1- to 4-K Refrigeration Techniques for Cooling Masers on a Beam Waveguide Antenna

D. L. Johnson
Radio Frequency and Microwave Subsystems Section

The status of technology is reported for various 1- to 4-K commercially available refrigeration systems capable of producing 1.5-K refrigeration to cool masers and superconducting cavity oscillators on the proposed beam waveguide antenna. The design requirements for the refrigeration system and the cryostat are presented. A continuously operating evaporation refrigerator that uses capillary tubing to provide a continuous, self-regulating flow of helium at approximately 1.5 K has been selected as the first refrigerator design for the beam waveguide antenna.

I. Introduction

This past year, JPL installed a 2.3-GHz maser on the beam waveguide antenna in Usuda, Japan, to support the ICE mission and also to measure the performance of the antenna/maser combination. The results were impressive (Ref. 1). Comparing low-noise configurations of the 64-m beam waveguide antenna and a Deep Space Network (DSN) 64-m antenna at 2.295 GHz and at zenith, the measured total system noise temperature of the beam waveguide antenna was 15.0 K, whereas the measured total noise temperature was 16.0 K for the DSN 64-m antenna.

JPL is proposing to NASA that a 34-m beam waveguide antenna be built at Goldstone for research and development purposes. This antenna would support the new 32-GHz communications link. In addition to improved noise temperatures, there would no longer be limitations of size, variable elevation angle, and remote location of the feedcone as design parameters for the maser's refrigeration system. In this new design, the maser and its closed-cycle refrigerator (CCR) would be situated in a laboratory at the base of the antenna. The advantage of this plan is that the maser/CCR would no longer need to be orientation-independent or as compact; rather, it would be in a stationary, upright position, which would provide easy access to the maser(s) for modifications and maintenance, even during antenna tracking. This arrangement also eases the size and weight restrictions of the refrigeration system and provides a clean laboratory environment for the operators.

In addition to the 32-GHz maser, the beam waveguide antenna could support other masers and High Electron Mobility Transistor (HEMT) amplifiers. Masers require operating temperatures of 4.5 K or less. The HEMT amplifier requires only 12-K refrigeration, but for simplicity and convenience, the HEMT may also be cooled to 4.5 K.

Along with the amplifiers, the new cryostat would be designed to also contain a stabilized superconducting cavity oscillator, such as the one built by Caltech (Ref. 2). The cavity would replace the hydrogen maser as the frequency standard for the antenna. Initial measurements by Caltech using a ruby maser stabilized by a lead-on-sapphire superconducting cavity at 1 K indicated the stability $\Delta f/f$ to be 3×10^{-14} over 4000 seconds, which extrapolates to a stability of 10^{-15} for 1 second (Ref. 3). In contrast, the present DSN hydrogen maser operates with a stability $\Delta f/f$ of 10^{-15} for 1000 seconds. The theoretical stability of a superconducting stabilized oscillator can be up to three orders of magnitude better than the hydrogen maser, but is dependent on the physical temperature, the temperature stability, and the superconducting material used. With the lead-on-sapphire cavity at 0.6 K, the theoretical stability approaches 10^{-18} for 1000 seconds; at 1.5 K, the stability is reduced to 10^{-15} for 1000 seconds, but a stringent temperature stability of $<10\ \mu$K is also required. As an alternative, an all-sapphire cavity operating at 1.5 K could yield a stability better than 5×10^{-17} for 1000 seconds. This added stability could be traded for a less stringent temperature stability; however, use of an all-sapphire cavity would require much additional development work. The selection of the cavity type for use as the stabilized oscillator on the beam waveguide antenna will depend on the stability goal for the antenna and the temperature and temperature stability achievable by the refrigeration system.

Although the new cavity oscillator requires additional cryogenics to enable it to operate at or below 1.5 K, this oscillator can be put in the same cryogenic package as the masers. A decision must be made whether to cool the maser to this low temperature as well. Since the gain of the maser (in dB) is roughly inversely proportional to the physical temperature of the maser, lowering the maser temperature from 4.5 K to 1.5 K could improve the maser gain by a factor of three (or alternately, increase the maser bandwidth by a factor of three). This improvement in maser performance must be weighed against the added complexity of placing additional components and heat loads in the 1.5-K portion of the refrigeration system.

