
(a) Externally-Cooled Reservoir
(b) Internally-Cooled Reservoir

The packing in the reservoir must consist of an extended surface heat transfer material that can transfer heat from the condensing cryogen in the reservoir to the JT flow in the evaporator and a wicking material that retains the cryogen when the rapid pressure reduction causes violent boiling of the liquid cryogen. Open passages are also needed to let the gas excape without entraining liquid during depressurization. Porous copper and aluminum have been used for this purpose but a better type of packing has been developed as described in [1] A two-stage N_2/H_2 JT cryostat of this type which used the new packing material to solidify H_2 has been described in [2].

The second method of filling the reservoir, Fig. 1b, is to have cold gas/liquid from the JT heat exchanger flow directly into the reservoir and collect there. The packing in the reservoir for this process must serve as a phase separator to remove liquid from the JT flow which may have a high velocity. Other requirements for the reservoir packing are the same as for the externally cooled reservoir.

The externally cooled reservoir cryostat has the following relative advantages:

- By monitoring the pressure in the reservoir supply tank, it is possible to know when the reservoir is full and how much liquid has been condensed

- A higher temperature gas with higher JT cooling effect such as Ar can be used to condense a lower temperature gas such as N_2

The internally cooled reservoir cryostat has the following relative advantages:

- The reservoir can be lighter because less heat exchanger surface is needed.
- The reservoir can be lighter because it can be designed for a lower pressure.
- The residual gas in the heat exchanger is vented along with the gas from the reservoir.
- Less cryogen is vaporized to cool the reservoir from the fill temperature to the base temperature because the reservoir is lighter.

When venting to vacuum the minimum temperature that is reached depends primarily on the flow restrictions in the vent path. An internally filled reservoir that is vented through the heat exchanger would not reach as low a temperature as a design that had a separate, less restrictive vent tube with a valve that opens after JT flow has been stopped, ref. Fig. 1b option.

EXPERIMENTAL CRYOSTAT DESIGN

Figure 2 shows the design of the JT heat exchanger and internally cooled reservoir that was tested. A finned-tube heat exchanger with a central mandrel tube has an extension on the cold end such that the gas/liquid mixture flows out the end of the extension after flowing through the JT restrictor. The heat exchanger slides into a sleeve which has the reservoir connected at the cold end. Adjustments can be made to the JT restrictor by simply removing the heat exchanger.

The reservoir is designed with a thin stainless steel housing and a flat copper end cap that serves as the cold plate where the device being cooled is mounted. The packing in the reservoir consists of alternating layers of porous copper and wicking material which has a very fine pore size. The copper layers are soldered along the bottom edge to the cold plate. Gas from the JT heat exchanger impinges on the back side of the cold plate then flows radially out along the cold plate and back through the porous copper layers before returning to the heat exchanger. This flow path causes the cold plate to cool first and then liquid collects in the packing. Capillary attraction of the liquid in the pores of the wick is high, so that moderate gas velocities through the conductor are possible without blowing liquid out of the wick. Similarly, when the reservoir is depressurized the open structure of the conductor layer allows gas to escape with very little entrainment of liquid. The reservoir was designed to store 460 J of cooling after being filled with LN_2 at 80 K. In cooling to 70 K, 50 J is used to cool the reservoir and the remaining LN_2. Similarly 105 J is used to cool from 80 K to 60 K leaving 355 J available for cooling at 60 K

