IPN Progress Report 42-147 November 15, 2001

A 2.5-Kelvin Gifford–McMahon/Joule–Thomson Cooler for Cavity Maser Applications

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A 2.5-K cooler suitable for cooling cavity maser amplifiers is described. The device combines a 4-K Gifford–McMahon (GM) refrigerator with a Joule–Thomson (JT) circuit to provide 180 mW of cooling at 2.5 K. The device is compact and can operate in any physical orientation. A commercial two-stage GM cooler pre-cools the helium JT circuit flow. The JT circuit can be simplified as compared with existing systems. Only two counter flow heat exchangers are necessary. The 4-K GM operating temperature also allows the use of a single-stage compressor for the JT circuit. The JT circuit operates with a supply pressure of only 110 kPa. A commercial scroll vacuum pump is used as a compressor. The simplified system can be fabricated for less than the cost of current 4.5-K maser coolers.

I. Introduction

A multiple-cavity-type maser for operation at 32 GHz has been designed and is currently being tested at JPL [1]. An 8.4-GHz cavity maser is also planned. These masers need to operate at 2.5 K for optimum performance. Existing Deep Space Network (DSN) traveling-wave masers are cooled with hybrid Gifford–McMahon (GM)/Joule–Thomson (JT) coolers that operate at 4.5 K [2]. The traveling-wave masers require substantially more cooling capacity than the cavity masers and make operation below 4.5 K impractical [3].

The cooler described in this article uses a commercially available GM cooler operating at or below 4 K to pre-cool a separate JT circuit. The system uses a single JT compression stage provided by a commercial scroll vacuum pump that uses no lubricating oil. The system provides 180 mW of cooling at 2.5 K. It is simpler in design and can be fabricated at lower cost than existing 4.5 K systems.

II. System Description

A flow diagram for the cooler is shown in Fig. 1. The GM cooler pre-cools the JT circuit flow that provides the final stage of cooling. The GM cooler provides cooling in two stages: the first stage provides 50 W at 50 K, and the second provides 1.5 W at 4.2 K.