This report examines the design requirements of the cryostat and the cooling requirements of the maser and cavity oscillator, the availability of 1.5-K refrigeration systems and components in industry, and the feasibility of using such a system in a beam wavebuide antenna.

II. Design Requirements

The 2.3- and 8.5-GHz masers presently used in the DSN are cooled by 1-W closed-cycle refrigerators (CCRs). The 32-GHz maser package will be cooled by a 3-W CCR. The expected heat load for the 32-GHz maser is about 1 W. The superconducting cavity at Caltech has a measured heat load of 50 μW at 1.5 K due to the rf input power, negligible compared to that of the maser. Because of this disparity in cooling requirements, it is necessary to consider the option of cooling only the cavity oscillator to 1.5 K or less, versus cooling both the cavity and the maser(s) to 1.5 K. If the latter option is chosen, the difference in required temperature stabilities for the devices will also contribute to the complexity of the cryostat. The design requirements for the cryostat are listed below.

(1) Cavity and one or two masers housed in vacuum, cooled by conduction

(2) 1-2 week hold time at 4.2 K in event of power/mechanical failure

(3) 50 μW of refrigeration at 1.5 K, 300 mW at 4.2 K for the cavity

(4) $<10\ \mu$K stability at 1.5 K for the cavity

(5) 1 W of refrigeration between 1.5 K and 4.2 K for the maser

(6) <10 mK stability for the masers

The masers and the cavity must also be independently accessible for service or maintenance, preferably while the remainder of the electronics in the cryostat remain at the low temperature. Therefore, it would be convenient to be able to hang the electronics from the top of the cryostat. Also, there is a tradeoff between the allowable thermal conductance and the allowable rf losses in the waveguides feeding the maser and cavity in the cryostat.

In selecting a refrigeration system, it is desirable to find a system that is commercially available, with readily available parts and service, and low operator maintenance requirements. The refrigeration system should also require no liquid nitrogen precool in order to simplify cryogenic requirements.

III. 1- to 4-K Refrigeration Systems

Magnetic refrigeration, electrocaloric refrigeration, or evaporative cooling techniques can produce temperatures between 1.0 K and 4.2 K. However, above 1 K, evaporative cooling is most commonly used. The other refrigeration methods are not yet commercially available, but it is of interest to describe these alternate cooling techniques briefly and the progress made in their development.

A. Magnetic Refrigeration

Adiabatic demagnetization, or magnetic cooling, was first suggested in 1925 by two independent researchers, Giauque (Ref. 4) and Debye (Ref. 5), as a means to produce temperatures below those attainable by pumping on a liquid helium bath. The first continuous magnetic refrigerator was built by Collins and Zimmerman (Ref. 6) in 1953, but it used mechanical heat switches, which produced considerable vibrational heat leak. In 1954, Heer (Ref. 7) built the first continuous magnetic refrigerator with superconducting heat switches. That machine was capable of maintaining temperatures in the range of 0.2 to 1.0 K with a refrigeration capacity of a few microwatts. These refrigerators were made commercially by Arthur D. Little Corporation for a brief period until ^3He became commercially available in sufficient quantities for evaporative cooling. In the late 70s and early 80s, efforts were renewed to make a continuous magnetic refrigerator for the 2- to 4-K and the 4- to 20-K ranges. The French (Ref. 8) demonstrated the feasibility of a reciprocating magnetic refrigerator which, operating with cold-and hot-end temperatures of 1.8 K and 4.2 K, could produce 1.2 W of refrigeration for short periods of time. The Japanese have built two magnetic refrigerators that also operate in the 2- to 4.2-K temperature span – a rotational wheel magnetic refrigerator (Ref. 9), and a pulsed coil magnetic refrigerator (Ref. 10) – that have produced cooling powers of 1.5 W at 2.10 K and 0.6 W at 1.80 K, respectively.

