# Chapter 4
# Cryogenic Refrigeration Systems

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## 4.1 Introduction

Use of cryogenic cooling by the Deep Space Network (DSN) includes both open-cycle refrigeration (OCR) and closed-cycle refrigeration (CCR) systems. The temperatures achieved by these systems range from 1.5 kelvins (K) to about 80 K, depending upon the type of system used. These cryogenic systems are used to cool low-noise preamplifiers and some of the antenna feed system components for the DSN's receivers. Liquid nitrogen ($LN_2$) was used to cool reference loads (resistive terminations) used for noise temperature measurements, and liquid helium (LHe) was used to cool reference loads and antenna-mounted ruby masers. Russell B. Scott in *Cryogenic Engineering* [1] explains many aspects of cryogenic technology in terms that are easily understood. Progress since 1959, has given us many types of CCR systems that can be used for cooling low-noise microwave amplifiers.

Cryogenic refrigeration is a term that may be applied to the process of cooling equipment and components to temperatures below 150 K. The net capacity of a cryogenic refrigeration system at a particular temperature is the amount of heat that can be applied to a "cold station" in the system without warming the station above that particular temperature. The cold station may be a bath of cryogenic fluid, or the cold station may be a conductive surface cooled to the bath temperature to which equipment may be fastened.

Cryogenic refrigeration systems are different from the refrigeration equipment we encounter in our everyday environment. The refrigerants used in cryogenic systems are often helium (He), hydrogen ($H_2$), or nitrogen ($N_2$). Insulation techniques used to minimize heat leaks into the cooled parts of the systems usually depend on the use of high-vacuum technology, radiation shields, and structural materials with low thermal conductivity. Systems that use stored cryogens such as liquid helium, liquid hydrogen, or liquid nitrogen in a container called a "dewar" are usually refilled on a periodic basis. Solidified gases (such as hydrogen or methane) can also be used for cooling purposes, much as solid carbon dioxide (dry ice) is used to refrigerate perishable foods during shipment, but this has not been done in the DSN.

Development of cryogenic refrigeration equipment and systems for laboratory, military, and commercial purposes began many years before development of the ruby masers and other low-noise equipment used in the DSN. This was fortunate, but the personnel developing the DSN's low-noise amplifiers did not have all of the knowledge and expertise needed for developing or purchasing cryogenic equipment and systems. There was much to be learned and many pitfalls to be avoided.

Techniques and materials needed for the efficient transfer of electrical power and microwave signals from a room-temperature environment into a cryogenic environment are often not compatible with the techniques needed to provide adequate thermal isolation. The development of very low-loss microwave input transmission lines and waveguides with high thermal isolation was challenging. Vacuum seals or windows in the transmission lines or waveguides could be degraded by condensation collecting on surfaces that were cooled by conduction or radiation. Many problems like these were waiting to be solved during the early years of cryogenically-cooled low-noise amplifier (LNA) development for the DSN.

Transferring liquid helium into an open-cycle dewar required the use of a vacuum-jacketed transfer line. Inadequate insulation in the transfer line would cause an expensive failure, wasting the precious liquid helium. Our leader and teacher, Dr. Walter H. Higa, noted, in 1960, that the cost of a liter (L) of liquid helium was about the same as the cost of a liter of good Scotch whisky. About 6 L of liquid helium a day were used for each antenna-mounted maser. Construction or procurement and maintenance techniques for liquid-helium transfer lines were learned the hard way.

Difficulties encountered during the development and field use of the eventually successful antenna-mounted open-cycle liquid-helium-dewar systems provided incentives for an alternative approach. Dr. Higa wrote, in a 1962 memorandum, "The inconvenience of having to refill a dewar is quite obvious, and much effort is being expended to perfect a closed-cycle refrigerator (CCR) for maser applications." The memo included the photograph of a liquid-helium transfer at the apex of a 26-meter (m) antenna shown in Chapter 3, Fig. 3-1.

The early closed-cycle helium refrigerator systems were not without problems. Early model 210 Cryodynes® purchased from the Arthur D. Little Corporation (ADL) in Cambridge Massachusetts, experienced frequent gear failures in the drive units of the refrigerators. The compressors that supplied high-pressure helium gas to the antenna-mounted Cryodynes® often contaminated the helium with the lubricant used in the compressor. The expression “oil carry-over” was used often when reporting Cryodyne® warm-ups (failures). The Joule-Thomson (JT) counter-flow heat exchangers in the Cryodyne® had been plugged with lubricant that had solidified.

Our early learning period of using, maintaining, servicing, repairing, and modifying CCRs to cool masers on antennas in the field lasted from 1961 to 1966. Many problems were solved. Then, the development and production of the Model 340 ADL Cryodyne® in 1965 provided the world with a reliable two-stage Gifford-McMahon (GM) CCR. This 15-K CCR had adequate capacity for use with a JT counter-flow heat exchanger system developed by Dr. Higa and Ervin R. Wiebe [2]. This new CCR provided reliable 4.5-K refrigeration for DSN masers beginning in 1966.

The costs and difficulties experienced developing and using the early cryogenically-cooled masers seemed high, but the value of the low-noise masers proved to be more than worth the cost and effort. The expense to provide and operate larger antennas, or more antennas, that could be used to equal the existing antenna and maser-receiving system’s figure of merit $(G/T_{\mathrm{op}})$ was more than the cost of building and operating the masers by factors of tens to hundreds. Advances in cryogenic refrigeration technology continued, enabling improvements that helped to maximize the performance of deep space missions.

## 4.2 Advantages of Using Cryogenic Cooling

Cooling microwave components and LNAs to cryogenic temperatures enables significant reductions in the operating noise temperature $(T_{\mathrm{op}})$ of receiving systems. The sensitivity of a receiving system is directly proportional to $A/T_{\mathrm{op}}$, where $A$ is the receiving antenna’s effective collecting area. For example, when $T_{\mathrm{op}} = 80\ \mathrm{K}$, an array of four identical antennas and receivers is needed to equal the sensitivity of one such antenna and receiver with a $T_{\mathrm{op}}$ of $20\ \mathrm{K}$. In 1965, when 26-m-diameter antennas were in operation and 64-m-diameter antennas were being built for the DSN, ruby traveling wave masers (TWM) cooled by 4.5-K Cryodynes® were the logical economical choice of LNAs for DSN receivers.

Ruby cavity masers were used on antennas in the Deep Space Instrumentation Facility (DSIF) and the DSN beginning in 1960. The performance of a maser at DSN frequencies (below 40 gigaherz [GHz]) improves as the bath temperature is reduced. The bath temperature term $(T_b)$, is often used for the thermodynamic temperature of a maser whether it is immersed in a liquid-helium bath, or cooled by conduction with a closed-cycle refrigerator. The maser noise temperature is proportional to the bath temperature, and the maser electronic gain in decibels (dB) varies inversely with the bath temperature. The temperature dependence of masers is explained mathematically in Chapter 3. All DSN ruby masers are cooled to temperatures below 5 K. Transistor LNAs used in the DSN are less temperature dependent than masers and are often cooled to temperatures between 5 and 20 K.

Figure 4-1 is a photo of two X-band feedhorns mounted on an X-band maser during noise temperature measurements. $T_{\mathrm{op}}$ was measured by switching from the ambient load (located between the two horns) and either horn. The measurement was used to determine the noise temperature difference of the corrugated feedhorn and a smooth feedhorn. The corrugated feedhorn resulted in a $T_{\mathrm{op}}$ measurement that was 0.1 K lower than that measured with the smooth horn.

A high vacuum inside the CCR reduces heat transfer from the ambient vacuum housing to the cryogenically cooled assembly within the housing. A vacuum window in the X-band signal waveguide entering the CCR seals the system from the atmosphere while passing the microwave signals to the LNA system within the vacuum housing. The CCR vacuum window withstands the atmospheric pressure and attenuates the incoming signal by about 0.01 dB. This loss at 300 K adds 0.7 K to the X-band maser's effective input noise temperature as measured at the ambient interface of the maser package.

DSN X-band systems use waveguide components, including a diplexer to accommodate a transmit capability, a filter for out-of-band radio-frequency interference (RFI) and transmit signal rejection, and a polarizer preceding the receiver's LNA. These components cause loss and noise, thereby degrading the receiver's sensitivity. The microwave loss of components made of good quality electrolytic copper (oxygen-free high conductivity (OFHC) or electrolytic half-hard) drops by a factor of two when cooled from 290 K to 80 K, and by a factor of three when cooled from 290 K to 20 K. The microwave loss does not change below 20 K. These factors (ratios) are independent of frequency in the 2-GHz to 34-GHz range measured. The direct current (dc) resistance of electrolytic half-hard copper drops by a factor of about 9 when cooled from 290 K to 80 K and by a factor of about 100 when cooled from 290 K to 20 K. The microwave loss does not vary as the square root of the dc resistance at cryogenic temperatures. The process used to determine the noise contribution of components preceding LNAs was described in an earlier chapter and is not repeated here. Table 4-1 describes the advantages of cooling feed-system components preceding an X-band maser.