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

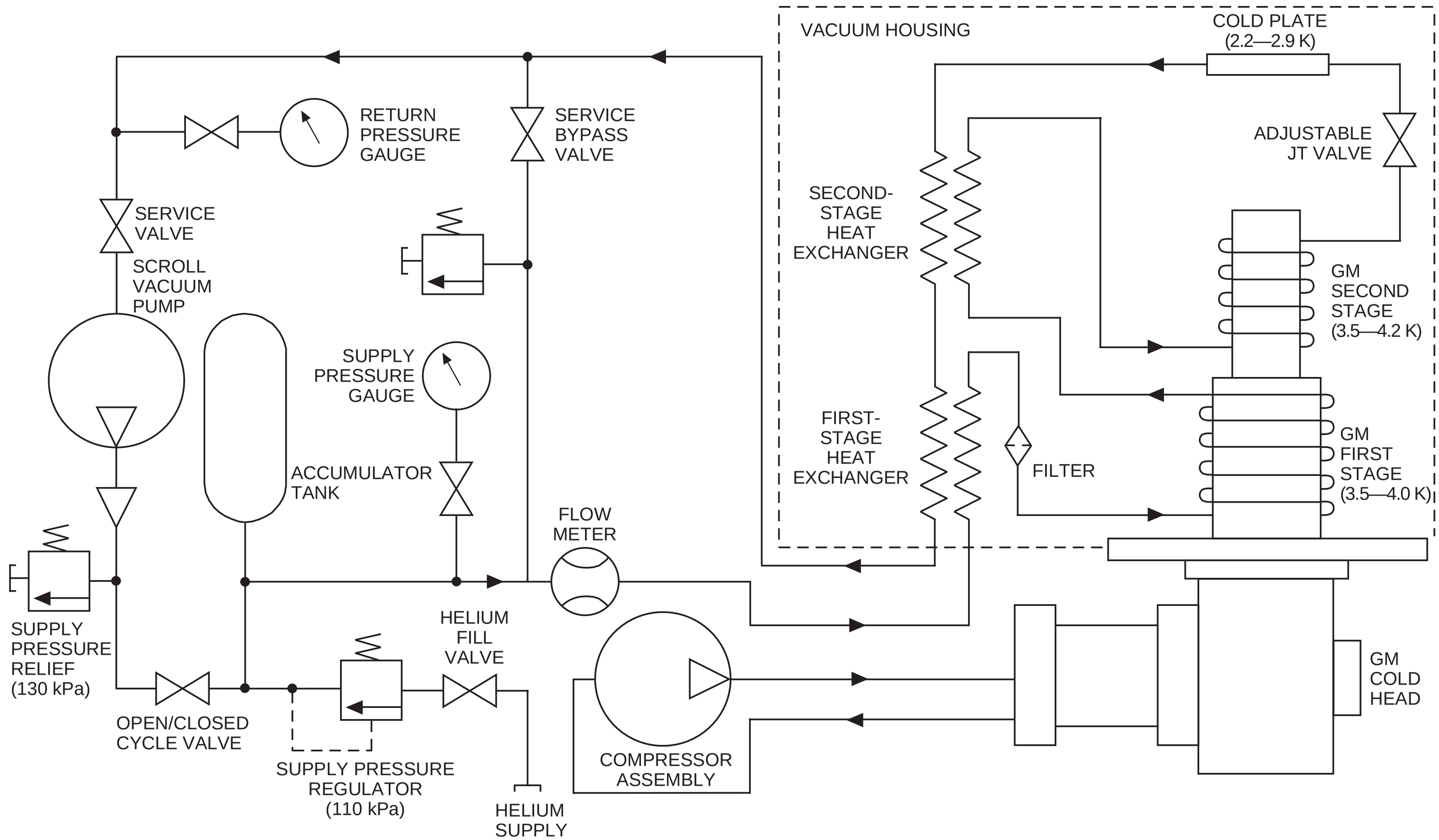

Fig. 1. A flow diagram for the cooler.

The JT ambient supply gas is supplied at 110 kPa. The JT gas passes though the first-stage counter-flow heat exchanger and is cooled by the return gas. It is cooled by the GM first stage to approximately 30 K. The helium is passed through a similar second-stage heat exchanger and is cooled by the GM second-stage to approximately 4 K. The flow is then throttled with an externally adjustable expansion valve to the third-stage operating temperature and pressure. The temperature at the final stage is the saturation temperature of helium at the pressure in the stage. The helium returns through the heat exchangers and is compressed back to the supply pressure and recycled.

The 4.2-K GM second-stage operating temperature allows the helium to be cooled below the liquid point before the JT expansion. This allows the cooler to operate without the third-stage heat exchanger normally used in JT coolers. Removing the third-stage heat exchanger reduces the cool-down time and system complexity. During cool-down, helium is supplied from an external helium bottle. The supply gas is regulated to maintain the supply to the cooler at 110 kPa. Once the cooler has reached thermal equilibrium, no more gas is supplied from the external bottle. An external buffer tank allows for small changes in the supply pressure due to gas expansion during changes in cooling load. An external 130 kPa relief valve limits the maximum supply pressure.

The complete cooler excluding the GM cooler compressor and the external helium supply are mounted on a 1-m^2 platform. The cooler is mounted on a gimbal to allow it to be oriented in different angles to simulate operation on a tipping antenna. A photograph of the assembled cooler is provided in Fig. 2. Figure 3 presents a detailed view of the components inside the vacuum housing.

III. Operating Temperature and Cooling Capacity

The pressure of the liquid helium controls the ultimate operating temperature of the cooler in the third stage. This is limited by the pumping speed of the scroll pump and the pressure drop in the heat exchangers. For a given pump and heat exchanger, the temperature is simply a function of the JT flow rate. The flow rate of the system is controlled with an adjustable JT expansion valve.

