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Two-Watt, 4-Kelvin Closed Cycle Refrigerator Performance

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This article describes a 2-watt, 4-K helium refrigerator using the Gifford–McMahon/Joule–Thomson cycle. The unit features a removable displacer cylinder and high-efficiency, low-pressure-drop heat exchangers. These improvements result in a 100 percent increase in cooling power over the existing DSN system. The effects of heat exchanger efficiency and Gifford–McMahon expander performance on refrigerator cooling capacity are also discussed.

I. Introduction

The 1-watt, 4-K refrigerator currently used to cool DSN traveling-wave masers was developed at JPL over 20 years ago [1]. It represented an order-of-magnitude improvement in reliability and performance over the commercial unit used previously. These systems have been used with only minor modification since that time.

Over the years, several problems have become apparent with the existing DSN design. Current DSN masers have grown to require more cooling power. The original 2.3-GHz maser required only 150 milliwatts of the 1 watt available, leaving a reserve of 850 milliwatts. Some current designs reduce the reserve to 500 milliwatts. Experience in the DSN has shown that systems with reduced capacities have shorter mean times between failures.

Many DSN refrigerators have been in operation long enough to experience a reduction in cooling capacity due to wear of the Gifford-McMahon (GM) expansion engine displacer cylinder. Replacement of the cylinder requires moving the entire Joule–Thomson (JT) circuit, which is a costly and time-consuming operation.

The current DSN refrigerator is also difficult and expensive to produce. Fabrication is very labor intensive, and some materials are difficult to obtain.

The cost of the refrigerator alone is a very significant part of a complete maser system. The new 2-watt refrigerator described in this article features substantially increased cooling capacity, simpler heat exchangers with improved efficiency, and a conveniently replaceable GM displacer cylinder. The unit will accept all current maser assemblies without modification. The physical size of the refrigerator and the input power for the system remain unchanged.

II. Thermodynamic Considerations

Both the existing DSN 1-watt system and the new 2-watt system described here use a combination of the Gifford–

McMahon (GM) and Joule–Thomson (JT) thermodynamic cycles. A gas flow schematic is shown in Fig. 1.

A. Cycle Description

The refrigerator uses a two-stage CTI Model 350 GM expansion engine that simultaneously provides 25 watts of cooling at 60 K and 5 watts at 15 K to precool helium gas flowing in the JT circuit. The JT circuit consists primarily of three heat exchangers and a JT expansion valve. High-pressure helium (300 psig) supplied by a compressor at ambient temperature (300 K) is cooled in the heat exchangers by the gas returning from the cold station and by the expansion engine. When the gas reaches the JT expansion valve, it has been cooled to nearly the temperature of the 4-K stage. The JT valve is simply a calibrated restriction that allows the high-pressure gas to expand into the low-pressure JT return line. During this expansion, the helium cools slightly, and a fraction of the flow condenses into 4-K liquid. Heat from the load–in this case, the maser–is absorbed by vaporizing this liquid.

B. Heat Exchanger Efficiency

Heat exchanger efficiency is one of the most critical aspects in the design of a JT refrigerator. It determines the amount of heat that must be removed from the supply helium by the GM engine. It also determines the helium flow rate required in the JT circuit to produce a given amount of cooling at 4 K. Heat exchanger efficiency is defined by

$$e = \frac{q_{actual}}{q_{max}}$$

where q_{max}, the maximum amount of heat that can be transferred to or from the helium, is a function of the fluid properties of the helium for a given temperature and pressure. The amount of heat actually transferred, q_{actual}, is primarily a function of the design of the heat exchanger (heat transfer area, material thermal conductivity, flow passage size, etc.).

The significance of heat exchanger efficiency can be seen by the fact that the production of 1 watt of cooling at 4K requires approximately 130 watts of heat to be transferred from the incoming gas upstream of the JT valve. Any heat not removed by the heat exchangers must be absorbed by the engine. Because the amount of heat to be removed from the helium is large compared to the capacity of the engine, the numeric efficiency must be high. Table 1 shows the estimated heat exchanger efficiencies for both systems.

Pressure drop in the return path of the heat exchangers is also important. The operating temperature of the 4-K stage is determined by the helium pressure at the cold station. Any pressure drop in the JT return line will increase the pressure, and therefore the temperature, of the 4-K stage.