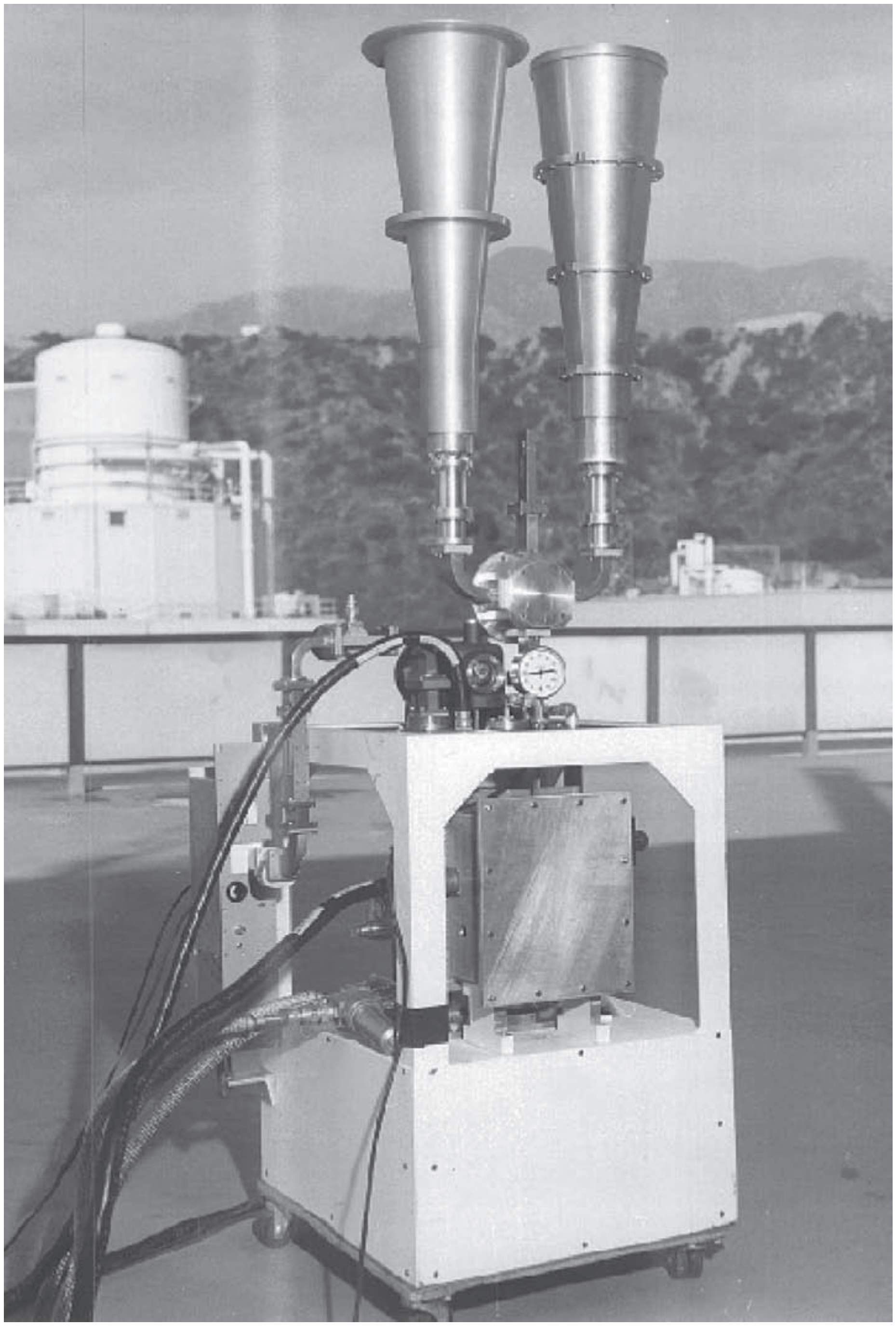


Fig. 4-1. X-band TWM with X-band feed-horns.

The system noise temperature ($T_{op}$) values shown in Table 4-1 are reasonable for 70-m DSN antennas currently operating at 8420 megahertz (MHz) (X-band) at an elevation angle of 30 degrees (deg) in clear dry weather. The noise from the antenna at the feedhorn input is 12 K. Component thermodynamic temperatures of 300 K, 80 K, 40 K, 20 K, and 4 K are used. Table 4-1 $T_{op}$ values are calculated at the feedhorn input, in the space just above the feedhorn.

Figure 4-2 shows three of the feed-system components (a) outside of the CCR vacuum housing at room temperature and (b) the same components inside the CCR vacuum housing at various cryogenic temperatures. The maser input noise temperature at the vacuum window ambient interface shown in Fig. 4-2 (a) is 3.0 K. The examples used in Table 4-1 gives the combined insertion loss of the three components at the various temperatures. $T_{op}$, the sensitivity changes, and the maximum data-rate percentages are calculated values, with 100 percent being the reference rate when the feed-system components are at ambient temperature. Ambient-temperature feed-system components at S-band and X-band were used in the DSN in most operational systems prior to the year 2002.

## 4.3 Open-Cycle Refrigeration

Liquid helium and liquid nitrogen in open-cycle dewars have been used in the DSN to cool resistive terminations (loads) for calibrations, LNAs, and microwave feed-system components. The normal boiling point of liquid nitrogen is 77.395 K at 760 millimeters of mercury (mm Hg) (1.000 atmosphere (atm), 101.32 kPa (kilopascals)), and the temperature varies with vapor pressure from 64 K at 109.4 mm Hg (0.1439 atm, 14.6 kPa) to 84 K at 1539 mm Hg (2.025 atm, 205 kPa), and up to a critical temperature of 126.1 K

**Table 4-1. System noise temperature, receiving system sensitivity change, and maximum data rate as a function of component physical temperature and loss.**

| Feed-System Components Temperature (K) | Feed-System Components Loss (dB) | System Noise Temperature (K) | Sensitivity Change (dB) | Maximum Data Rate (%) |
|---|---|---|---|---|
| 300 | 0.24 | 32.729 | 0.000 | 100 (Reference rate) |
| 80 | 0.12 | 17.800 | 2.645 | 183.9 |
| 40 | 0.10 | 16.475 | 2.981 | 198.7 |
| 20 | 0.08 | 15.902 | 3.135 | 205.8 |
| 4 | 0.08 | 15.603 | 3.217 | 209.8 |

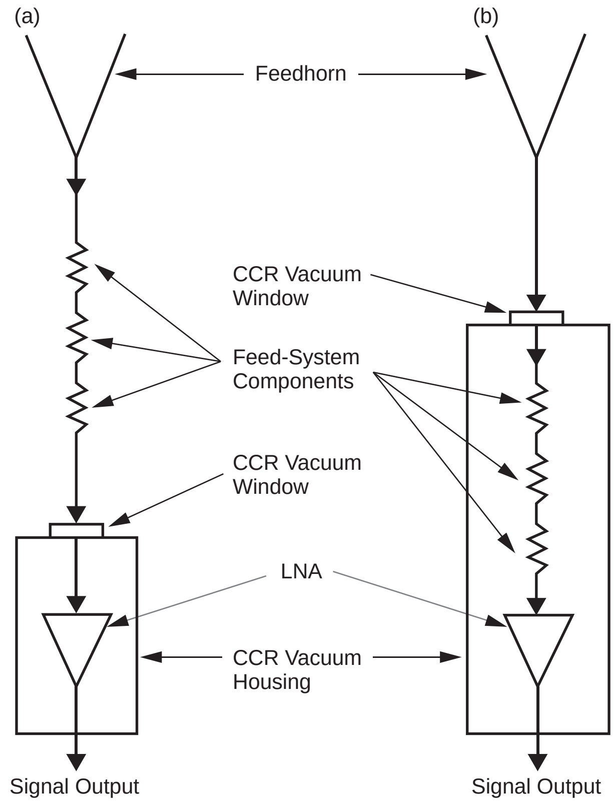



**Fig. 4-2. Feed-system components (a) outside of the CCR vacuum at room temperature and (b) inside the CCR vacuum housing and cooled.**

at the critical pressure of 25,454.2 mm Hg (33.49 atm, 3393 kPa, or 492.23 pounds per square inch absolute (psia)) [1]. Liquid nitrogen is available at a relatively low cost that ranges from about 20 cents to 2 dollars per liter in United States currency, depending on the circumstances. Liquid nitrogen has sufficient cooling capacity for many applications.

Measurement techniques used to determine the effective input noise temperature of a receiver (when the receiver is connected to an ambient load and then to a liquid-nitrogen-cooled load) were described in Chapter 2. The accuracy of the measurement is dependent upon the accuracy of the knowledge of the noise temperature of the loads at the input to the amplifier system. The temperature of the liquid nitrogen is dependent upon the pressure of the vapor above the liquid. When this vapor pressure is determined by atmospheric pressure that supports a 760-mm column of mercury (101.3 kPa, 14.7 psia) at sea level, the temperature of the liquid nitrogen varies with altitude as shown in the graph below (Fig. 4-3).

The graph in Fig. 4-3 is based on the vapor pressure data found in reference [1], a portion of which is summarized in Table 4-2 for liquid nitrogen and liquid helium.

A reduction in pressure of 12.68 mm Hg (1.69 kPa) from 760 mm Hg to 747.32 Hg (101.32 kPa to 99.63 kPa) causes a reduction in the temperature of

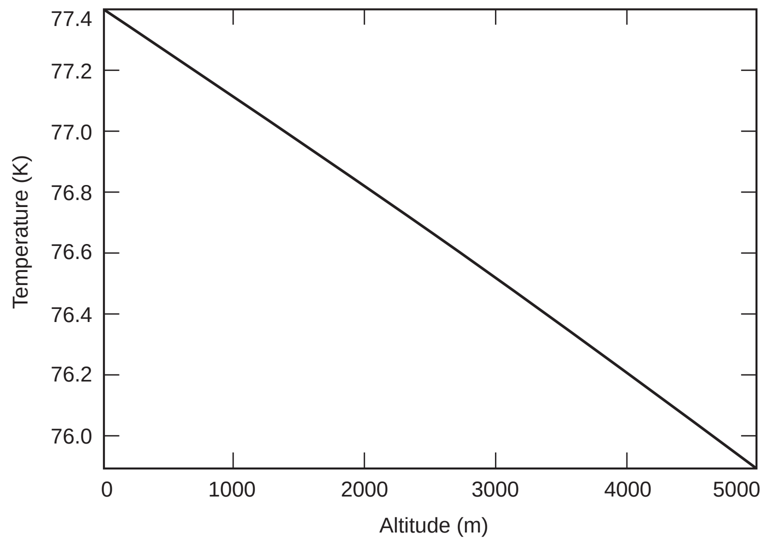



**Fig. 4-3. Liquid nitrogen temperature versus altitude.**

**Table 4-2. Altitude, Boiling Point of Liquid Helium and Liquid Nitrogen, and Pressure**

| Altitude, feet (meters) | Temperature (K) | | Pressure | | | |
|---|---|---|---|---|---|---|
| | Liquid Helium | Liquid Nitrogen | (mm) Hg | (psia) | (inches Hg) | kPa |
| 0 (0) | 4.216 | 77.395 | 760 | 14.70 | 29.92 | 101.3 |
| 1000 (304.8) | 4.181 | 77.119 | 735 | 14.22 | 28.94 | 98.0 |
| 2000 (609.6) | 4.145 | 76.832 | 710 | 13.73 | 27.95 | 94.7 |
| 3000 (914.4) | 4.108 | 76.534 | 685 | 13.25 | 26.97 | 91.3 |
| 4000 (1219.2) | 4.007 | 76.224 | 660 | 12.77 | 25.98 | 88.0 |
| 5000 (1524) | 4.031 | 75.902 | 635 | 12.28 | 25.00 | 84.7 |

liquid nitrogen by 0.1 K. A reduction in the pressure of the same amount causes a 0.0127-K reduction in the temperature of liquid helium.

Liquid helium is used to cool components to temperatures below 4.2 K by using a vacuum pump to reduce the vapor pressure above the liquid helium in the container. As with liquid nitrogen, liquid helium is readily available on a commercial basis at a higher cost than liquid nitrogen. Today's cost of liquid helium ranges upward from $3 per liter in United States currency, depending on the circumstances.

The cooling capability of liquid helium, in terms of watts per liter (W/L), is lower than the cooling capability of liquid nitrogen by a factor of about 63. It takes 0.716 watt (W) for a period of one hour to convert 1 L of liquid helium at 4.2 K to gas. It takes about 45 W for a period of one hour to convert 1 L of liquid nitrogen to gas. For comparison, it takes about 628 W for a period of one hour to convert 1 L of water at 100 deg C to gas (steam). Dewars used to store liquid helium and liquid nitrogen are shown in Fig. 4-4.

Scott, in reference [1], page 215 writes, "The invention of the vacuum insulated vessel for liquefied gases by James Dewar in 1892 was a break-through in the field of thermal insulation that has not yet been matched by further developments. All of the advances since Dewar's time have been improvements on Dewar's original concept, usually by means of reducing radiant heat transfer by attaining surfaces of higher reflectivity or by interposing shields which reflect or intercept radiant energy." These words are still true today.