B. Electrocaloric Refrigeration

Analogous to the magnetic refrigerator, the electrocaloric refrigerator uses an applied electric field to cause the electric dipoles in a dielectric material to become ordered at a higher temperature. Dielectric materials that have transition temperatures in the 1- to 4-K range do exist, but their small dipole entropies make them incapable of producing significant refrigeration. Shepherd (Ref. 11) reported using an OH-doped KCl dielectric material to produce cooling at 0.3 K from a starting temperature of 1.3 K. The only reported application of electrocaloric refrigeration has been the use of the OH-doped KCl for thermostating crystals below 1 K while they were radiated with short light bursts (Ref. 12). New dielectric materials will have to be developed for this temperature region before electrocaloric refrigeration will become a viable refrigeration method.

C. Evaporative Cooling

Evaporative cooling, or subatmospheric refrigeration, has been used for many years as the means of lowering the bath temperature of the liquid cryogen. The temperature of the liquid is lowered below the normal boiling point by reducing the vapor pressure over the liquid. Temperatures as low as 0.3 K and 0.8 K can be attained with liquid ^3He and ^4He, respectively, down from their normal boiling temperatures of 3.2 K and 4.2 K at atmospheric pressure. This refrigeration technique is being used in many research programs today because of its ease of operation and the wide range of refrigeration capacity and temperatures achievable. Evaporative cooling is the most suitable at this time for maser cooling on a beam waveguide antenna. Various evaporative cooling methods will be discussed next and the configurations most suitable for use on a beam waveguide antenna will be described.

Temperatures down to 2.3 K have been achieved with the use of an ejector (Ref. 13). An ejector uses the momentum of a high-velocity stream of gas to entrain and accelerate a slower moving gas into which it is directed (Fig. 1). This reduces the pressure in the slower moving gas stream, lowering its temperature. The ejector can be placed outside the cryostat (Ref. 14), as in Fig. 1, driven by the side stream of the main compressor, or it can be installed in the Joule-Thomson (J-T) circuit near the J-T heat exchanger (Refs. 13,15), as shown in Fig. 2. The cold ejector has the benefit of not requiring the room temperature compressor to operate at subatmospheric pressures, thereby avoiding possible air leaks into the gas stream. Staging of ejectors could possibly produce temperatures lower than 2.3 K, but not without significant development work.

Vacuum pumping the vapor above the liquid bath can produce the low temperatures mentioned previously. Pumping the vapor causes the liquid to boil as it tries to maintain a pressure equilibrium between the liquid and the vapor. In so doing, the liquid cools itself, but at the expense of reducing the volume of liquid remaining in a dewar. At 1.5 K, only about half of the original volume of liquid remains, requiring either the use of a larger dewar or more frequent refilling of the dewar, which may be inconvenient for experiments that could last for days. In addition, this process of temperature reduction has low efficiency because it does not use the sensible heat of the helium vapor leaving the dewar. However, the simplicity of this cooling method makes it attractive for research experiments requiring small refrigeration loads where the test duration is on the order of hours.

The vacuum pumping process can be turned into a continuous low-temperature refrigeration system by connecting the low-temperature pot to the outer jacket of 4.2 K liquid helium with a capillary tube (Ref. 16, Fig. 3). The capillary tube provides a continuous flow of 4.2-K liquid to the pot. Helium transfer is only required to top off the 4.2-K jacket, which will not influence the temperature of the pot. The incoming liquid to the pot produces a small heat leak, which may raise the temperature of the pot slightly.

The cryostat used to cool the superconducting cavity at Caltech uses capillary tubing but also incorporates a manual shut-off valve at the entrance to the tubing. This keeps the refrigeration from being continuous and operator-free, but permits lower temperatures to be reached. When the pot is in need of refilling, the valve is opened to the 4.2-K liquid helium jacket. By vacuum pumping and refilling simultaneously, the liquid entering the pot is cooled to a temperature near 1 K.

The valve is closed off when the pot is filled, resulting in only a small fraction of the liquid being boiled off as the system is further cooled to 0.8 K. In the Caltech cryostat, the 0.5-liter volume of liquid in the pot will keep the superconducting cavity at a temperature of 1.0 K for about 5 days before requiring refilling with LHe.