C. Gifford–McMahon Expansion Engine Performance

Expander performance is another crucial factor in GM/JT refrigerator operation. As stated earlier, the expansion engine absorbs any heat not removed from the supply gas stream before it reaches the final-stage heat exchanger. The engine also cools the radiation shield that intercepts thermal radiation from ambient-temperature sources.

The expander is a reciprocating mechanical device with several moving parts that are subject to wear. As this wear occurs, the efficiency of the engine decreases and the operating temperatures of the engine stages increase. This increase in engine operating temperatures has a dramatic effect on the 4-K cooling capacity of the refrigerator.

Another factor that affects engine performance is external heat load from sources other than the helium gas in the JT circuit. Thermal radiation from room temperature is intercepted by radiation shields cooled by the engine first stage. Radiation load from large shields can equal the load from the helium. Heat conduction through waveguides, supports, and wiring also contributes to engine load.

III. Hardware Description

Both the DSN 1-watt refrigerator and the new 2-watt refrigerator are shown in Fig. 2. They are nearly identical in physical size and weight. The new refrigerator was designed to accept existing maser hardware without modification. Many of the components developed for the initial design are used in the new system. The most significant changes are the use of improved efficiency heat exchangers and the addition of a "bolt-in" expander cylinder.

The new heat exchangers are based on a concept developed at JPL [1] and later refined at the National Radio Astronomy Observatory. They consist of a spiral coil of convoluted tubing wound on a Micarta mandrel and enclosed in a thin stainless steel tube (Fig. 3). The supply helium travels through the inside of the convoluted tubing, and the return gas passes axially over the outside. This new design contains more than three times the heat transfer area of the original design.

The expander–displacer cylinder is a commercial unit supplied by CTI. The heat stations are bolted to flanges on the cylinder rather than being soldered. The cylinder is bolted to the vacuum housing end plate using an O-ring seal. The cylinder is shown removed from the JT circuit in Fig. 4.

Fabrication costs and assembly time have been reduced by as much as 50 percent on the new refrigerator. Fabrication of the original displacer cylinder involved several machining, welding, heat treatment, and inspection processes that resulted in high cost and long delivery times. Interestingly, the entire 2-watt refrigerator was built and tested while waiting for two of the original-design cylinder assemblies to be fabricated. Eight solder or weld joints have been eliminated from each heat exchanger. Joints of this type are often the cause of internal helium leaks that plague the construction of helium refrigerators. The materials used in the construction of the heat exchangers are easily obtainable.

IV. Performance

Performance specifications for the existing system and the new design are shown in Table 2. The 4-K cooling capacity of the new unit is more than double that of the existing design. The input power required remains unchanged. This results in a 100 percent increase in thermodynamic efficiency for the total closed-cycle refrigerator system.

Figures 5 and 6 represent the effects of first- and second-stage engine loading on 4-K capacity. The data shows a substantial improvement in the refrigerator's resistance to external heat loads.

V. Conclusions and Recommendations

Cooling capacity at all three stages of refrigeration has been improved substantially in the new 2-watt system. This results in an increase in the refrigerator's resistance to GM expander performance degradation and external heat loads. The extra cooling power should result in a marked improvement in DSN traveling-wave maser closed-cycle refrigerator-system mean time between failures. The reduction in fabrication expenses makes the unit a cost-effective replacement for aging 1-watt systems.

Future projects such as the 32-GHz maser and masers with cryogenically cooled feeds may require the extra cooling this refrigerator provides. HEMT amplifiers can also be cooled to 4 K to reduce system noise temperature. Although the HEMT device itself does not benefit greatly from 4-K operation, thermal noise contribution from microwave components at the device's input (e.g., from filters and isolators) can be reduced by lowering their physical temperature.

Acknowledgment

The author would like to thank T. Hanson of Bendix Field Engineering for providing the superb craftsmanship that went into the fabrication of the prototype refrigerator. He was also responsible for the initial cryogenic testing of the unit.

Reference

[1] W. H. Higa and E. Wiebe, "One Million Hours at 4.5 Kelvins," *National Bureau of Standards Technical Publication No. 508*, pp. 99–107, April 1978.