The dewars shown in Fig. 4-4 (at Goldstone) were commercially available for use with liquid nitrogen and liquid helium long before their first use at the DSS-11 DSIF Goldstone Tracking Station in 1960. The forklift planned for the transportation of dewars did not materialize, but the "HAPPY-TIME *RACER*" (little red wagon) shown in Fig. 4-4, requested by Walter H. Higa and provided by Charles T. Stelzried, was adequate for the task. These dewars can be used to store liquid helium and liquid nitrogen for many weeks with minimal loss. The liquid-helium dewar contains a liquid-nitrogen tank that surrounds the helium tank to intercept radiation from the ambient environment. Styrofoam containers can be used to hold liquid nitrogen for short periods. A Styrofoam coffee cup will hold liquid nitrogen for many minutes, and a Styrofoam container (such as the one shown in Fig. 4-5) will hold liquid nitrogen for several hours.

Figure 4-5 shows manual switching between an ambient load and a liquid-nitrogen temperature load. Dr. Walter H. Higa is holding a Styrofoam bucket containing liquid nitrogen and a calibration load. Robert S. Latham is facing the camera, and the author has his back to the camera. The walls of the Styrofoam bucket were about 2.5 centimeters (cm) (1 in.) thick, providing adequate insulation for the liquid-nitrogen-cooled calibration load. The noise temperature of a cavity maser was being measured.


**Fig. 4-4. Liquid helium and liquid nitrogen dewars on "HAPPYTIME *RACER*" utility vehicle with the cherry picker (High Ranger) and cherry-picker fiberglass basket in the background.**

The cavity maser and dewar system shown in Fig. 3-3 was typical of the dewars used for antenna-mounted operation of masers during the 1960-through-1965 time period. The dewar operated during antenna motion as the antenna was moved to track planets or spacecraft from about 10 deg above the eastern horizon to about 10 deg above the western horizon. The hold time for the 3-L liquid-helium tank was about 36 hours during the antenna-mounted tracking operations. Refills were accomplished on a daily basis using the High Ranger (cherry picker) partially shown in Fig. 4-4 (and completely shown in Fig. 3-1).

Fig. 4-5. Noise temperature measurement (manually switching between ambient and liquid nitrogen temperature loads) showing use of styrofoam container for storing liquid nitrogen.

This first dewar used to cool a 960-MHz cavity maser to 4.2 K on a DSIF antenna in 1960 was designed by Dr. Walter H. Higa. The dewar and maser were built and serviced in the field by members of his group. The dewar had a liquid-helium capacity of 3 L and a liquid-nitrogen capacity of 7 L. The liquid-helium tank was surrounded by the liquid-nitrogen tank, and aluminum radiation shields were attached to the top and bottom of the liquid-nitrogen tank. This geometry accommodated the application of the magnetic field needed for maser operation by a large permanent magnet located at ambient temperature, outside of the dewar.

Neoprene O-ring seals were used in several locations, between the vacuum housing and the top and bottom plates, and at the flanges supporting the cryogen fill-tubes and the coaxial transmission line. Neoprene is not impervious to helium gas. Initial evacuation of the dewar was followed by filling the dewar with liquid helium. The 4.2-K temperature caused residual gases in the vacuum jacket of the dewar to be trapped (solidified) on the surface of the liquid-helium tank. The residual gas pressure in the vacuum jacket dropped to less than

$1 \times 10^{-6}$ torr ($1.333 \times 10^{-4}$ Pa) for many hours. Unfortunately, small amounts of helium gas diffused through the neoprene O-rings and could not be trapped. Within a few days, the accumulation of helium gas in the vacuum jacket of the dewar was sufficient to destroy the insulating properties of the vacuum jacket. A Vac-ion® pump that could pump air at the speed of 5 liters-per-second (Lps) and helium at a speed of nearly 1 Lps was installed on the dewar, and this pump solved the problem.

The 36-hour liquid-helium lifetime of the 3-L tank in the dewar described above indicates a total heat leak and maser pump energy load into the helium bath of about 0.06 W. The liquid-nitrogen lifetime was about the same as the liquid-helium lifetime, indicating a heat load of about 9 W. The liquid-helium and liquid-nitrogen tanks were refilled on a daily basis. The exiting cold helium gas could have been used to reduce the amount of heat entering the dewar conductively along the coaxial signal transmission line, but this particular design did not take advantage of helium-vapor cooling.

The dewar design described above was used for the 2388-MHz single-cavity maser in the 1961 Venus Radar experiment and for several 960-MHz masers supporting spacecraft missions to Venus and the Moon. A slightly larger dewar with a similar design was used for the two-cavity 2388-MHz maser for the reception of radar signals from Venus and Mars in 1962 and 1963.

Commercially available liquid-helium dewars that were suitable for antenna mounted maser operation became available about the time that DSN switched to cryodyne CCRs for cooling masers. One commercially available liquid-helium dewar was used on a 9-m-diameter antenna at the DSN's research station (DSS-13) to cool a multiple-cavity X-band maser purchased from the Hughes Aircraft Corporation in El Segundo, California.

## 4.4 Heat Transfer

Unwanted heat transfer by radiation and conduction into cryogenically cooled equipment should be minimized. The 9-W heat load observed on the liquid-nitrogen tank in the dewar designed by Dr. Higa is typical of cryogenic systems where a cold surface near liquid-nitrogen temperature is about 1/3 of a square meter ($m^2$). The insides of the ambient-temperature aluminum vacuum housing were polished mechanically, and the surface emissivity was probably less than 0.05.

Emissivity of the stainless-steel liquid-nitrogen tank was probably about 0.1. The emissivity of a cryogenically cooled surface is often degraded with time. Gases subliming on cold surfaces are capable of raising the emissivity to values close to 1. The emissivity of other room temperature surfaces (flanges, extensions, welds, and gaps) might have ranged from 0.1 to 1.

Scott wrote [1], "The rate at which a surface emits radiation is given by the Stefan-Boltzmann equation,

$$W = \sigma e A T^4 \tag{4.4-1}$$

where

$e$ is the total emissivity at temperature $T$, K

$A$ is the area,

σ is a constant having the value of 5.67 × $10^{-12}$ W/cm$^2$, K$^{-4}$

The net exchange of radiant energy between two surfaces is given by the expression

$$W = \sigma E A\left(T_2^4 - T_1^4\right) \tag{4.4-2}$$

where subscripts 1 and 2 refer to the cold and warm surfaces, respectively, and *A* is an area factor. In the case of cylinders or spheres, it will be taken as the area of the enclosed (inner) surface; in the case of parallel plates it is obviously the area of either surface. *E* is a factor involving the two emissivities."

Scott's further explanation [1] of the value of *E* is not repeated here. The complications of specular reflection and diffuse reflection, gray surfaces, and surface irregularities can produce errors that seem difficult, if not impossible, to define. Scott lists the "Emissivity (Total Normal)" of various materials in a later chapter [1], Chapter X, pp. 347 and 348, and explains, "It will be noted that the emissivity (or adsorptivity) of metals decreases with decreasing temperature. At a fixed temperature the emissivity must equal the adsorptivity. (If these differed, there could be a net transfer of heat between two surfaces at the same temperature—a violation of the second law of thermodynamics). The rate of radiant heat transfer between two surfaces at different temperatures, where the geometry permits multiple reflections, depends in a complicated way upon the emissivities of both surfaces and their absorptivities of the radiant energy emitted by the opposite surface as well as upon the geometric configuration. Fortunately, in the region of the electromagnetic spectrum of importance in cryogenic insulation, metals are approximately "gray bodies"; that is, their emissivities (and absorptivities) are almost independent of the wavelength of the radiation, so their emissivities for one distribution of wave lengths are nearly equal to their absorptivities for another distribution. Thus, the formula for radiant heat transfer given in Chapter 6 (p. 148 [1]), will give acceptable results."

One of the formulae on page 148 [1] is for diffuse reflection when long coaxial cylinders or concentric spheres are used to determine the value of *E*.

$$E = \frac{e_1 e_2}{e_2 + \dfrac{A_1}{A_2}\left(1 - e_2\right) e_1} \tag{4.4-3}$$

where $A_1$ is the area of the inner surface, $A_2$ is the area of the outer surface, $e_1$ is the emissivity of the colder inner surface, and $e_2$ is the emissivity of the warmer outer surface. This equation is suggested for use with the OCRs and CCRs used to cool preamplifiers in the DSN. The intent here is to provide a rough estimate of the radiation heat transfer that must have been part of the 9-W total heat load on the liquid nitrogen tank in Higa's dewar. Heat transfer by radiation is an important design consideration for CCRs as well as dewars. Using $A_1 / A_2 = 0.5$, $e_1 = 0.1$, and $e_2 = 0.05$ gives a value of about 0.0513 for $E$. Use of this value of $E$ in Eq. (4.4-2) indicates heat transfer rates into the liquid nitrogen tank at 77.4 K of

(1) 10.13 W at an ambient temperature of 320 K (116.3 degrees Fahrenheit (deg F)),

(2) 7.82 W at an ambient temperature of 300 K (80.3 deg F), and

(3) 5.92 W at an ambient temperature of 280 K (44.3 deg F).

It is important to consider the environmental extremes to be encountered when designing such a system. The ambient environment at DSN tracking stations can vary between 266 K (19 deg F) and 322 K (120 deg F).

A change in the emissivity of the liquid-nitrogen tank from 0.1 to 0.2 would cause the radiation heat load from a 320-K surface to increase from to 10.13 to 13.62 W. The emissivity of a surface may vary as a function of time and conditions during use. The out-gassing of materials in a vacuum chamber and gases entering through leaks will change the emissivity of the surfaces on which these gases are solidified. The emissivity of these surfaces can increase to values far higher than those of the original clean configuration. Scott [1] lists the emissivities of smooth ice ($H_2O$) and glass at 0.94, paper at 0.92, white lacquer at 0.925, and candle soot at 0.952. Appearances can be deceiving. A white, or light-colored surface, is often not a good reflector of radiation at the wavelengths emitted by room-temperature surfaces.

Heat transfer from the ambient vacuum housing to the liquid-nitrogen and liquid-helium tanks by conduction through support structures, microwave transmission lines, waveguides, and wires used for electric circuits must be considered. Materials such as nylon, Perspex® (polymethylmethacrylate), Teflon® (polytetrafluoroethlyne), and fused quartz are very good insulators, especially at low temperatures. The thermal conductivities of materials at various temperatures are found in handbooks [3,4] and in graphs by Scott [1]. These thermal conductivity values for materials of interest for cryogenic applications are shown in Table 4-3.