Fig. 2. A view of the assembled cooler.

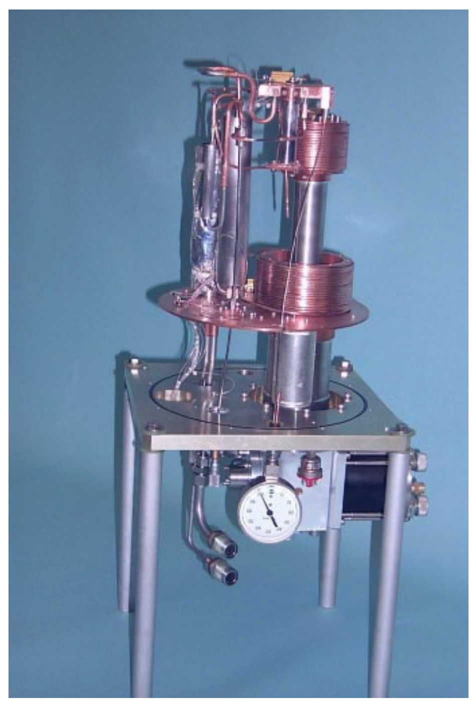

Fig. 3. A detailed view of components inside the vacuum housing.

The capacity of the cooler is dependent on a number of factors, including the JT flow, the GM pre-cooler operating temperature, and the efficiency of the heat exchangers. To the first order, the cooling capacity is proportional to the JT flow. Figure 4 shows the measured capacity as a function of flow rate.

Increasing the flow results in a higher-pressure drop in the heat exchangers and increases the pressure at the input to the scroll pump. The result is a substantial difference in cooling capacity at different operating temperatures. Figure 5 shows the measured cooling capacity as a function of operating temperature. The cooler provides useful refrigeration from 50 mW at 2.2 K to 600 mW at 2.9 K.

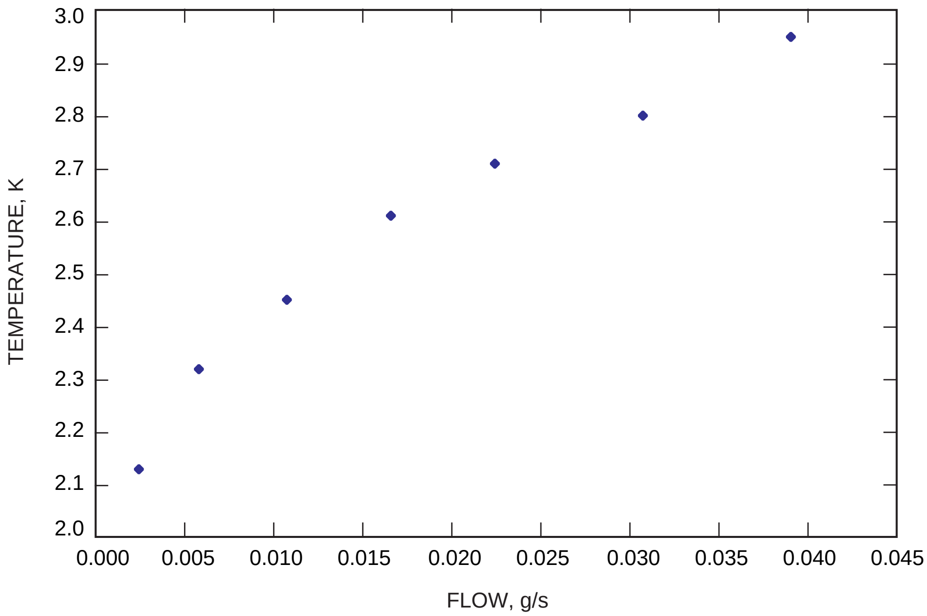

Fig. 4. Operating temperature as a function of JT flow rate.