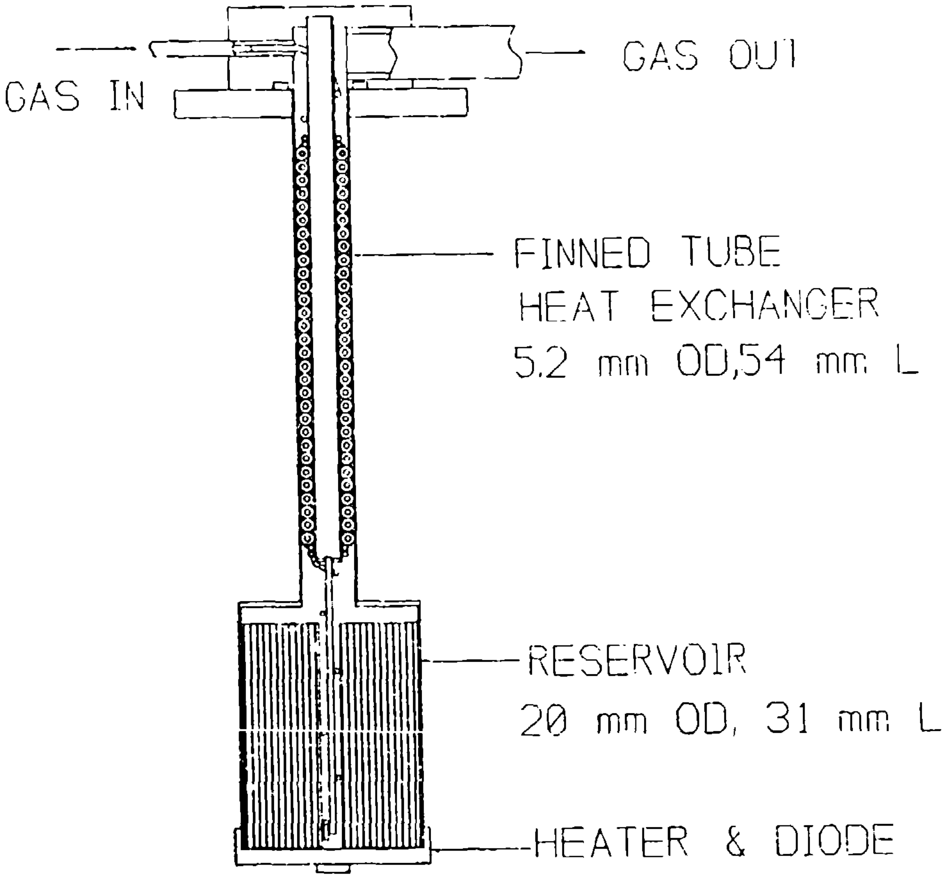

FIGURE 2 Experimental Cryostat Having a Finned-Tube Heat Exchanger Flowing Cold Gas / Liquid Through An Internally-Cooled Reservoir

TEST ARRANGEMENT

Fig. 3 shows a schematic diagram of the test setup that was used to simulate the operation of the experimental cryostat in a sounding rocket. The mission that is envisioned would occur in the following four phases.

Phase 1 Open V1 & V2. The unit would cool down on the ground with N_2 supplied at constant pressure from a standard cylinder and vacuum provided by a pump, both to be left on the ground. A temperature of about 70K is maintained to do a ground test of the instrument.

Phase 2 Close V1 then V2. Just before launch, the gas supply and vent lines are sealed and disconnected so that during the 2-minute flyout the cryogen in the reservoir is warming and the pressure is increasing