**Table 4-3. Thermal conductivity of various materials, milliwatts/cm K.**

| Material | Temperature (K) | | | | |
|---|---|---|---|---|---|
| | 4.2 | 20 | 76 | 194 | 273 |
| Paper-fiberglass-foil layers | - | - | 0.001 | 0.001 | 0.001 |
| Polystyrene foam | - | - | 0.33 | 0.33 | 0.33 |
| Teflon | 0.45 | 1.3 | 2.3 | - | - |
| Fused quartz | 1.3 | 1.6 | 4.8 | 9.5 | 14 |
| Alumina | 5 | 230 | 1500 | 480 | - |
| Sapphire (36 deg to c-axis) | 1100 | 35000 | 11000 | - | - |
| Stainless steel (321) | 3 | 20 | 80 | 130 | 140 |
| Constantan | 9 | 86 | 170 | 190 | 220 |
| Beryllium copper | 20 | 100 | 350 | 650 | 800 |
| Steel, SAE 1020 | 130 | 200 | 580 | 650 | 650 |
| 50–50 lead–tin solder | 150 | 550 | 505 | 510 | - |
| Brass | 23 | 120 | 390 | 700 | 1200 |
| Aluminum 2024-T4 | 32 | 170 | 560 | 950 | 1300 |
| 6063-T5 | 330 | 1600 | 2300 | 2000 | 2000 |
| 1100 | 500 | 2400 | 2700 | 2200 | 2200 |
| Phosphorus deoxidized copper | 75 | 420 | 1200 | 1900 | 2200 |
| Electrolytic tough pitch copper | 3300 | 13000 | 5500 | 4000 | 3900 |
| Copper, high purity | 120000 | 105000 | 6600 | 4100 | 4000 |
| Silver, 99.999% pure | 144000 | 51000 | 5200 | 4200 | 4180 |
| Silver solder | - | 120 | 340 | 580 | - |
| Helium gas | - | 0.21 | 0.62 | 1.15 | 1.51 |
| Nitrogen gas | - | - | - | 0.18 | 0.26 |

The thermal conductivity value for paper-fiberglass-foil layers appears to be for a composite material that is sometimes called super insulation, but is normally referred to as multi-layer-insulation. The value shown may apply in a clean, hard-vacuum environment, but not when residual gas, condensed or frozen, forms a path for heat transfer through the layers.

Heat transferred by conduction through a material depends upon the thermal conductivity of the material ($k$), the length ($L$), and the cross-sectional area ($A$) of the material and the temperature difference ($\Delta T$) across the length of the material. The rate of heat transfer is:

$$W = k\left(\frac{A}{L}\right)\Delta T \tag{4.4-4}$$

The thermal conductivity of materials often varies as a function of temperature, as shown in Table 4-3. The expression then becomes:

$$W = \frac{A}{L}\int_{T_c}^{T_h} k, dT \tag{4.4-5}$$

The integral has been solved for many common cryogenic materials and temperatures [5]. Heat transferred from the higher temperature $(T_h)$ to the lower temperature $(T_c)$ may be calculated in steps by using numerical integration with a sufficient number of steps. An example of the temperature profile and heat transfer through a 321 alloy stainless-steel rod having a length of 30 cm and a cross-sectional area of 1 $cm^2$ is shown in Fig. 4-6.

One watt is transferred from 300 K to 4 K, yet the temperature near the midpoint is 200 K, and the temperature is 100 K at a point close to the 4 K end. The same geometry of stainless steel transfers 0.088 W from 70 K to 4 K, and the 50-K point is near the midpoint. The center conductor of a coaxial transmission line made of thin-wall stainless-steel tubing stays at a higher temperature for a greater length into a cryogenic system than it would if the thermal conductivity of the stainless steel was constant as a function of temperature. The unfavorable temperature profile added to the loss and noise contributed by input transmission lines in early S-band masers.

## 4.5 Antenna-Mounted Operation

All OCRs and CCRs developed for use in the DSN between 1960 and 1990 were capable of operation at the primary or secondary (Cassegrainian) focal points of large fully steerable antennas. The DSN's construction of 34-m beam-waveguide (BWG) antennas after 1990 provided an ideal environment for cryogenically cooled equipment, for large transmitters that require liquid cooling, and for other electronics that benefit from operation in a stable, non-tilting environment. The BWG research antenna at DSS-13 was built for the purpose of developing Ka-band technology for future missions. The BWG antenna concept had been used successfully in many Earth terminals for commercial satellite applications. The 64-m Usuda (Japan) BWG antenna built

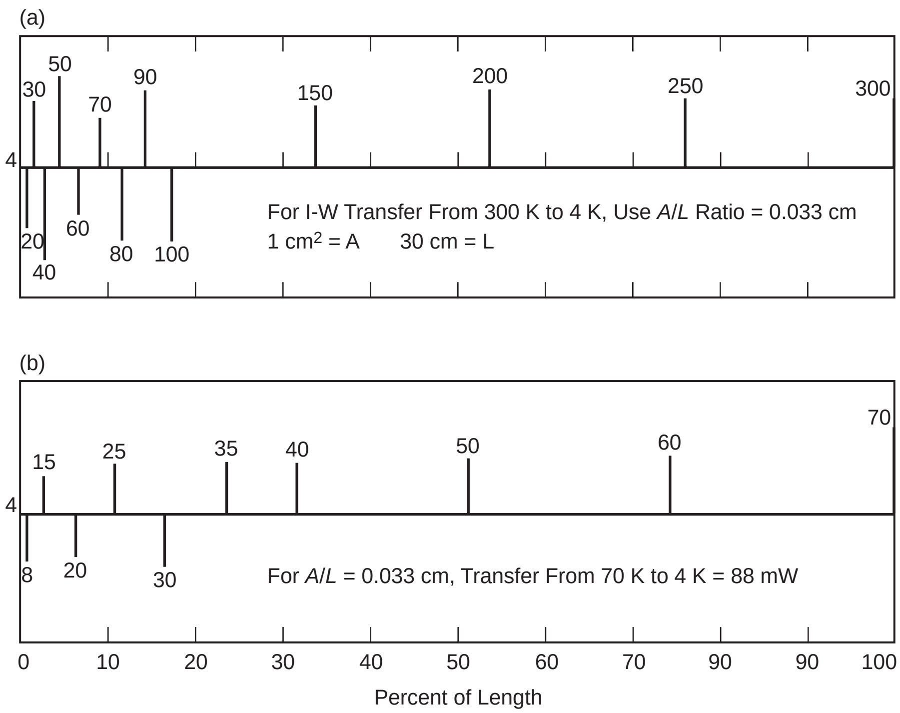



**Fig. 4-6. Temperature profile of stainless steel for two conditions: (a) warm end 300 K and cold end 4 K; (b) warm end 70 K and cold end 4 K.**

by Mitsubishi had demonstrated the low-noise characteristics needed for deep-space applications.

BWG antennas use a system of microwave reflectors (mirrors) to transfer the focal point of a large parabolic reflector antenna to a convenient location, such as a stationary room on the ground. The BWG concept is much like the optical coude telescope developed in 1888. The stationary environment of the DSS-13's front-end-area room is ideal for the use of liquid-helium dewars of the type shown in Fig. 4-7. This commercially available helium dewar was used in 1992 to cool a 33.7-GHz maser to 1.5 K for a Ka-band 'Link' experiment (KaBLE) with a spacecraft on its way to Mars. The 33.7-GHz maser was also used for dual-polarization radio astronomy observations. An X-band traveling-wave maser (TWM) operating at 1.8 K in a dewar similar to the one shown in Fig. 4-7 is used for planetary radar support at DSS-13.

The environment provided by super-fluid helium at temperatures below 2.19 K (liquid helium II) is ideal for masers and for calibration loads. The heat transport through liquid helium II is such that it is not possible to measure a temperature gradient anywhere in the bath. The temperature of any component

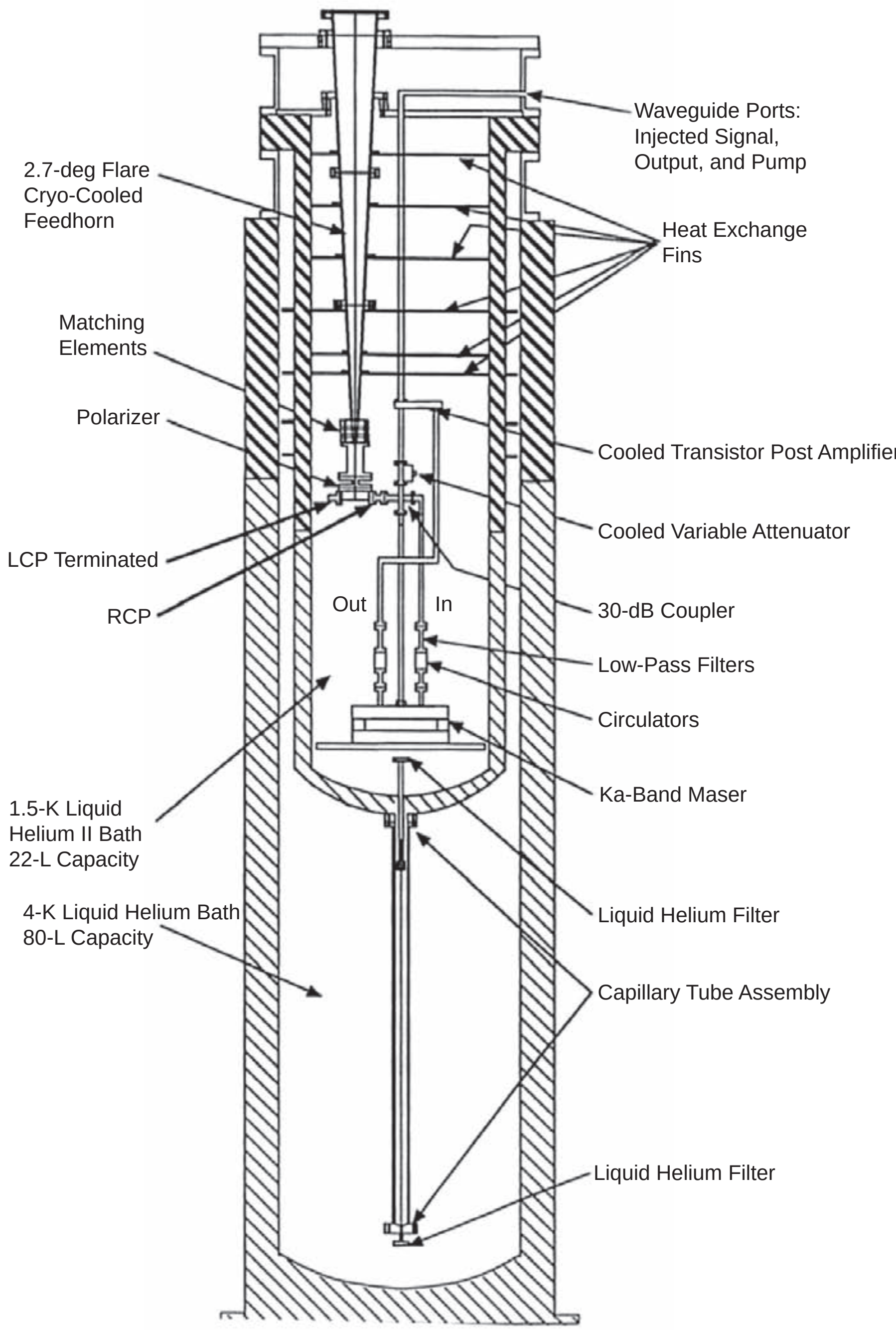



**Fig. 4-7. Continuously cooled liquid-helium dewar with cooled feedhorn and Ka-band maser.**

in the liquid-helium II bath is known precisely, based on the vapor pressure above the liquid (3.63354 mm at 1.5 K and 12.56124 mm at 1.8 K for example) (0.484 and 1.675 kPa, respectively).