Cryostats with capillary tubing have been used to produce mW of refrigeration at 1 K. However, with the proper sizing of the capillary tubing, it should be possible to attain the 1 W of refrigeration required for the maser. The Caltech cryostat uses an open-cycle process. Liquid helium is transferred periodically from a storage dewar into the 4.2-K jacket of the cryostat. The helium vapor pumped from the pot by the vacuum pump is vented to air. This process can be turned into a closed-cycle process to conserve helium by returning the pumped helium vapor to the compressor of a liquefier for reliquefaction. An important requirement for a DSN system is that the vacuum pump be helium-tight to prevent gas contamination.

If refrigeration on the order of watts or more is required, then maximizing the thermal efficiency of the refrigeration process is of great importance. The thermal efficiency can be improved by incorporating a heat exchanger to recover the refrigeration available in the sensible heat of the exiting helium vapor. Collins (Ref. 17) analyzed and compared the work input required to provide cooling at 1.85 K for refrigeration systems that do and do not incorporate a high-efficiency heat exchanger. His rêsults showed a five-fold improvement in efficiency for a continuous closed-cycle refrigerator using a heat exchanger over an open-cycle method in which 4.2-K liquid is first produced and then the bath temperature is lowered. The heat exchanger may be added either in the gas circuit of the refrigerator (Fig. 4) or as an entirely separate closed-loop gas circuit in heat exchange with the refrigerator circuit (Fig. 5).

A specially designed heat exchanger built into the refrigerator circuit as shown in Fig. 4 was tested by Collins (Ref. 17). The liquefier-refrigerator produces 7-K helium gas[1] which is introduced to the high-pressure supply side of the heat exchanger. High-pressure, 300-K helium gas is also introduced to the heat exchanger to recover all the available refrigeration of the exiting low-pressure helium gas. The exiting gas flows over the finned-tube heat exchanger, cooling the incoming gas. At 7 K, the streams combine and flow through the remainder of the exchanger with the expansion valves. The intermediate expansion valves are used to reduce the supply pressure at the lower temperatures so that the enthalpy change (change in heat content) in the high-pressure stream is more nearly equal to that of the low-pressure stream. This permits recovery of more of the refrigeration capacity of the low-pressure gas, thereby increasing the heat exchanger efficiency.

A heat exchanger of this type is used to cool the linear accelerator at the University of Illinois. Coupled with a CTI Model 1400® liquefier, the university's heat exchanger, without the LN_2 precool, is capable of producing 11 W of refrigeration at 1.85 K. This heat exchanger is contained in a vacuum chamber separated from the liquefier and the accelerator cryostat. The accelerator cryostat is filled with the 1.85-K liquid that has been transported from the heat exchanger through an evacuated transfer line. The transfer line is precooled by the exhaust vapors being pumped from the cryostat. Following the development of this 1.85-K refrigerator, a 300-W, 1.85-K refrigerator was designed and built for Stanford University. The designs are similar, but the Stanford refrigerator requires the LN_2 precool, along with four-stage vacuum pumping of the heat exchanger.

A JPL heat exchanger design using a separate closed-cycle loop in heat exchange with the refrigerator (Fig. 5) was demonstrated in 1975 (Ref. 18). The JPL design used the 1-W CCR as a 4.5-K precooling stage. Room temperature helium gas is supplied to the added heat exchanger loop by the existing CCR compressor. The gas in the loop is cooled at the 70-K, 15-K, and 4.5-K stages of the CCR before passing through a single J-T expansion valve to provide 3-K temperatures. The added heat exchanger loop used the same size heat exchangers as those in the J-T circuit of the unmodified CCR. By regulating the supply pressure to the heat exchanger loop to 3.04×10^5 Pa (3 atm), 200 mW of refrigeration was achieved at 3.1 K. Use of a vacuum pump with a greater pumping speed and heat exchangers with less restrictive low-pressure return paths would have permitted lower temperatures to be reached.