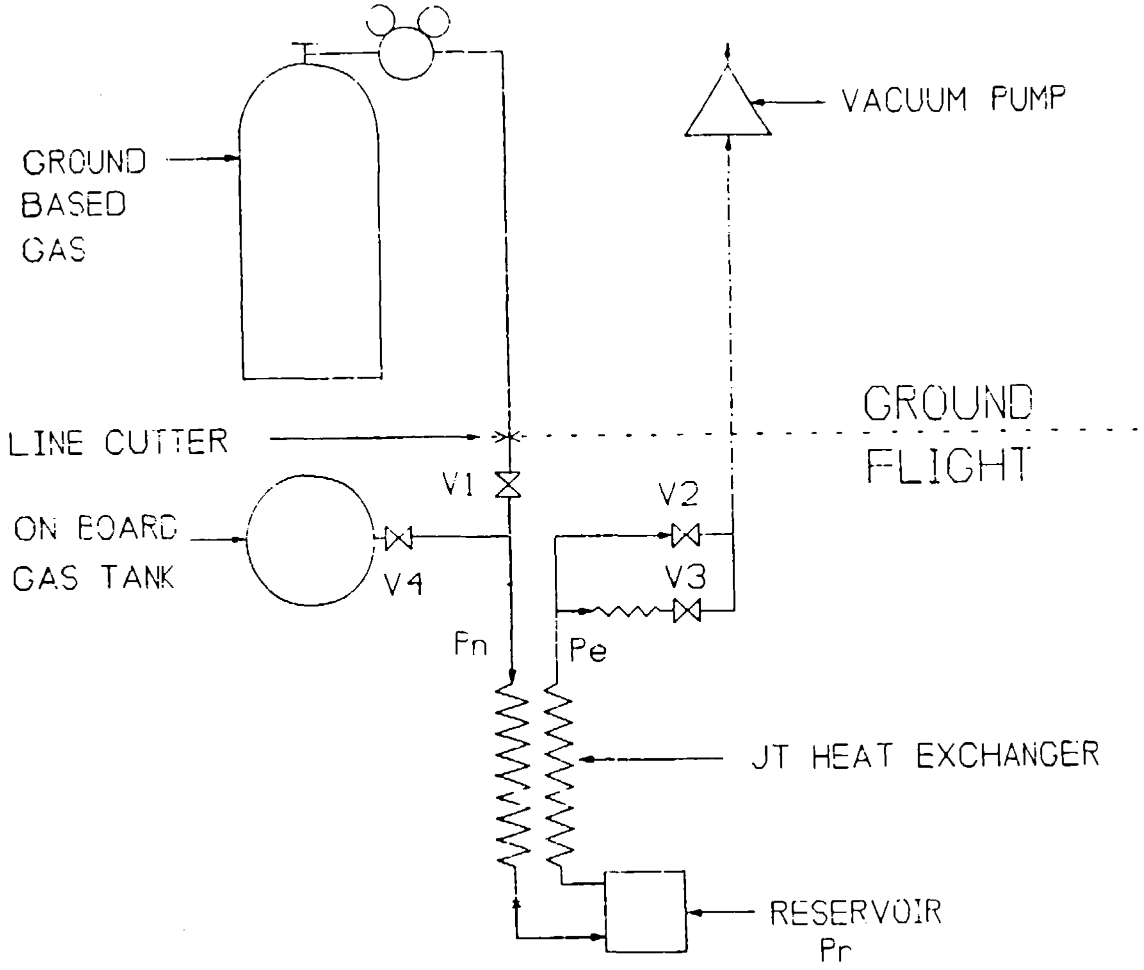

FIGURE 3 Experimental Test Set Up to Simulate a Space Flight Including Cooling on the Ground From a Large Tank, Cooling in Space From an On-Board Bottle, and Coasting on Cryogen Stored in the Reservoir

Phase 3 Open V2. When the flight unit has reached a space environment the vent valve is reopened and the valve on the on-board gas supply bottle is opened. The cryostat then returns to the cold operating temperature, which will be the same as on the ground, if a pressure regulator maintains the same supply pressure. The liquid cryogen that boiled off during the flyout is replenished as gas flow continues. If the gas supply line does not have a pressure regulator, then the reservoir temperature will drop as the bottle pressure and gas flow rate drop.

Phase 4 Gas flow is stopped and cooling is maintained by evaporation or sublimation of the cryogen that has been stored in the reservoir. Stopping the gas flow results in low pressure drop in the heat exchanger, which causes the reservoir temperature to drop if V2 is left open. In order to keep the temperature during the coast period at about the same temperature as when gas is flowing, the vent flow can be redirected to flow through a restrictor by closing V2 and opening V3.

TEST RESULTS

A liquid nitrogen boiloff test venting to atmospheric pressure was run to measure the static heat loss. It was measured to be 345 mW. For subsequent tests the thermal capacity of the cryogen in the reservoir was calculated as being equal to the applied heat load, plus 345 mW times the coast time.

The following parameters were varied in running the tests:

a) JT orifice flow rate, Co = 5.3, 2.0 and 1.0 L/min at standard conditions, N_2 at 0.8 MPa and 21°C

b) Fill temperature - 66 K to 81 K

c) Orientation - Up, down

d) Gas - N_2, Ar

e) Vent line pressure - < 1 kPa to 101 kPa

The gas supply was changed from 40 MPa for cooldown to 15 to 20 MPa during the fill period. Temperature during the fill period was dependent on pressure drop in the heat exchanger and the setting of the vent valves.

Stored Refrigeration Capacity

Initially, the JT restrictor was set with a flow of 5.3 L/min at standard conditions. Fill temperatures for N_2 were in the range of 77 K to 81 K and vent pressures were set so hold temperatures in the range of 60 K to 79 K. Thermal storage capacity for these tests are shown in Fig. 4. Results for the cold end down orientation show results that are comparable to the predicted values. When the unit was oriented cold end up, however, the retained N_2 was only about 60% of the predicted amount.