## 4.6 Closed-Cycle Helium Refrigerators

The DSN's first CCR was a model 200 Cryodyne®. All of the CCRs used to cool operational DSN ruby masers between 1961 and the present time used the combination of a JT liquefaction process with a GM cycle CCR.

The JT process cools a gas passing through an expansion valve only when the gas is below the inversion temperature. For helium gas, the inversion temperature is near 40 K. Helium heats when passing through an expansion valve (called the JT valve) at temperatures above 40 K. Typical pressure on the high side of the JT valve in a DSN CCR is at 20 atmospheres (2.03 MPa). The low-pressure side of the JT valve is at 1.2 atmospheres (0.122 MPa).

Helium entering a JT valve at 300 K and 20 atmospheres (2.03 MPa) exits the JT valve at a pressure of 1.2 atmospheres (0.122 MPa) and at a temperature between 301 K and 302 K. Helium entering a JT valve at 40 K (close to the inversion temperature) and at a pressure of twenty atmospheres (2.03 MPa) exits the JT valve at a pressure of 1.2 atmosphere and at a temperature of 40 K.

Helium at 20 atmospheres (2.03 MPa) and 300 K enters the CCR and must be cooled to about 15 K to enable a JT cooling effect of about 2.5 K. The enthalpy of helium at 20 atmospheres (2.03 MPa) is about 1570 joules per gram (J/g) at 300 K and about 80 J/g at 15 K. The JT flow of DSN 4.5 K CCRs is about 0.12 grams per second (g/s) of helium. Removal of about 179 joules per second (J/s) at 15 K would be required to cool the helium to 15 K. This is equivalent to cooling a 179-W heater, leading to the use of counter-flow heat exchangers.

A gas stream flowing from 300 K to 15 K, and then returning from 15 K to 300 K, can use exhausting cold gas to cool the incoming gas stream. This can be accomplished by connecting the two separate sets of tubing used to contain the two streams in a manner that enables heat transfer from the incoming to the outgoing gas. The simplest form of a counter-flow heat exchanger connects two long tubes with solder so the thermal path between the two tubes is very short. The tubes are long, because conductive transfer from 300 K to 15 K must be minimized.

The short heat-transfer path through metal between the two passages of a counter-flow heat exchanger is easy enough to accomplish. The main problem is transferring heat from the gas to the metal walls of the passage. The thermal conductivity of helium is very low in comparison to metals, as shown in Table 4-3. The geometry of an efficient counter-flow heat exchanger becomes complex. The complexity is increased by the requirement for minimizing the pressure drop, especially in the low-pressure side of the heat exchanger.

A heat exchanger with 100-percent efficiency would result in a heat load of about 2.2 W on the 15-K station of the GM stage used to cool the JT flow in a 4.5-K CCR. This heat load is caused by the enthalpy difference between 300 K and 15 K of the incoming helium at a pressure of 20 atmospheres (2.03 MPa) and the exiting helium at a pressure of 1.2 atmospheres (0.122 MPa). Counter-flow heat exchangers with 96-percent efficiency were considered to be excellent for use with CCRs having a 1-W cooling capability at 4.5 K. The added heat load to the 15-K station due to heat exchanger inefficiency between 300 K and 15 K would be about 7 W. The use of one or two intermediate stages of GM cooling between 300 K and 15 K eliminates the excessive heat load on the 15-K stage of the GM cooler. An intermediate stage at 70 K in the JPL CCR reduces the heat load on the 15-K stage to about 3 W.

Helium entering a JT valve at 20 K and a pressure of 20 atmospheres (2.03 MPa) exits the JT valve at a pressure of 1.2 atmospheres (0.122 MPa) at a temperature of about 18.5 K. Helium entering a JT valve at 15 K and at a pressure of 20 atmospheres (2.03 MPa) exits the JT valve at a pressure of 1.2 atmospheres (0.122 MPa) at a temperature of about 12.5 K. Helium entering a JT valve at 10 K and at a pressure of 20 atmospheres (2.03 MPa) exits the JT valve at a pressure of 1.2 atmospheres (0.122 MPa) at a temperature of about 6.5 K.

Increasing the JT high-side pressure from 20 to 30 atmospheres (2.03 to 3.04 MPa) gives an improvement of about 0.5 K to the cooling effect when the temperature is 15 K. A reduction of the low-side pressure from 1.2 atmospheres to 0.5 atmospheres (0.122 to 0.051 MPa) improves the cooling effect by about 1 K when the high-side temperature is 15 K. The choice of 1.2 atmospheres (0.122 MPa) for the low-side JT pressure was made to maintain a higher-than-atmospheric pressure in the JT return line. This choice is based on the type and length of the gas lines going from the helium compressor located near the base of the antenna to the CCR mounted near the secondary focal point of a large cassegrainian antenna. The gas lines are typically about 100 m in length and use flexible sections to traverse the antenna axes.

Loss of helium pressure in the storage tank of a CCR compressor indicates the presence of a leak. Positive pressure in all helium lines prevents massive air contamination when a leak is large. The 1.2-atmosphere (0.122-MPa) helium pressure in the JT return line does not eliminate the danger of air entering the system in cases of small leaks or when using certain types of seals. Small leaks and O-ring seals made of rubber allow air to diffuse into the helium-filled line. The partial pressure of helium is less than that of air, so the advantage of having the JT return line above atmospheric helium pressure to avoid contamination is compromised. The partial pressure of a gas is the measure of thermodynamic activity of the molecules. Gases flow from a region of higher partial pressure to one of lower pressure; the larger this difference, the faster the flow.

Suitable liquefaction in the 4.5-K station following the JT valve is obtained by using a counter-flow heat exchanger with high efficiency between the CCR stage at 15 K and the JT valve. A high-efficiency counter-flow heat exchanger minimizes heat transfer between the two heat stations connected to ends of the heat exchanger. Removing heat from the 4.5-K station of a DSN CCR during the initial cool-down process requires a way of transferring heat around (bypassing) the counter-flow heat exchangers in the JT loop.

An attempt to explain the cooling and liquefaction that occurs as result of the JT effect begins here with the 15-K GM station and the 4.5-K JT station, both at 15 K during the CCR cool-down process. Helium at a pressure 20 atmospheres (2.03 MPa) and cooled to 15 K enters a high-efficiency counter-flow heat exchanger and travels to the JT valve. When reaching the JT valve, the helium expands through the valve to a decreased pressure of 1.2 atmospheres (0.122 MPa). The helium cools from 15 K to 12.5 K during the expansion. The 12.5-K gas removes heat from the final stage and travels through the low-pressure side of the counter-flow heat exchanger, removing heat from the incoming stream of helium. The heat exchanger cools the incoming stream from 15 K to a lower temperature at the high-pressure entrance to the JT valve, depending on the amount of heat being removed from the 4.5-K station. The helium reaching the JT valve, now at a temperature below 15 K, expands through the valve and drops to a temperature lower than 12.5 K. This progressive process continues and lowers the helium temperature until the expansion through the JT valve produces some liquid helium at 4.5 K.

Parasitic heat leaks and counter-flow heat exchanger inefficiency affect the percentage of liquid helium produced. The ideal case, with no external heat leak and 100-percent heat exchanger efficiency, would not result in 100-percent liquefaction. The 15-K temperature at which the helium enters the final JT loop counter-flow heat exchanger limits the liquefaction percentage. The liquid-vapor helium mixture flows through a series of perforated copper disks imbedded in the copper 4.5-K heat station and then into the low-pressure side of the counter-flow heat exchanger. Heat transferred to the final stage through supports, radiation, heat exchanger inefficiency, microwave transmission lines, and wiring is about 0.4 W. The net refrigeration capacity (reserve capacity) without the application of additional heat is about 1 W.

The 4.5-K JT stage produces liquid helium at a rate that is sufficient to fill a large part of the low-pressure side of the counter-flow heat exchanger with the 4.5-K liquid-vapor mixture. Without the application of additional heat to the 4.5-K stage, the boiling liquid and vapor mixture of helium fills more than 3/4 the length of the heat exchanger. The efficiency of the counter-flow heat exchanger between the 15-K stage and the 4.5-K stage drops as the active length of the heat exchanger is shortened. The active part of the counter-flow heat exchanger is that section nearest the 15-K station that contains only helium gas (no liquid) in the low-pressure side. The heat transferred from the 15-K station through the shortened active section of heat exchanger to 4.5-K point increases until the final stage can no longer produce additional liquid. The temperature of the helium at 20 atmospheres (2.03 MPa) on the high-pressure side of the final heat exchanger is at 4.5 K for about 3/4th the length of the heat exchanger when no additional heat is applied to the 4.5-K station.

Application of sufficient heat to the 4.5-K JT stage empties the liquid–vapor mixture from the low-pressure side of the final counter-flow heat exchanger. The heat load is then adjusted to a level that converts all of the liquid helium produced to vapor (about 1 W). This amount of heat represents the reserve capacity of the JT stage. A resistive heating element is mounted on each stage of the refrigerator for the purpose of measuring reserve capacity. With the cold end of the heat exchanger at 4.5 K, and with 96-percent heat exchanger efficiency, the helium gas leaving the heat exchanger at the 15-K station, at 1.2 atmospheres (0.122 MPa) would be 14.6 K, about 0.4 K less than the temperature of the incoming gas at 20 atmospheres (2.03 MPa). The enthalpy of helium gas at 15 K and 20 atmospheres (2.03 MPa) is about 80 J/g. The enthalpy of helium gas at 14.6 K and 1.2 atmospheres (0.122 MPa) is about 92 J/g. The gas leaving the heat exchanger has an enthalpy that is about 12 J/g higher than the gas entering, thereby removing heat from the final stage. The helium flow through the JT loop of a DSN 4.5-K 1-W CCR is about 1.5 standard cubic feet per minute (scfm) or 0.12 grams/second (g/s). This shows a total heat removal of about 1.44 W at the 15-K end of the final counter-flow heat exchanger. Steady-state operation of the JT loop producing liquid helium at 4.5 K does not involve a temperature change at the JT valve. Heat removed from the 4.5-K station converts the liquid to vapor.

GM-cycle Cryodynes® were used to cool the JT loop to temperatures of 100 K, 35 K, and 15 K in the case of the Model 200 and 210 Cryodynes®, and to 70 K and 15 K in the case of the JPL-developed 4.5-K CCR [2]. The GM cycle was considered to be the most efficient and reliable combination available with the appropriate capacity at the time the ADL Model 200 and 210 Cryodynes® and JPL CCRs were developed. The combination of efficiency, reliability, and appropriate capacity is emphasized here. There may have been more efficient cryogenic refrigeration cycles that were not sufficiently reliable and there may have been more reliable cycles that were not sufficiently efficient. Large cryogenic refrigerators with hundreds of watts of cooling power at 4.2 K can be very efficient and reliable. These large systems do not scale down effectively to the size needed for the DSN's LNA applications.