IV. JPL Refrigerator Design

The desire for a 1- to 2-week reserve capacity at 4.2 K requires use of a helium liquefier and an intermediate LHe storage dewar. For an expected heat load of 1 W at 1.5 K, a liquefaction rate of 2 liters per hour is required. Two liquefiers for this liquefaction rate are commercially available. Both have been recently designed and developed for hospital use with nuclear magnetic resonance imaging (MRI). The Model 1200® liquefier, manufactured by Koch Process Systems, Inc., is capable of producing liquid helium at a rate of 5 liters per hour. Its screw compressor can adjust the flow rate to lower the liquefaction rate to 2 liters per hour. A number of these systems are already in operation. The other liquefier is the Model TCFII®, manufactured by Sulzer of Switzerland. This is a 5-liter-per-hour liquefier, and is now undergoing

[1]Collins reports minimal improvements when 4.2-K gas is used.

final pre-marketing tests. It is expected to be commercially available by the end of the year. Although both liquefiers are designed to use LN_2 precooling for optimum performance, both can operate without the LN_2 precool with a slight decrease in liquefaction rate.

For the first engineering design, the JPL refrigeration system should incorporate a cryostat that uses a capillary tube for the continuous flow of helium to the 1.5-K pot and direct vacuum pumping on the 1.5-K bath. A possible configuration for the JPL closed-cycle refrigerator system for the beam waveguide antenna is shown in Fig. 6. All items are commercially available with the exception of the cryostat. The buffer tank is used to store the helium gas when the cryostat and the storage dewar are warm. The compressor and vacuum pump would be set off in a separate room. A vacuum pump having a 150-l/s pumping speed would handle the boil-off from the 1-K pot. The liquefier and the storage dewar can be positioned in close proximity to the cryostat. A 250-liter storage dewar would amply hold a 1-week supply of 4.2-K liquid and would supply the liquid for the cryostat's continued operation in the event of a mechanical failure or electrical power failures. During a mechanical or power failure, the boil-off from the cryostat may be vented to the atmosphere or may be collected in a large bladder for future repurification and reuse. The liquid in the pot would warm to 4.2 K, but the maser's superconducting magnet would remain charged in the superconducting state.

A cryostat that takes into consideration all design requirements for the masers and the superconducting stabilized oscillator will be designed and fabricated at JPL. The design scheme has not yet been determined. Of particular interest is the possibility to warm and remove for maintenance either the maser or the cavity without interfering with the operation of the other. The different temperature stability requirements for the cavity oscillator and the masers may require separate 1.5-K pots, with separate pumping schemes for each. This would permit individual control of the temperature and temperature stability for each pot. The exhaust gas stream will be used to cool outer radiation shields, thus using some of the sensible heat of the venting vapor. This design will determine whether the continuous liquefaction/vacuum pumping refrigeration approach will be sufficient for the 1-W refrigeration requirement.

V. Conclusion

This report has introduced the various methods of attaining temperatures between 1 K and 4.2 K. Magnetic refrigeration, electrocaloric refrigeration, and evaporative cooling techniques are all possibilities. Of these, evaporative cooling is the only commercially available refrigeration method that fills the requirements set forth for cooling the masers and the superconducting stabilized cavity oscillator on a beam waveguide antenna. This method requires a liquefier to provide a supply of 4.2-K liquid to a storage dewar. The stored liquid is then transferred as needed to the cryostat to provide both a 4.2-K bath as a radiation shield and the supply to the 1.5-K pot which cools the masers and cavity. This refrigeration system will be used in a closed-cycle mode, recycling the pumped helium vapor to the refrigerator for reliquefaction.