Two tests were run in which the temperature of the reservoir was reduced to about 70 K by flowing He through the heat exchanger venting to atmospheric pressure rather than using a vacuum pump. Temperature could be changed by changing the He flow rate. The heat exchanger is efficient enough so that there is a relatively small loss of stored cooling in doing this.

The flow in the JT restrictor was reduced to 2.0 L/min at standard conditions and a test was run at the same fill temperature of 80 K followed by pump down to 60 K in the cold end up orientation. A thermal storage capacity 50% greater than anticipated was measured (plotted in Fig. 4). This indicates that the higher flow rates were causing liquid to be blown out of the wick during the fill period.

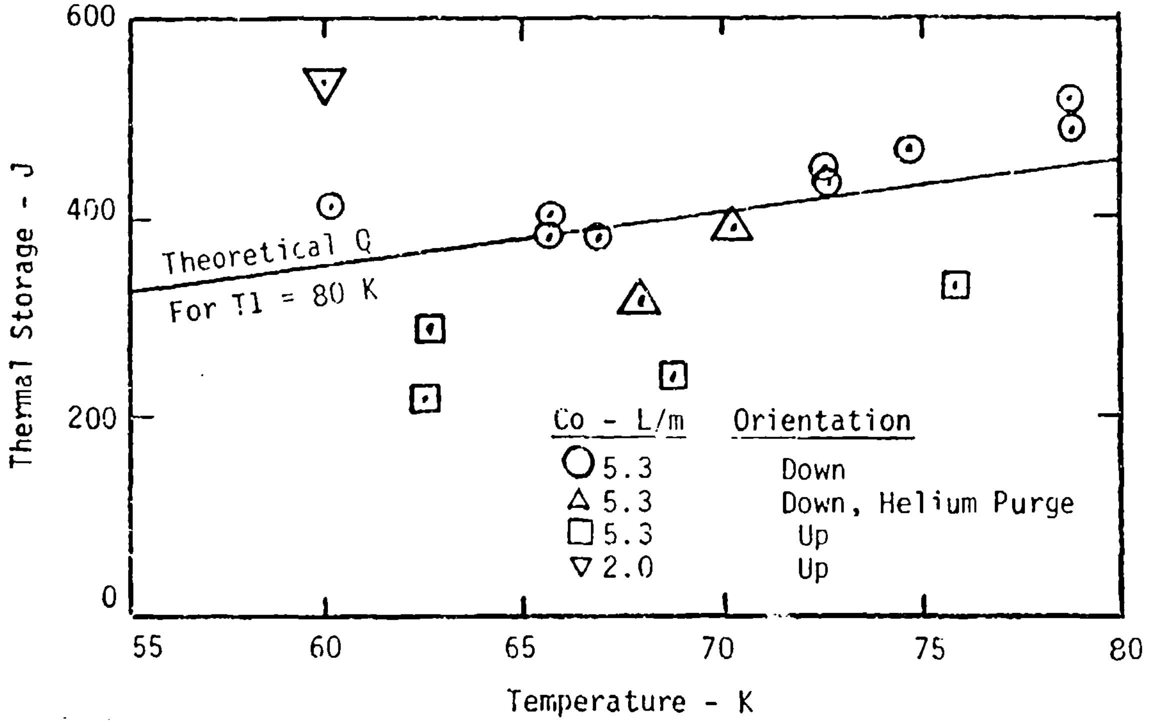

FIGURE 4 Measured Thermal Storage Capacity for LN_2 Filling the Reservoir at 77 K to 81 K

More tests were run with the JT restrictor set at 2.0 and 1.0 L/min at standard conditions. The lower flow rate resulted in lower pressure drop in the heat exchanger so that the reservoir could be filled at temperatures in the range of 67 to 70 K, for which the reservoir is calculated to retain 520 J of cooling with LN_2 Results of thermal capacity measurements for this series of tests are shown in Fig. 5. In the cold end up orientation, the stored refrigeration is close to the predicted value, while with the cold end down, the capacity is almost twice the predicted amount.

Temperature Change

As heat flows into the reservoir from the cold plate, the cryogen closest to the cold plate vaporizes first. As the cryogen vaporizes, the distance to the remaining cryogen increases and the heat transfer surface area of the cryogen decreases. These two factors cause the temperature difference between the cold plate and cryogen to increase at an increasing rate.