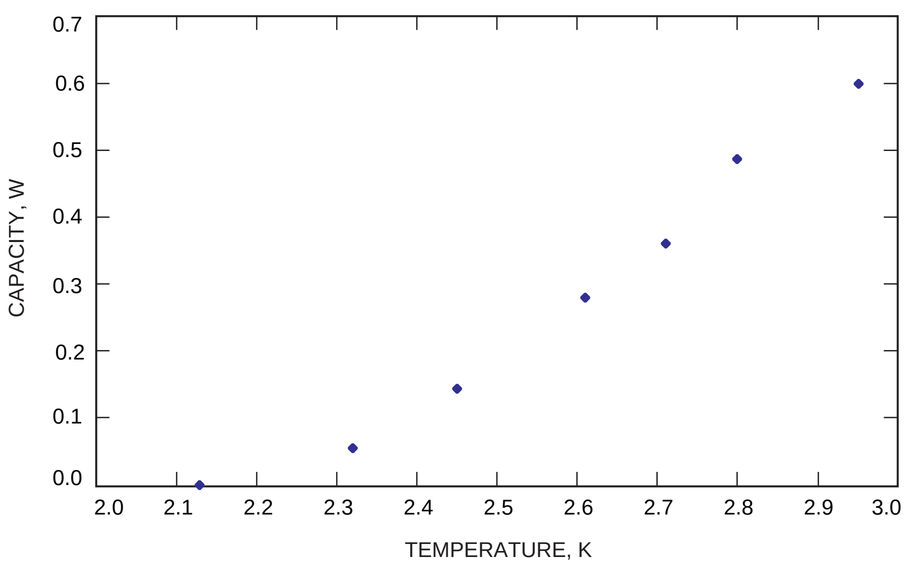

Fig. 5. Cooling capacity as a function of operating temperature.

IV. Cooling-Capacity Requirement

The cooling capacity required for maser operation is the sum of the passive heat load from mechanical supports, signal inputs, wiring and thermal radiation, and the active load of the microwave "pump" power required for maser operation. The 32-Ghz cavity maser requires much less pump power than do previous designs. A conservative estimate for the 32-GHz cavity maser pump power is 20 mW.

Another advantage of this system is that the GM cooler provides cooling at 4 K. Careful attention to intercepting the passive load by heat-sinking components to the GM stage will limit the additional passive load to 50 mW or less. The total cooling capacity required, therefore, is 70 mW. This leaves an adequate reserve capacity of 110 mW. If the required cooling capacity could be reduced, a slightly lower operating temperature could be achieved.

V. Temperature Regulation

The gain of maser amplifiers is extremely sensitive to temperature. The requirement for temperature stability over 10 seconds is ± 3 mK. A commercial temperature controller that uses a silicon diode sensor was used in the system. The unit uses a proportional-integral-differential (PID) controller to regulate a small current on a resistor on the third stage. The unit also serves as the temperature readout.

The temperature controller also allows accurate and simple measurements of the capacity of the cooler. The controller is simply set to the desired temperature, and the device displays the heat applied to achieve the set-point temperature. Figure 6 is a plot of the temperature stability over 5 minutes. The measurements were made with a calibrated carbon-glass resistor and a computerized data acquisition system. The system measures 14 readings per second. The average temperature was 2.400 K with a standard deviation of 1.53 mK.