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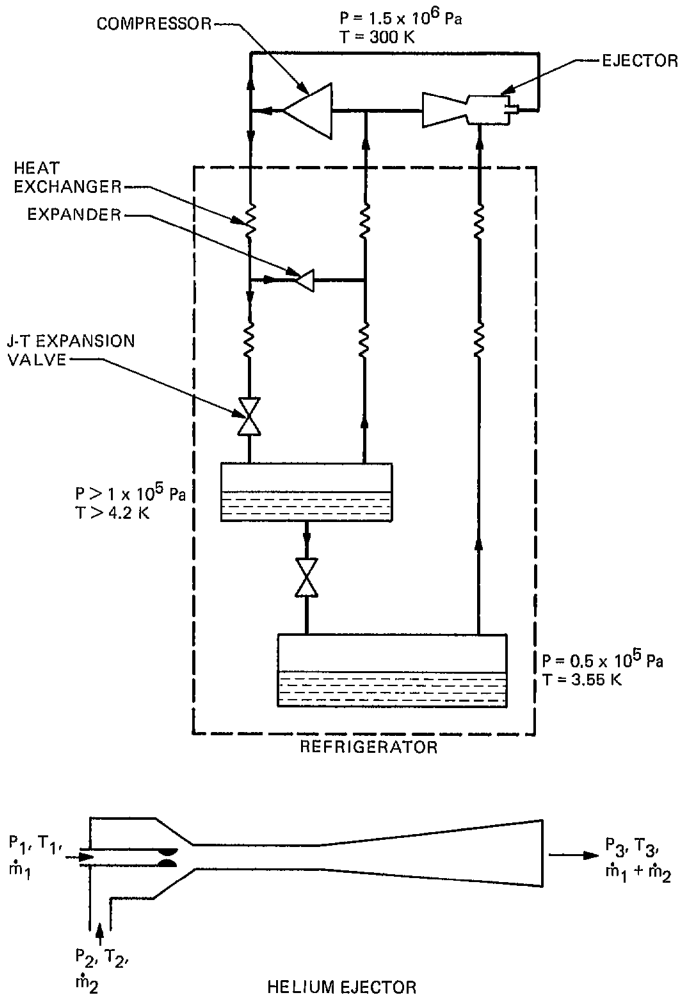

Fig. 1. Helium refrigerator using a room temperature ejector (after Ref. 14)

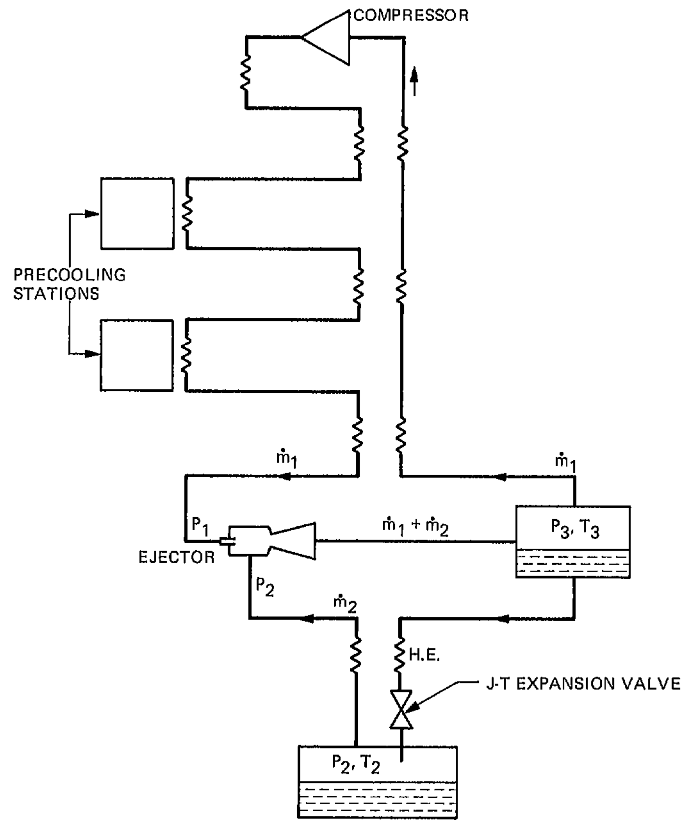

Fig. 2. Diagram of the low-temperature end of a helium refrigerator equipped with a cold ejector (from Ref. 13)