Temperature change versus time for the last 10 minutes of the hold period is plotted in Fig. 6 for a number of tests. All of the tests follow paths that are quite similar. Temperature during the last 2 minutes is seen to increase from an average difference of 1.3 K to an average difference of 3.2 K

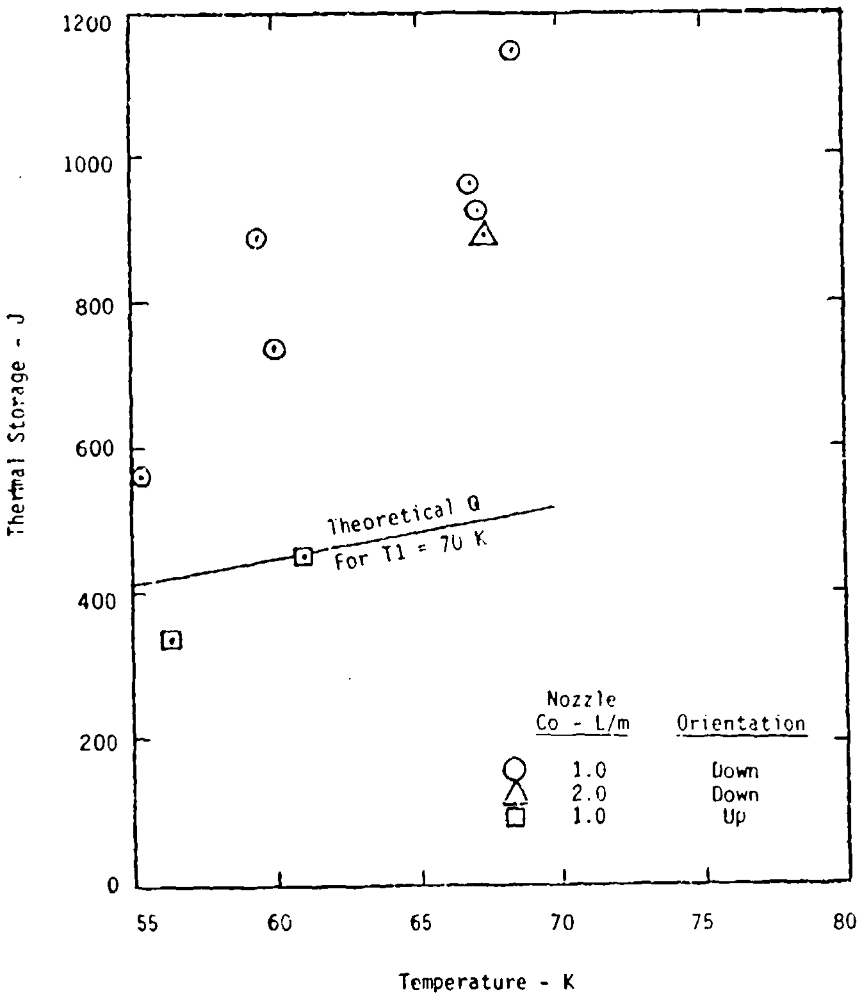

FIGURE 5 Measured Thermal Storage Capacity for LN_2 Filling the Reservoir at 67 K to 70 K

If an application requires that the temperature be more constant, there are several options, as follows:

a) design the reservoir for extra capacity so that only about 80% of the cryogen is vaporized during the period when cooling is needed.

b) design the reservoir with a higher ratio of thermal conductor to wick and smaller length to diameter ratio.

c) use a variable restrictor in the vent line coupled to a controller to reduce the cryogen pressure and temperature as the ΔT increases