VI. Operation in Different Physical Orientations

DSN Cassegrain antennas require the maser to be mounted in the feed cone. The cooler tips in elevation with the antenna. It was thought that the liquid helium in the heat exchangers might be affected by

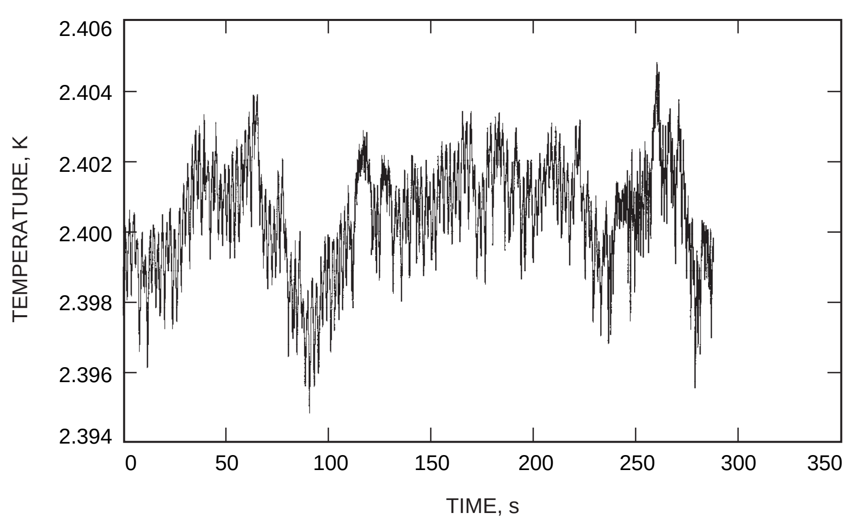

Fig. 6. Temperature stability over 5 minutes.

the orientation of the cooler and change the operation of the cooler. To test this, the cooler was mounted on a simple gimbal that allowed the unit to be tilted. Figure 7 shows the cooler tipped on the gimbal.

The capacity of the cooler was measured with the GM unit upright, at 45 deg, 90 deg (horizontal), 135 degrees, and upside down. No significant change in the capacity was observed at any angle. This will allow the cooler to be mounted at any angle to ease implementation of the system.

VII. Heat Exchangers

The heat exchangers used are similar to those used in some existing DSN coolers. A partially assembled heat exchanger is shown in Fig. 8. The design uses a commercially available 6-mm-diameter corrugated phosphor–bronze tube wound in a helix. The helix is housed in a stainless-steel tube and is wound around a threaded mandrel of Micarta. End caps are welded to the ends of the tube and provide mounting flanges for the gas connections. The supply helium travels through the inside of the 6-mm tube. The return gas passes over the outside of the helix between the mandrel and outer tube.

The heat exchangers provide low-pressure drop, are easy to assemble, efficient, and inexpensive. The Micarta mandrel was ideal for the 4.5-K coolers that operated at 20 MPa and at higher flow rates. During the testing of the 2.5-K cooler, it was discovered that, due to the low flow rates used, the specific heat of the solid Micarta was limiting the cool-down time. Future designs will use stainless-steel tubing rather than Micarta.

VIII. Cool-Down Time

Although it is not a primary requirement, the time required to cool the system to operating temperature after maintenance is an operational concern. Due to the low JT supply pressure and low flow rate, it

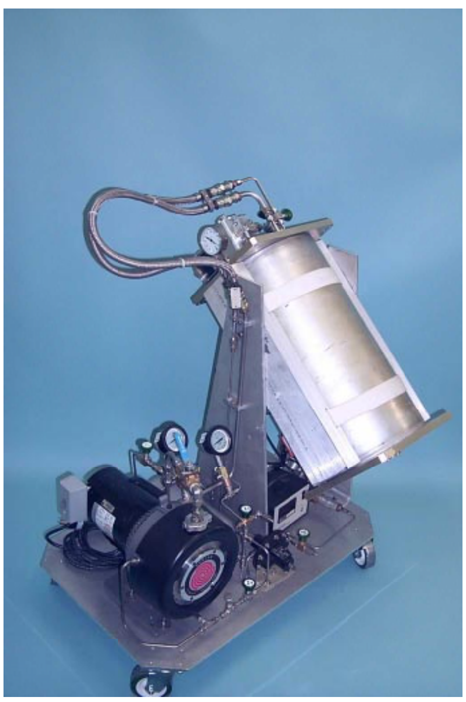

Fig. 7. A view of the cooler tipped on the gimbal.