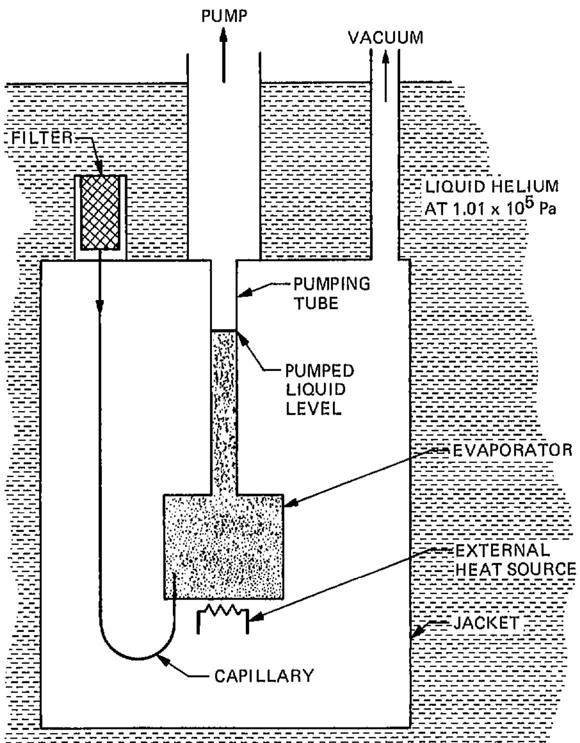

Fig. 3. Schematic of a continuously operating helium refrigerator (after Ref. 16)

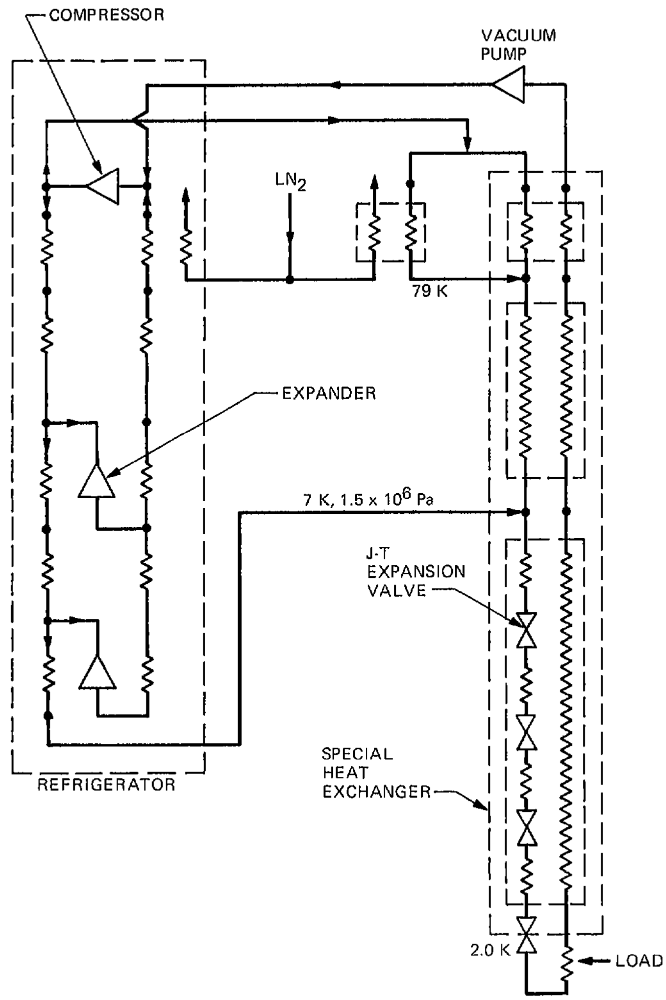

Fig. 4. Test apparatus for a 2-K closed cycle refrigerator (from Ref. 17)