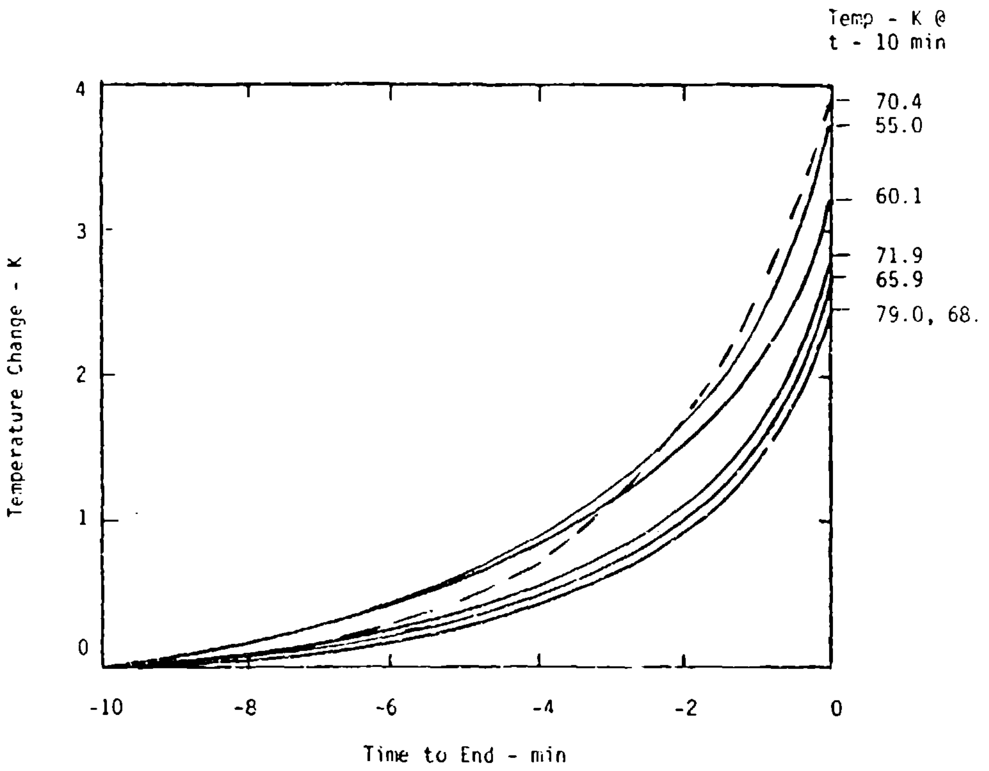

FIGURE 6 Temperature Rise During the Last 10 Minutes of the Coast Period
For N_2 ______ and Ar - - - - in Test Reservoir.
250 mW applied Load + 345 mW of Static Load.

Flight Simulation

Tests were run to simulate cooldown and operation on the ground, launch into space, cooling from an on-board gas bottle, followed by coasting from the stored cryogen.

Fig. 7 shows a plot of a test that was run with the JT restrictor set at 2.0 L/min at standard conditions for which we tried to maintain a temperature of about 70K during the flight phases. This test was run with N_2 in a cold end down orientation, and no additional heat load applied After cooldown, a temperature of 74 K was held as established by the pressure drop in the heat exchanger and restriction in the vent line, V2 open and V3 closed. Just prior to launch, the gas supply valve is closed and the reservoir allowed to cool to 68 K before closing the vent valves. During the next 120s, the temperature in the reservoir rises back to 74 K. Vent valve V3 is then reopened to vacuum, after which V4 is opened to supply gas to the cryostat. During the period of operation from the .5 L on-board gas bottle, the supply pressure drops from 32 MPa to 10 MPa and the temperature drops from 74 K to 70 K.