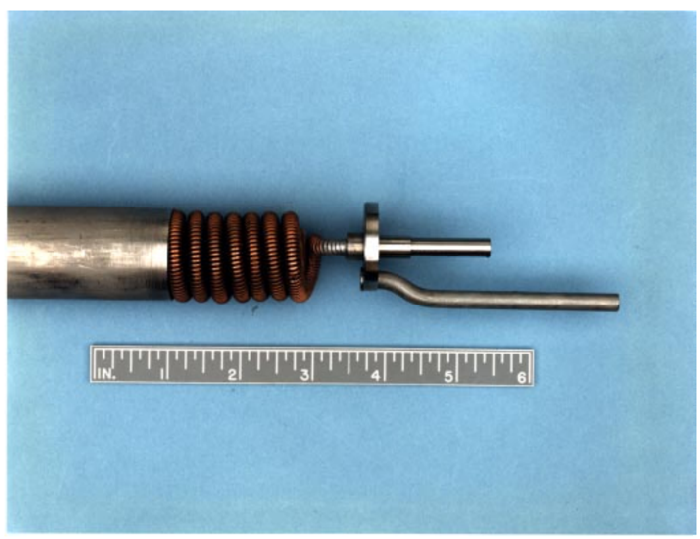

Fig. 8. JT heat exchanger detail.

takes substantially longer for the JT circuit to reach operating temperature than for the GM pre-cooler. A standard DSN hydrogen thermal switch was connected between the GM 4-K stage and the JT third stage. In this configuration, the system will cool to operating temperature in 7 hours and 40 minutes with an additional 2-kg mass of copper simulating the maser on the cold stage. This is faster than the existing 8.4-GHz masers cool without nitrogen pre-cooling and is quite acceptable.

IX. Adjustable JT Expansion Valve

The demonstration system uses an externally adjustable JT expansion valve. It is extremely valuable in characterizing the performance of the cooler. This allows the flow to be metered independently from the supply pressure. It allows the flow and therefore the operating temperature to be optimized for any application. The adjustable valve also has a gauge port on the low-pressure side of the valve. This was useful for measuring the pressure drop in the return path of the heat exchangers.

Adjustable valves of this type are sensitive and have caused problems on operational systems in the past and were removed in place of fixed JT orifices. The system has been tested with the valve set to a fixed position with no problem. Future systems may use an adjustable valve that is more robust or a commercial motorized micrometer valve.

X. Sensitivity to GM Cooler Performance

The system is sensitive to the operating temperature of the second stage of the GM cooler. The helium entering the expansion valve needs to be cooled by the GM cooler to 4 K or lower to provide useful cooling capacity. The 2.5-K capacity as a function of GM operating temperature is shown in Fig. 9. Typical second-stage operating temperatures are from 3.6 to 3.8 K. The data show only a 10 percent loss in 2.5-K cooling for GM operating temperatures up to 4 K, with a dramatic reduction in cooling above 4.1 K.

The measured cooling capacity of the GM second stage as a function of temperature is shown in Fig. 10. At 4.0 K, 1.25 W of cooling are available. The load on the second stage of the GM from the JT stage is less than 0.3 W. This leaves a reserve of 0.95 W that should be adequate for most uses. Adding a third-stage JT heat exchanger can reduce the sensitivity of the final-stage capacity to GM temperature. This may be required if the maser is used in a system with a high passive thermal load.