The GM-cycle Cryodynes® and JT loops can use a helium compressor that is located a long distance from the cryogenic refrigerator. This is convenient for the DSN implementation on large antennas, as shown in Fig. 3-6. The compressor provides about 1.6 g/s of helium at a pressure of about 21 atmospheres (2.13 MPa). Most of this gas stream is used by the GM

Cryodynes®, returning to the compressor at pressures between 5 and 8 atmospheres (0.507 and 0.811 MPa), depending on the type of system used.

Figure 4-8 shows a schematic diagram of the JPL CCR with a two-stage GM refrigerator and a JT loop. The "supply" gas stream from the compressor is split at the refrigerator, with about 1.48 g/s at a pressure of 21 atmospheres (2.13 MPa) going to the CCR drive unit. About 0.12 g/s goes to a pressure regulator and then to the JT loop inlet at a pressure of about 20 atmospheres (2.03 MPa).

The GM cycle uses isentropic expansions of helium in combination with displacers and regenerators to achieve low temperatures. Helium at high pressure (about 21 atmospheres, 2.13 MPa) enters through the inlet valve when

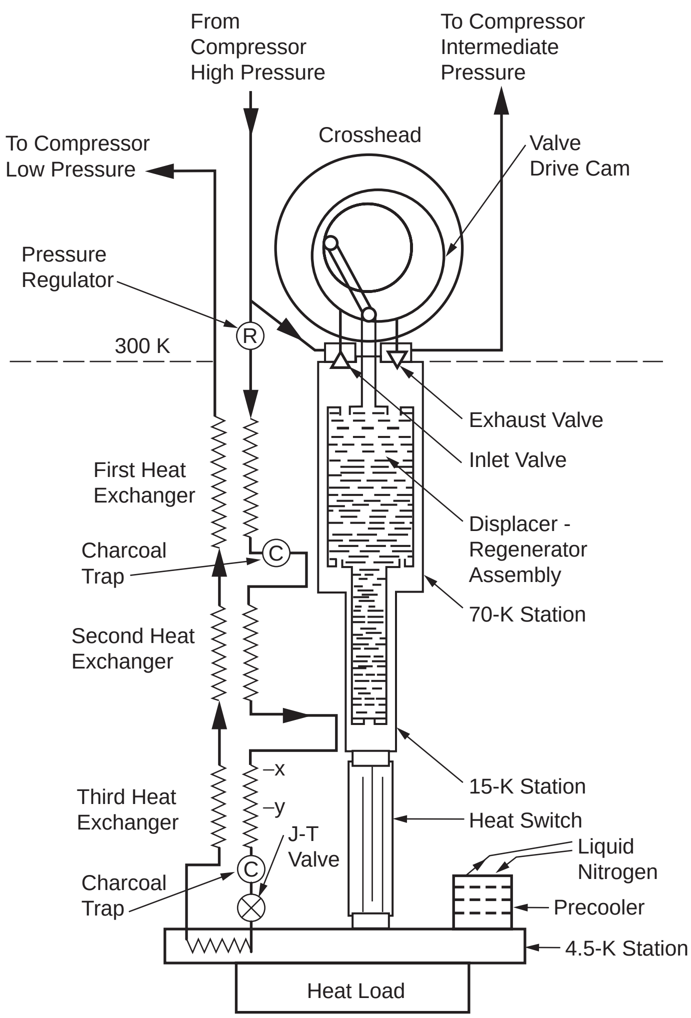



**Fig. 4-8. JPL CCR schematic diagram.**

the displacers are furthest away from the crosshead. The volume at the cold ends (shown as the bottom ends in Fig. 4-8) of the cylinder containing the displacer and regenerator assemblies are near minimum at this point in time. The volume above the regenerators is near maximum at this point in time. Pressurization of this volume causes heating, and the heat is later stored at the upper or warm ends of the regenerators.

The regenerators are made of materials having high specific heat in the temperature ranges appropriate to each stage. The goals of the regenerator designs are to (1) store heat, (2) transfer heat quickly between the helium and the regenerator material, (3) minimize the heat transfer from one end to the other end of the regenerator, (4) minimize the dead volume (void space) thus maximizing the filling factor of the regenerator material, and (5) minimize the restriction through the regenerator material.

After pressurizing the volume above the regenerators, including the entire volume of the displacers and regenerators, the displacers are moved towards the crosshead, causing the high-pressure helium gas to flow through the regenerator matrices into the increasing volume at the cold end of the regenerators. After the volume at the cold end of the regenerators is maximized and filled with high-pressure helium, the inlet valve is closed, and the exhaust valve is opened. The high-pressure gas in the now large volume at the cold end of the regenerators experiences an isentropic expansion. The cooled gas passes back through the regenerator matrices, removing the stored heat in the process. The displacer is then moved away from the crosshead, again minimizing the cold-end volume and causing the last of the cold gas, now at the intermediate pressure, to pass through the regenerator and further cool the cold end of the regenerators. Each repetitive cycle causes a significant drop in the temperature at the cold end of the regenerators until the ultimate low temperatures are reached. In the two-stage GM system of the JPL CCR, these temperatures are at about 70 K (1st stage) and 15 K (2nd stage) with the typical heat load of the JT loop, radiation shield, and conductive heat transfer through supports and microwave transmission lines.  A radiation shield made of copper is attached to the 70-K station, and it surrounds the components at temperatures below 70 K.

The Model 200 and 210 Cryodynes® used a three-stage GM system with the JT loop. The temperatures of the three stages were at about 100 K, 35 K, and 15 K. The regenerator material in the 100-K stage, and in the 70-K stage of the JPL CCR, was brass screen. The regenerator material in the 35-K stage and 15-K stage of the GM systems was lead, in the form of small spheres. Three Micarta displacers of the Model 200 and 210 Cryodynes® were contained in independent stainless-steel cylinders, with regenerators in separate stainless-steel cylinders external to the displacers, connected with copper or stainless-steel tubing. The concentric assembly of the model 340/350 Cryodyne® used in the JPL CCR is shown in Fig. 4-8 consisted of Micarta displacers that contained the regenerator material. Seals, preventing helium gas flow around the displacers, were made of Teflon with 25-percent fiberglass. These seals, not shown in Fig. 4-8, were located at the warm ends of each displacer. Schematic diagrams of the Model 200 and 210 Cryodynes® are not shown, but significant differences between these early DSN cryogenic refrigerators and the much more successful JPL CCR seem worthy of mention. Reliability problems and failures with the early systems resulted in the development of repairs, modifications, and upgrades that helped provide knowledge and insight, and leading to the development of the 4.5-K JPL-CCR that has been used in the DSN since 1966, more than forty years.

A lesson about early success with new equipment was learned. Trouble-free performance with the Model 200 Cryodyne® was demonstrated for 5000 hours on the 26-m research antenna at DSS-13. Subsequent experience with model 210 Cryodynes® on operational DSN antennas was less successful. Helium compressors with inadequate helium purification allowed migration of compressor lubricant into the CCRs. LB 400 Union Carbide compressor lubricant traveled from the compressors to the refrigerators in helium high-pressure supply lines without wetting the lines. Liquid appeared in the refrigerator return lines and in the intermediate pressure areas of the drive units. The regenerators in the GM CCRs were acting as agglomererators, clustering tiny oil droplets, which traveled like vapor with the helium gas through the supply lines. This condition indicated improper assembly of the agglomerators in the compressors used for the early-model 210 Cryodynes®.

The helium compressors used modified "3-HP" (2.24-kW) Copeland Freon® compressors. These modified Copeland Freon® compressors each draw about 7 kW electrical input power in this application. Coolant is needed to reduce the temperatures caused by compressing helium from a pressure of 1.1 atmospheres (0.11 MPa) to the intermediate pressure and then to the 21-atmosphere (2.13-MPa) supply pressure. A large quantity of lubricant is circulated through the compressor to keep the helium temperature below 80 C. The high-pressure helium gas and lubricant mixture is cooled to ambient temperature by the compressor's air-cooled heat exchangers. A properly assembled series of agglomerators causes the lubricant droplets to collect and flow to the bottom of the agglomerators. The lubricant is then returned to the compressor through a series of filters or screens and orifices, and the lubricant-free helium is sent on to a charcoal and molecular-sieve filter for further purification.

Unfortunately, the pipe thread connectors used to attach the sintered metal agglomerators of the early model 210 Cryodynes® compressors were not tightened sufficiently during assembly. The first-stage agglomerators fell apart during the early months of use. Second-stage agglomorators, made of fine glass wool (an artificial substitute for fine lamb's wool), were not packed with sufficient density. "Oil-carry-over" problems plagued these systems during the early days.

Other problems complicated the situation. Cryodyne® drive unit gear failures occurred within a few hundred hours of operation. This failure mode was not seen in model 200 Cryodyne® during the first 5000 hours of operation. The drive mechanism for the displacers used a very small gear at the end of the motor shaft to achieve a high reduction ratio. The small gear drove a large gear and a complex gear arrangement to approximate a square-wave displacer motion at 105 revolutions per minute (rpm). The load on the small gear caused rapid wear and early failures. The load on the gear train was aggravated by accumulations of lead and Micarta® dust mixed with compressor lubricant, forming a sticky mixture on the displacers. A "fix" to eliminate the source of lead dust was to plate the lead spheres with a shiny hard-surface metal. This "fix" added another contaminant; the plating flaked off of the lead spheres during the thermal cycling and vibration of operation.

The tight implementation schedule needed to support the first Mariner-Mars mission launched in November 1964 forced repairs, modifications, and upgrades to be done at JPL and at the DSN Stations, rather than sending the Cryodynes® back to ADL. With the support of ADL personnel, Walt Higa's group completed the work enabling the use of these systems for the Mariner-Mars mission. Much was learned in the process. Ervin (Erv) R. Wiebe at JPL was key to finding solutions to the problems. For example, Erv modified a drive unit to achieve a sinusoidal displacer motion and eliminated the need for the complex "square-wave" gear drive mechanism. The speed was slowed to simulate performance that would result from the use of a 72-rpm direct-drive motor. Capacity measurements showed performance equivalent to the square-wave drive that was previously thought to be ideal for the displacer motion. Several compressor and drive-unit fixes, modifications, and upgrades (including the installation of 72-rpm direct-drive motors) were implemented in a short time period at JPL and at the DSN tracking stations. The six TWM CCR systems, implemented in time to support the Mariner-Mars encounter in July 1965, performed without failure during the Mars picture-playback sequence in July and August 1965.

Walt Higa and Erv Wiebe were the leaders in the development of the JPL CCR that was first used in the DSN on the 64-m antenna at DSS-14 in 1966. Professor William Gifford consulted for our group during that development period. The team that made this development successful included Rex B. Quinn, a precision machinist, microwave technician and engineer, whose contributions to maser development, ultra-low-noise systems, and cryogenic refrigerators continued for decades. Robert S. (Bob) Latham is another of the team members that deserves mention; Bob's guidance in dealing with operational situations was most valuable.