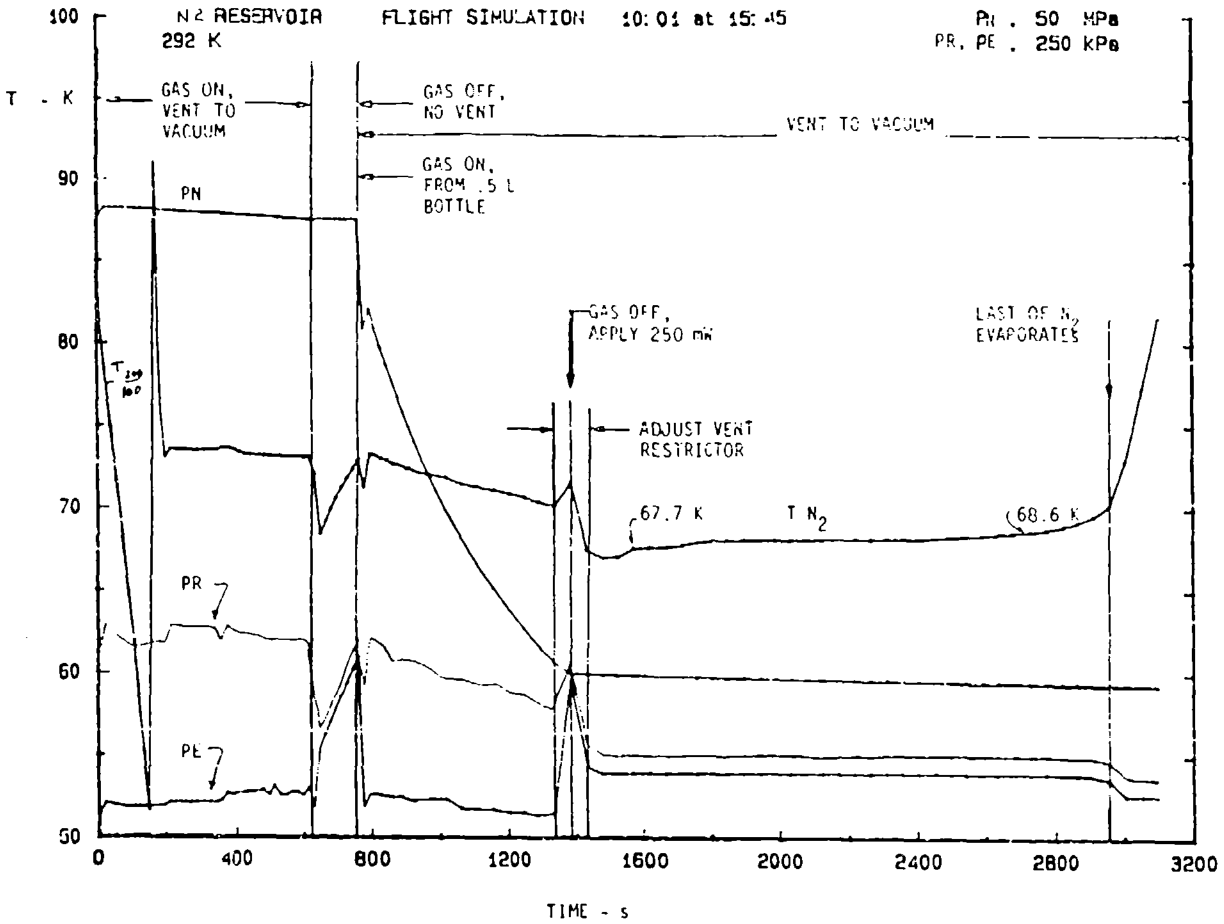

FIGURE 7 Experimental Flight Test with N_2 in Which the Vent Valves are Adjusted to Maintain a Temperature of About 70 K.

The coast phase is initiated by increasing the restriction in the vent line, opening V3 and closing V2, then closing the gas supply valve V4, and closing V3 at a rate that gets to the desired coast temperature fast without getting too cold. The valve adjustment for this test resulted in a temperature of 67.7 K after the temperature stabilized, rising to 68.6 K when about 85% of the LN_2 had vaporized.

Fig. 8 shows another test for which the JT restrictor flow was 1.0 L/min at standard conditions and the unit was oriented cold end up. Both vent valves, V2 and V3, were set full open during all but the launch phase of the test. This resulted in a temperature of 66 K being held on the ground with no applied heat load, and 67.5 K dropping to 67.0 K when operating with the on-board bottle and 250 mW applied. During the coast phase, the temperature dropped to 56.3 K with 250 mW applied and 55.0 K when the heater was turned off.