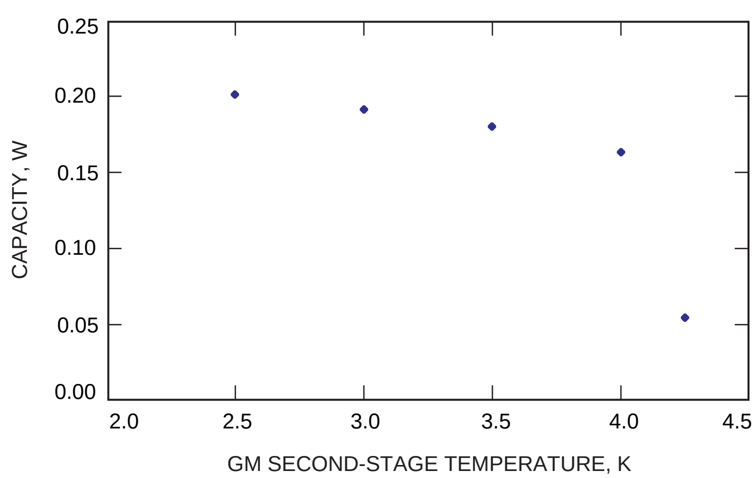

Fig. 9. The effect of GM operating temperature on 2.5-K cooling capacity.

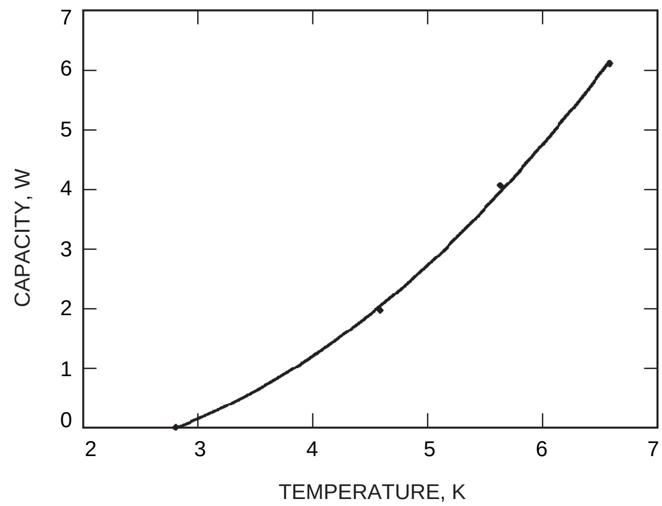

Fig. 10. Cooling capacity of the GM second stage.

XI. Reliability and Operational Concerns

The reliability and maintainability of DSN cryogenics systems is a major concern. This design is a substantial change from current DSN closed-cycle coolers. The system has the advantage of not having lubricating oil migration or breakdown in the JT circuit. It has a disadvantage of the JT low-pressure circuit operating at less than 1 atm. Any substantial leak will allow air in the system. This, however, is unavoidable with any JT system operating below 4 K using helium as a working fluid.

The reliability of the scroll pump is also unknown. The manufacturer recommends service at 7000 hours. It is not expected that scheduling pump replacement at 7000 hours should be a problem. The scroll pump was not tipped with the cooler during the tip tests. More testing will be required if the system is used on a Cassegrain antenna.

The system did operate in the laboratory continuously for 1200 hours with no failures or measurable degradation in performance. More experience with this system is required before a decision can be made on its long-term reliability. The system hardware was designed for a laboratory demonstration. Work will be required to repackage the system for use in operations.

XII. Conclusion

A cryogenic cooler for cooling a 32-GHz cavity maser was designed, fabricated, and tested in laboratory conditions. The system produces refrigeration between 2.2 and 2.9 K. It provides 180 mW of cooling at 2.5 K, which is more than adequate for the application. A single-stage, oil-less scroll vacuum pump was used for the JT stage compressor. The operating temperature, cooling capacity, temperature stability, and cool-down time are sufficient to meet the requirements for use with the maser. The system operated continuously for 1200 hours with no problems. It is simple, easy to fabricate, and low-cost. It is substantially different from existing DSN systems and will need to be studied further to evaluate its long-term reliability.

Acknowledgments

Thanks to R. Clauss for suggesting using a two-stage JT circuit and many other technical hints.

Thanks to S. Montenez for his support in the fabrication and assembly of the system.

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