Table 1. Estimated heat exchanger efficiency

Heat exchanger	1-watt CCR	2-watt CCR
First stage	0.94	0.96
Second stage	0.93	0.96
Third stage	0.97	0.99

Table 2. Comparison of heat exchanger specifications

Specification	1-watt CCR	2-watt CCR
Operating temperature	4.5 K	4.4 K
Cooling capacity at operating temperature	0.95 W	2.2 W
JT mass flow	1.5 SCFM	2.3 SCFM
Compressor input power required	8000 W	8000 W
Net thermodynamic efficiency	8400 W/W	3600 W/W

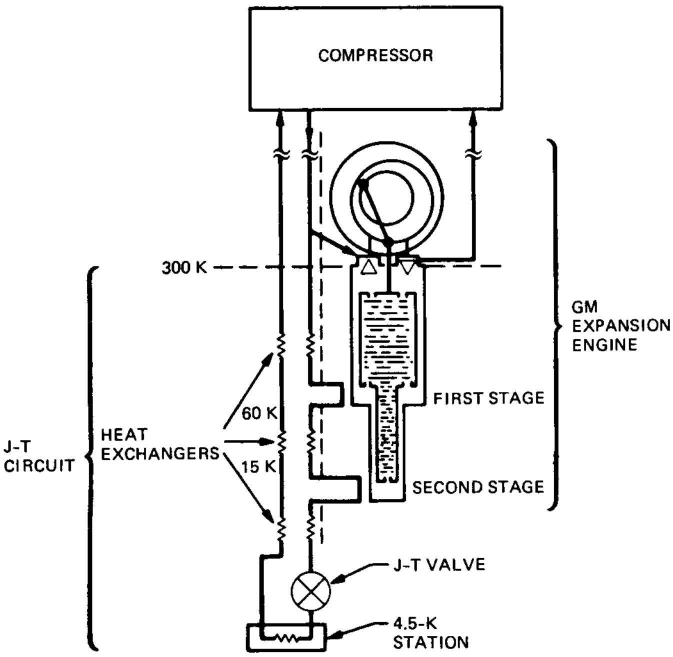

Fig. 1. GM/JT refrigerator gas flow schematic