The ADL Model 340 Cryodyne® was chosen to pre-cool a JT loop developed by Higa and Wiebe [6]. The efficiency of counter-flow heat exchangers developed by Higa and Wiebe resulted in a 1-W capacity at 4.5 K at a JT flow of about 0.12 g/s. The first and second stages of the GM Cryodyne® operated at 70 K and 15 K, respectively, in combination with the JT loop. The use of a fixed JT valve simplified the operation and eliminated a failure mechanism encountered with the adjustable JT valve used in Model 200 and 210 Cryodynes®. The cool-down time for the JPL CCR was shortened and simplified through the use of a hydrogen-filled thermal switch invented by Erv Wiebe. The novel switch eliminated the need for a heat-exchanger bypass valve used during the cool-down process in model 210 Cryodynes®.

Figure 4-9 shows an S-band maser package as used on the 64-m antenna in 1966, with inserts showing key features. The upper right insert (a) shows a cut-away section of the inlet and outlet connections in a counter-flow heat exchanger. Details of the inner construction are shown in Fig. 4-10. Flexible phosphor-bronze "hose" with helical convolutions is used between snug-fitting inner and outer stainless-steel tubes. The region between the inner stainless-steel tube and the corrugated phosphor-bronze hose provides one passage through the counter-flow heat exchanger. The region between phosphor-bronze hose and the outer stainless-steel tube forms the other passage. The two gas streams, flowing in opposite directions, transfer heat from one to another. The thin wall between the two streams enables efficient heat transfer between the two streams, but the long length of the heat exchanger assembly minimizes heat transfer from end-to-end. The helical convolutions cause turbulence, helping to transfer heat through the helium and maximizing the efficiency of the counter-flow heat exchanger.

The restriction through the passage at low pressure affects the pressure of the JT loop at the liquid stage of the refrigerator. For this reason, Higa suggested another design using phosphor-bronze hose with helical convolutions. The geometry of this design is shown in Fig. 4-11. The low restriction in this design enabled increased JT flow, and this was later used to increase the capacity of DSN CCRs.

Insert (b) in Fig. 4-9 shows an exploded view of a thermal switch (three parts on the left side), a charcoal-filled filter (upper right), and the fixed JT valve. The small needle near the center of the insert is part of the fixed JT-valve. This valve in the JT loop, dropping the JT pressure from about 20 atmospheres to 1.2 atmospheres (2.03 to 0.122 MPa, respectively) consists of a hypodermic needle having an inner diameter of 0.007 inch (in.) (0.018 cm) partially filled with a stainless-steel wire having an outer diameter of about 0.006 in. (0.015 cm). The length of the tubing and wire is about 2 cm. The diameter of the wire can be reduced to decrease the restriction through the valve to provide JT flow of about 0.12 g/s during normal operation.

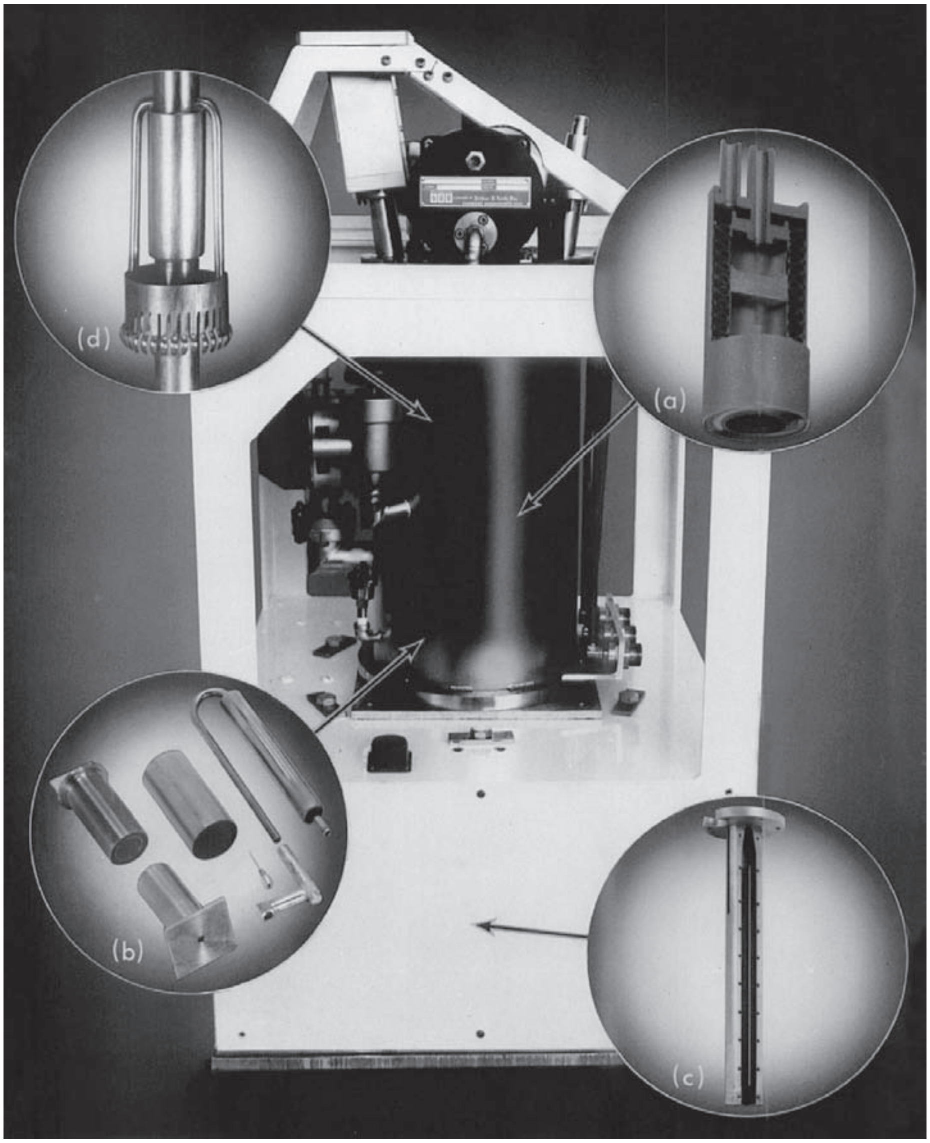
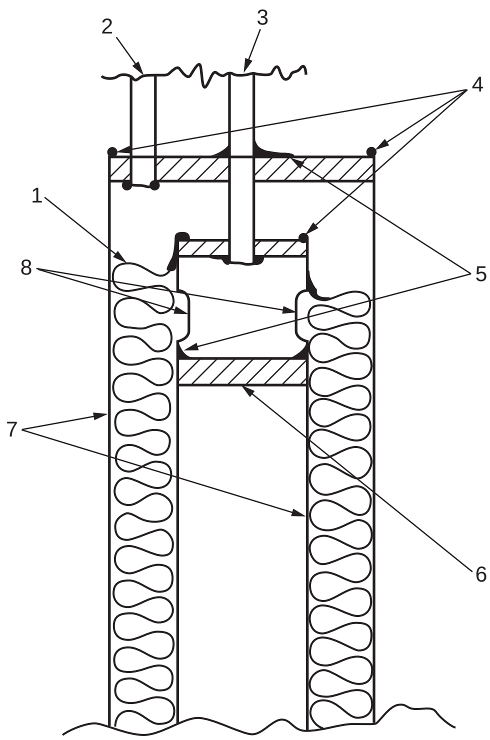



**Fig. 4-9. S-band JPL TWM/CCR package with key features shown in expanded views (a) cut-away section of the inlet and outlet connections in the counter-flow heat exchanger; (b) charcoal-filled filter to the upper right of the insert, the JT valve housing and hypodermic-needle-part of the fixed JT-valve to the lower right, and the thermal switch parts (in the center, on the left side, and the bottom of the insert; (c) an S-band TWM comb structure (discussed in Chapter 3); and (d) a quarter-wavelength thermal conductor between the center conductor and outer conductor of an S-band coaxial input transmission line, transparent to the microwave signal.**




Notes:

1. Helium gas or liquid flows in opposite directions through phosphor–bronze flexible hose with helical convolutions providing two long spiraling gas passages, one on either side of the convolutions. (Note: annular convolutions cannot be used for this application.)
2. Connection to passage between outer stainless steel tube and phosphor–bronze hose.
3. Connection to passage between inner stainless steel tube and phosphor–bronze hose.
4. Stainless steel welds shown with dot at joint.
5. Silver soldered (brazed) joints used to seal: plug (6) into ends of inner stainless steel tube, phosphor–bronze hose to inner stainless steel tube, and connection to inner passage (3) at point passing through the heat exchanger end caps.
6. Plug located at each end of inner stainless steel tube.
7. Thin-wall (typically 0.025 cm) stainless steel tubes positioned inside and outside of the phosphor–bronze hose with dimensions providing a snug fit on either side of the convolutions.
8. Short slots near ends of the inner stainless steel tube to allow gas to pass from the connection tube (3) to the inner spiraling passage between the inner stainless steel tube and the phosphor–bronze convolutions.

**Fig 4-10. Construction details of counter-flow heat exchanger, which transfers heat from the incoming stream at high pressure to the exhausting stream at low pressure.**

The fixed JT valve replaced an adjustable JT valve used in the model 200 and model 210 Cryodynes®. The adjustable JT valve of those systems used a long tapered stainless-steel needle in an orifice that was about 0.089 cm in diameter. The tapered needle was moved through the orifice by a long shaft attached to an external micrometer drive mechanism at an ambient surface of

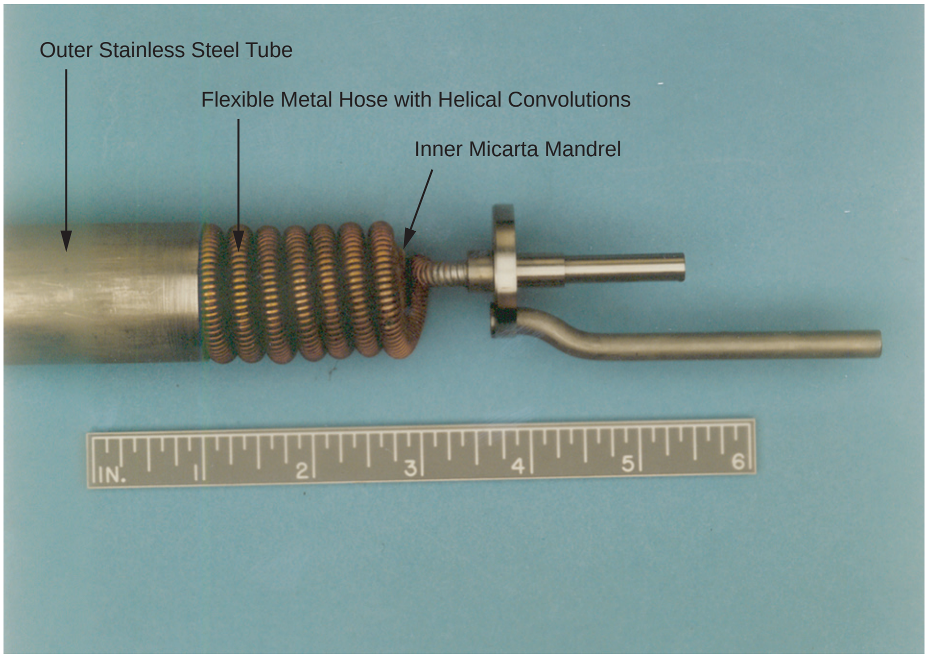



**FIg. 4-11. Improved counter-flow heat exchanger (low restriction) (partially disassembled view).**

the Cryodyne®. The micrometer adjustment for JT flow was manually controlled. High JT flow during CCR cool-downs was used to help to transfer heat from the final stage of the CCR to the upper stages. A manually controlled bypass valve sent the helium from the low-pressure side of the JT valve around the output passages of the second-, third-, and final-stage counter-flow heat exchangers. This arrangement required the attendance of an operator at the antenna-mounted assembly during the CCR cool-down process. Improper adjustments of the valves sometimes caused the cool-down process to fail.