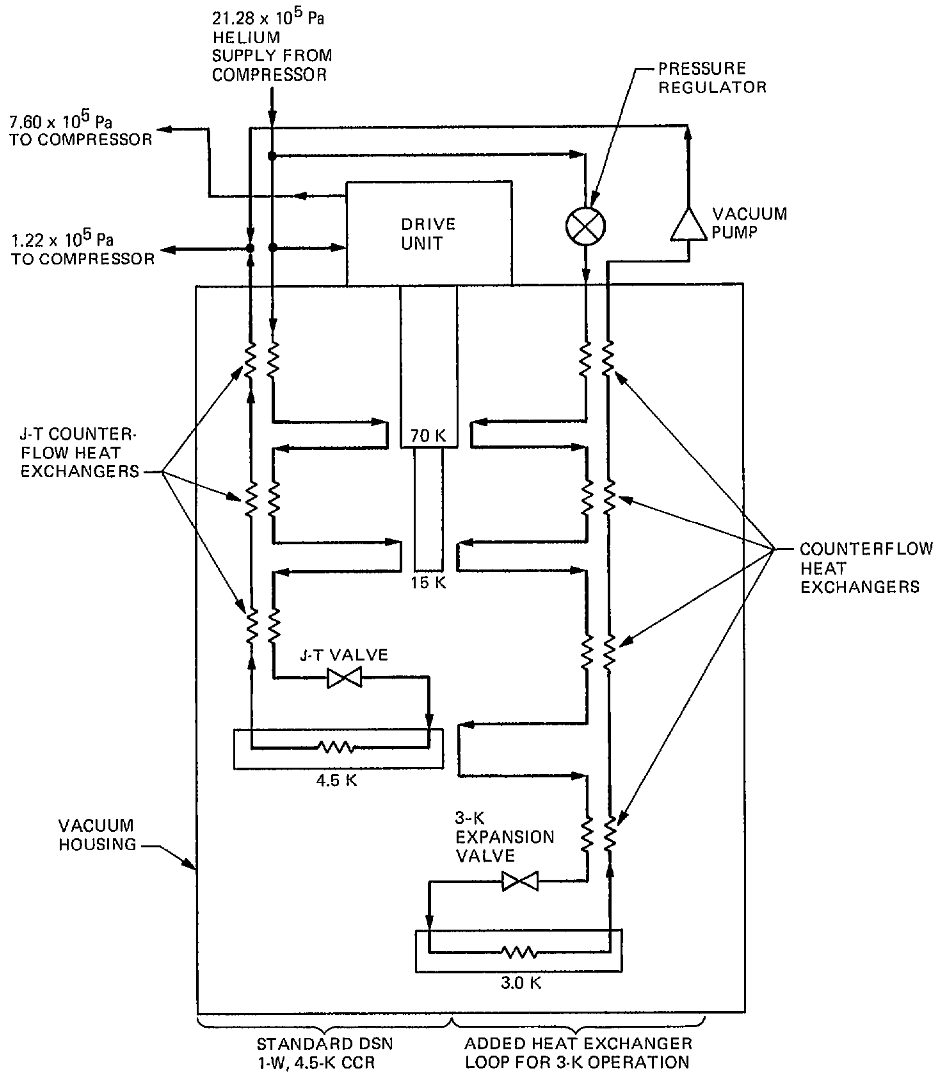

Fig. 5. Schematic of a 3-K closed-cycle refrigerator built at JPL (from Ref. 18)

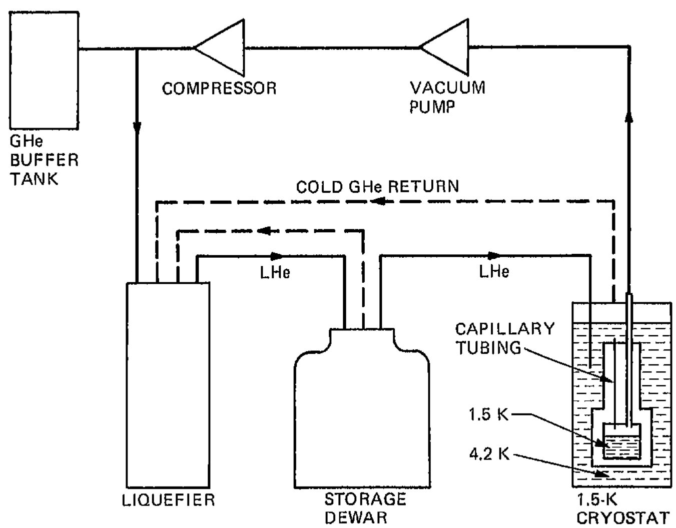

Fig. 6. Block diagram of a 1.5-K refrigerator for a beam waveguide antenna