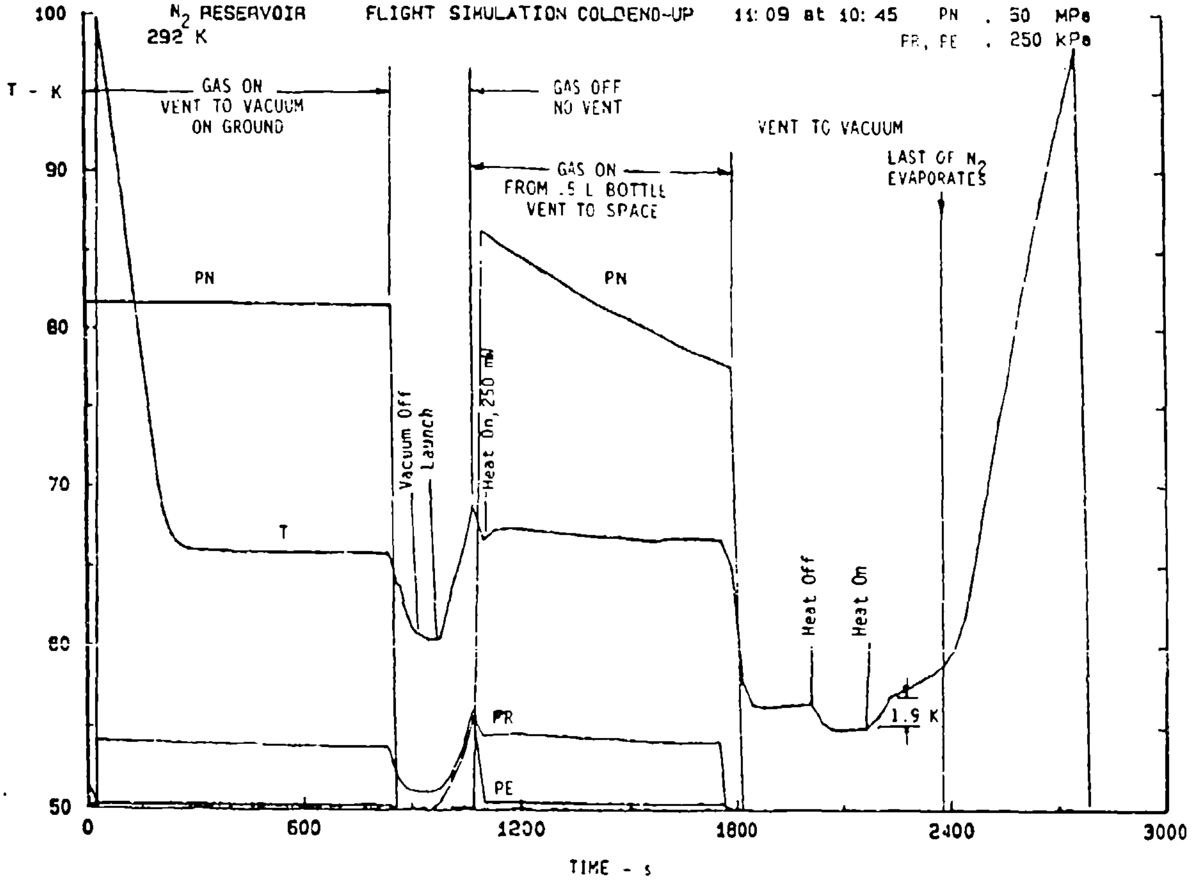

FIGURE 8 Experimental Flight Test with N_2 in Which the Vent Valves are Fully Opened to Demonstrate Minimum Temperatures.

Similar tests with Ar showed temperatures to be about 10 K warmer than for N_2 and coast times to be longer.

SUMMARY

A JT Cryostat with an integral reservoir has been built and tested with N_2 and Ar venting to vacuum. The reservoir packing which consists of layers of thermally-conducting porous copper and a non-thermally conducting wick is effective in removing liquid direct from the JT flow stream and retaining it in the wick during the fill period and during the period of rapid depressurization in a cold-end up orientation

Simulation of an experiment that starts on the ground then flies into space showed that when using N_2 it is possible to operate at 66 K while on the ground venting to a vacuum pump and in space venting to vacuum with gas supplied from an on-board bottle. When flow was stopped, the temperature dropped to 55 K then warmed about 1.5 K at the time when 85% of the solid N_2 has sublimed. The temperature difference between the load and the solid cryogen is a function of the heat transfer path and the load. Temperature can be controlled by adjusting a vent line valve which affects the pressure at which the cryogen in the reservoir sublimes.

Argon enables the unit to cool down faster and store more refrigeration than N_2, but the temperature for comparable conditions is about 10 K greater. The temperature in the reservoir can also be depressed without using a vacuum pump by having He flow through the heat exchanger and stored cryogen.

REFERENCES

1. R. C. Longsworth, "Cryogen Thermal Storage Matrix" -- U. S. Patent 5,012,650; May 1991.

2. R. C. Longsworth, W. A. Steyert and R. L. Pittenger, "J-T Cryostat with Solid Cryogen Storage for Short Missions" -- Proceedings of the Second Interagency Meeting on Cryocoolers -- Easton, MD; September 1986 (Restricted Distribution).