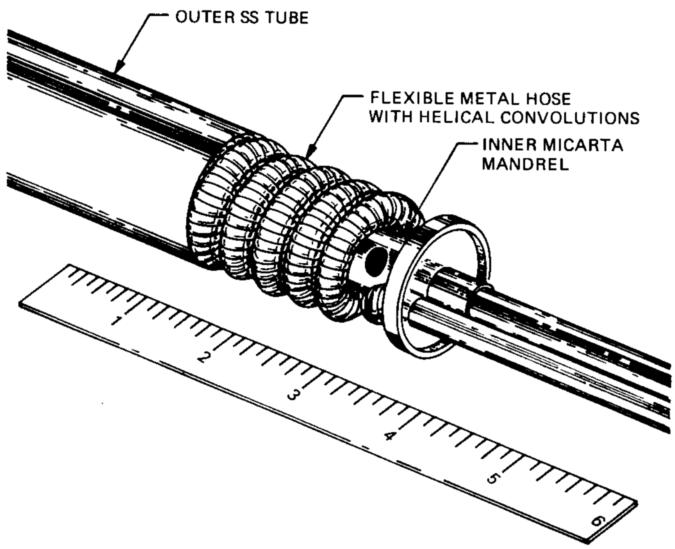

Fig. 3. New heat exchanger

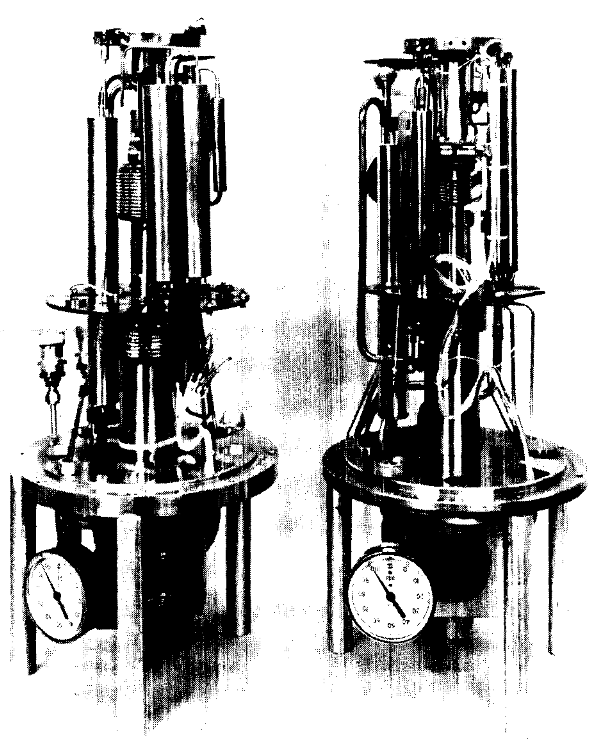

Fig. 2. Two-watt refrigerator (shown on right) and 1-watt refrigerator

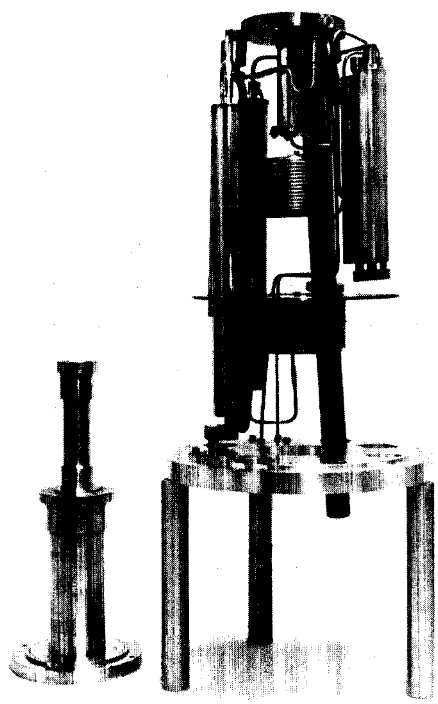

Fig. 4. Displacer cylinder removed from refrigerator, leaving JT circuit intact

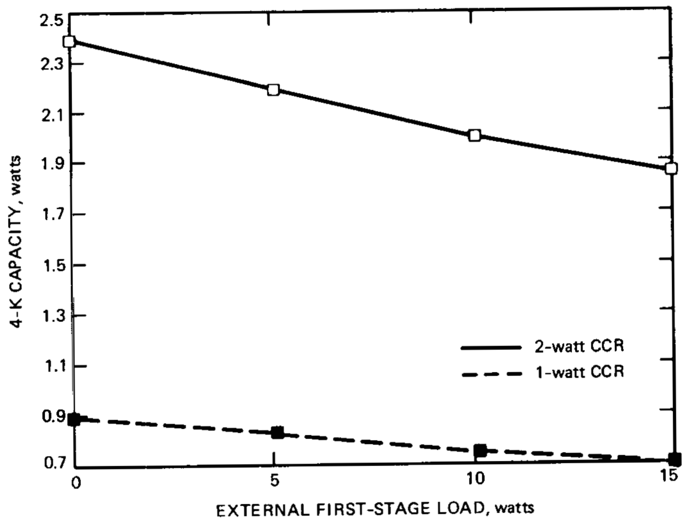

Fig. 5. Four-kelvin capacity versus first-stage load

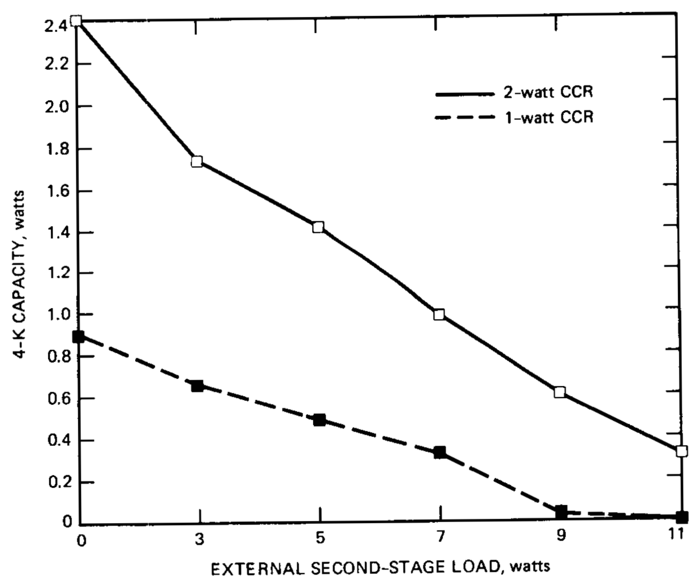

Fig. 6. Four-kelvin capacity versus second-stage load