The CCR final-stage temperature following a successful cool-down was dependent upon the JT flow because the vapor pressure at the final stage was dependant on the restriction through the low-pressure side of the counter-flow heat exchangers. Closing the JT valve reduced the JT flow and the final-stage temperature. Reducing the JT flow also reduced the final-stage refrigerator capacity. The temptation of lowering the final-stage temperature often induced an operator to close the JT valve completely. The sudden CCR warm-up that resulted could be remedied by opening the JT valve. Unfortunately, the stainless-steel needle sometimes stuck in the stainless-steel orifice. The galling effect of forcing the two stainless-steel surfaces together was like a welding process. Major surgery was required to repair several CCRs.

The combination of the fixed JT valve and the hydrogen-filled thermal bypass switch (also shown in insert b) eliminated the need for an adjustable JT valve and a bypass valve. The use of a wire in a capillary tube as a JT valve was suggested by automotive air conditioning specialist Richard W. Clauss.

Higa and Wiebe summarized the first ten years of the use of the JPL CCRs in a presentation at the Cryocooler Applications Conference (sponsored by the National Bureau of Standards in Boulder, Colorado in October 1977) with a presentation entitled, "One Million Hours at 4.5 Kelvin" [6]. Higa's team was responsible for all aspects of the TWM/CCR system. Higa's plan was to avoid controversies between specialized groups by having one group that was responsible for all the necessary technologies, including cryogenics, microwaves, ferrite isolators, quantum physics, crystallography, high-vacuum systems, power supplies, monitor and control equipment, and noise temperature measurements. The entire team learned about the whole system, not just individual areas of expertise. Higa's plan and approach were successful.

The team changed with time. Cancer caused Erv Wiebe to slow down in 1976 and Frank McCrea took over the task of producing the 4.5-K CCRs for the new Block II X-band masers. These masers were needed to reduce the system noise temperature of the DSN 64-m antennas for the upcoming Voyager-Saturn encounters in 1980 and 1981. Frank McCrea devised and patented a choked X-band (WR125) waveguide input assembly for coupling signals into a cryogenically cooled LNA. This device (U. S. Patent 4,215,327) [7] enabled cooling the input waveguide to the first-stage temperature near 70 K within a small fraction of a millimeter from the ambient vacuum window. Coaxial stainless-steel support tubes surrounding the cold copper waveguide were connected in cascade to provide a folded low-conduction path from the room-temperature vacuum housing to the cold side of the choke joint in the waveguide. The new low-noise waveguide input assembly provided the major part of a 7-K noise temperature reduction, enabling increased data rates from Voyagers I and II at Saturn in 1980 and 1981.

Walt Higa retired and Sam Petty, an experienced engineer and group leader, became the group's supervisor in 1981. Sam continued leading the team for another 24 years. Block II-A masers systems and cooled high-electron-mobility transistor (HEMT) systems were implemented to support Voyager encounters at Uranus and Neptune. A cooperative effort with the National Radio Astronomy Observatory (NRAO) in the mid-1980s resulted in the production of low-noise X-band HEMTs for use at the NRAO Very Large Array (VLA) during the Voyager-Neptune encounter. A variety of additional low-noise amplifier systems, cooled by 4.5-K JPL CCRs, 15-K GM CCRs, and dewars operating at 1.5 K and 1.8 K were implemented in the DSN between 1981 and 2006.

Cooperative maser and CCR work with Craig Moore and Howard Brown of the NRAO in the mid-1970s contributed to the development of improved masers and more powerful refrigerators. Mike Britcliffe and Ted Hanson continued this work, increasing the capacity of the 1-W 4.5-K JPL CCR to 2 W in the 1980s. The 1965 version of the CCR was modified by installing the improved heat exchanger design shown in Fig. 4-11 and increasing the JT flow to about 0.18 g/s. The details of the 2-W 4.5-K CCR and the compressor with greater capacity are reported in Telecommunication and Data Acquisition Progress Reports [8,9]. Britcliffe and Hanson also investigated and developed a prototype CCR system using two JT expansion stages, achieving 700-mW capacity at 2.5 K [10]. Figure 4-12 shows a simplified flow diagram of the "5-HP" (3.73-kW) compressor.

The concentric two-stage model 340 Cryodyne® developed by ADL and marketed in 1965 was originally referred to as a parametric amplifier (par-amp) cooler. Parametric amplifiers were used as LNAs during that time period and achieved fairly low-noise temperatures (near 50 K) when cooled to 15 K or 20 K. Use of the model 340, and later the model 350 Cryodynes®, in combination with a JT loop to provide cooling at 4.5 K was not anticipated by the staff at ADL who developed the concentric two-stage Cryodynes® (Fred F. Chellis, Walter H. Hogan, Robert W. Stuart, and others). Their unique and efficient design soon found far greater use in high-vacuum systems (cryo-pumps) than for cooling LNAs. Microwave field-effect transistors after 1975 and then high-electron-mobility-transistors (HEMTs) after 1983 showed significant performance improvements at cryogenic temperatures, and the two-stage Cryodynes® were used to cool transistor amplifiers in many radio-astronomy and space-communications facilities around the world. Implementation and operation of masers continued between 1975 and 1995 because of the low-noise temperature advantage during those years.

Emphasis on better reliability and lower costs after 1995 resulted in implementation of fewer maser systems and more HEMTs, taking advantage of commercially available two-stage GM CCRs. The simplicity of the two-stage concentric GM CCR became even more attractive after 1995 when superior regenerator materials enabled 4-K performance. The lead regenerator material had limited the useful minimum temperature of the second stage to about 15 K. James S. Shell of JPL purchased early models of the two-stage GM cycle 4-K CCRs built by Leybold Cryogenics North America (Hudson, New Hampshire) and by Sumitomo (Tokyo, Japan), beginning evaluations in February 1997. The Sumitomo two-stage 4-K CCRs were selected for use in the DSN. Operation of an X-band maser cooled by a commercially available two-stage Sumitomo SRDK-415 GM CCR was demonstrated [11]. A Sumitomo Heavy Industries two-stage GM CCR [12] was recently used at JPL to cool a dual-channel X-band HEMT to 6.5 K; the measured input noise temperature was 4.4 K at the ambient interface to the amplifier package [13].

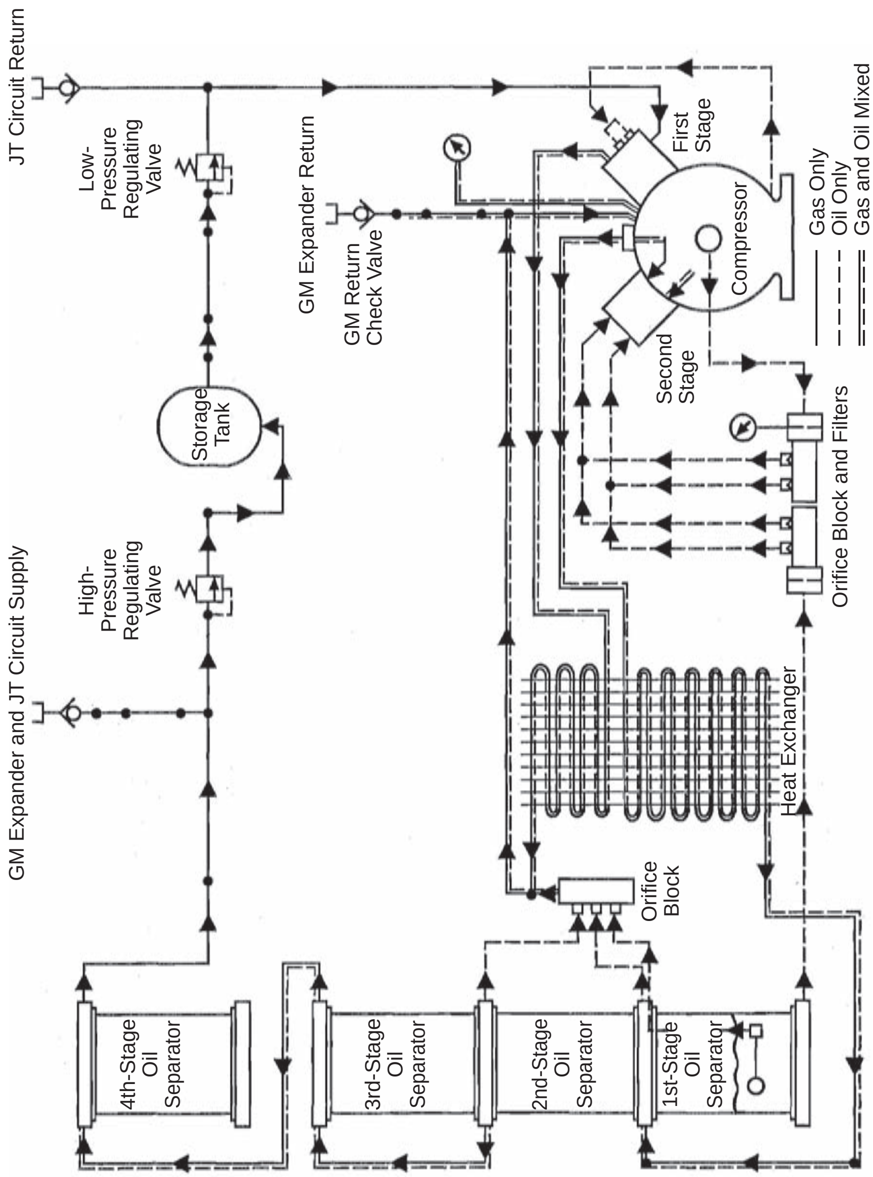



**Fig. 4-12. Simplified flow diagram of the "5-HP" (3.73-W) compressor. (This modified Freon® compressor draws about 7 kW electrical input power in this application.)**

## 4.7 Conclusion

Many at JPL contributed to the development of low-noise systems for the DSN. Robertson (Bob) Stevens was our section leader in 1959, then our division manager, and then the chief engineer for JPL's Telecommunications and Data Acquisition Office from 1979 to 1992. Bob would not let us give up on the goal of improving sensitivity through the reduction the DSN's system noise temperature, even if the reduction was only a fraction of a kelvin.

The development and use of cryogenic refrigeration systems for cooling LNAs and feed system components to improve the sensitivity of DSN receiving systems for deep space mission support was essential and cost effective. The development and implementation of even more advanced cryogenic systems is now practical and logical. Commercially available 4-K GM CCRs can be used to liquefy helium and to intercept heat leaks to a final stage at a temperature near 1.5 K. These advanced cryogenic refrigeration systems will enable the use of LNAs having noise temperatures within 1 K of the quantum limit at all DSN frequencies.

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