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4K REFRIGERATORS WITH A NEW COMPACT HEAT EXCHANGER

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ABSTRACT

Two refrigerators have been developed which have nominal capacities of 0.25W and 0.5W at 4.2K. These use standard two stage Displex[R] expanders and compressors combined with a new compact heat exchanger which is concentric with the expander cylinder.

These refrigerators can be used to cool superconducting electronic devices by direct attachment to the 4K heat station, or they can be plugged into the neck of a liquid helium superconducting magnet cryostat where they can cool the radiation shields and reliquefy helium.

Key Words: Compact heat exchanger; cryogenic refrigerator; helium recondenser; superconducting electronics; superconducting magnet

1. Introduction

The use of superconducting magnets for Magnetic Resonance Imaging (MRI) represents the first major commercial application of superconductivity. The magnets presently in use utilize liquid cryogens, helium and nitrogen; however, a number of options for cooling magnets using small refrigerators or liquefiers have been studied [1]. The approach to cooling a superconducting magnet which is the size of an MRI magnet that appears most promising to the authors is to have a multistage refrigerator mounted integrally into the magnet cryostat. This refrigerator will fit into the neck of the cryostat, cool one or two radiation shields, and recondense the helium. This approach has the advantage that heat is removed from the system very close to the point where it enters the system, thus avoiding additional thermal losses associated with transferring refrigeration from a remote liquefier and minimizing temperature drops between the cryostat and refrigerator. The Japanese National Railway in evaluating refrigerators for their magnetically levitated train program recently concluded that multiple Stirling plus J-T cycle coolers are less efficient than one central Claude cycle refrigerator, but the losses in the cryogenic transfer system add so much to the refrigeration requirement of the Claude cycle system that it consumes more power than multiple Stirling plus J-T coolers. They have thus decided to use individual Stirling plus J-T cycle refrigerators mounted in each magnet cyrostat [2].

The most widely used small 4K refrigerators today consist of a two-stage Gifford McMahon type expander with a J-T exchanger [3,4]. These units utilize rather long and bulky finned tube or corrugated tube heat exchangers for the J-T loop, making them difficult to install in the neck of a helium cryostat. These systems would also have thermal losses due to convective heat transfer between the heat exchangers, the expander, and the neck tube.

Recognizing the potential need for a heat exchanger which would fit compactly in the annular space around a two-stage GM type expander cylinder and which would match the temperature gradient in the cylinder, a program was initiated to study heat exchanger designs that would be suitable for this application. This led to an experimental program to test the newly designed heat exchangers by utilizing them in a nominal 0.25 W and a 0.5 W 4K refrigerator. The experimental program also included studies of heat station design, interaction of the refrigerator with magnetic fields, servicing the refrigerator and control of contaminants. This paper describes the results of this work.

2. Design Description

The two units which have been built and tested are designated as a CS302 and a CS304 with nominal capacities at 4K of 0.25 W and 0.5 W, respectively; they consist of standard Displex[R] refrigerators having 20K capacities of 2 W and 6 W, respectively. A J-T heat exchanger and a second slightly modified standard compressor for the J-T return flow are added to provide the 4K refrigeration.

After studying many heat exchanger designs and experimenting with different fabrication techniques, we elected to utilize a heat exchanger design which consists of multiple high and low pressure tubes in a close contact, coiled configuration. The heat exchanger is continuous from 4K to 300K and is coiled around the expander cylinder in such a way that the temperature in the heat exchanger matches the temperature in the adjacent cylinder. It is thermally bonded to the cylinder at the two heat stations. Adsorbers are installed at the inlet to the heat exchanger and just upstream of the J-T orifice.

Figure 1 shows the essential features of the 0.5 W expander which is designed to fit into the neck of a helium cryostat. A plug at the 20K heat station is designed to fit snugly into a mating receptacle in the neck tube to cool a radiation shield. For cryostats which use liquid nitrogen to cool a shield at 77K, a heat station on the first stage of the refrigerator is unnecessary. The 4K heat station consists of a finned tube which serves to recondense helium boil-off.

The 0.25 W unit which we built is designed to be operated in a vacuum. It has a warm heat station to which a radiation shield can be attached and a 4K heat station for conductively cooling a device and/or instrumentation. This unit has a very small pneumatically actuated J-T valve which permits high J-T flow rates to be maintained during cooldown and adjustment of the operating temperature with maximum capacity when cold.

The adjustable J-T valve is convenient for a research worker who can set it manually but is difficult to automate. A fixed J-T orifice is used in the 0.5W unit. The flow rate is quite low when the helium is warm so cool-down of the 4K heat station is prolonged when the unit is run in a vacuum. This does not matter when the unit is plugged into a cryostat with helium in it because some venting helium cools it quickly. Temperature is set by means of a pressure regulator which controls J-T return pressure. Flow through the fixed orifice is constant so for any pressure above the minimum design pressure, the regulator bypasses the excess flow in the low pressure compressor.

The CS304 unit shown in Figure 1 incorporates several features that facilitate installing and removing it from the neck of a helium cryostat. Guide sleeves are mounted on the valve motor housing which slide over rods that keep the refrigerator centered as it is raised or lowered. A radial "O" ring seal on a short skirt at the warm end allows for axial contraction while maintaining good thermal contact at the 20K heat station. The warm end skirt is also used to tie on an elastomer sleeve which prevents air from getting into the neck tube when the refrigerator is removed to be serviced.

3. Experimental Program

3.1 Refrigeration Capacity

Both size expanders were built with pressure taps just upstream of the orifice in order to monitor contaminant freeze out in the heat exchanger, and temperature sensors on each stage of the refrigerator. Heaters were added as required for specific tests. The capacity of each refrigerator was measured by mounting it in a vacuum pot and wrapping it with six to ten layers of aluminized mylar.

Figure 2 shows the relationship between temperature and heat load applied to the 4K heat station for different settings of the J-T valve in the CS302. This test was run with no heat loads applied to the upper two stages; however, the second stage can carry about 0.5W and the first stage, about 5W without seriously reducing the refrigeration available at the third (4K) stage. Radiation and instrument lead conduction are estimated to impose an additional 100mW heat load on the third stage. A radiation shield attached to the first stage would thus make more refrigeration available at 4K.

Temperature at the 4K heat station is set primarily by the pressure at which the helium leaving the J-T valve is evaporating. Closing the J-T valve reduces the helium flow rate and the compressor return pressure drops. The slight increase in temperature with load is due to an increase in heat transfer between the surface of the heat station and the evaporating liquid as the heat load is increased. At sufficiently high heatloads all of the liquid produced is evaporated and the gas stream itself is heated. A J-T unit has the characteristic that the refrigeration produced drops rapidly when the maximum capacity is exceeded because the flow rate drops as the temperature of the gas flowing through the J-T valve increases.

Figure 3 shows the interrelationship between the refrigeration available at the three heat stations for the CS304 unit. This data was obtained by setting heat loads on the first and second stages and increasing the heat load on the third stage until the unit warmed up. An example of how to interpret Figure 3 is that a load of 15W on the first stage, 3 watts on the second stage and from 0 to 0.5 W on the third stage results in temperatures of 80K and 16K on the first and second stages respectively. The third stage capacity is available over a temperature range of about 3.9 to 4.5K depending on the setting of the pressure regulator.

3.2 Heat Exchanger Performance

Heat exchanger efficiency was measured by adding differential thermocouples (iron doped gold vs. chromel) to the warm ends of each section of the heat exchanger. Figure 4 plots the data in dimensionless heat transfer and pumping energy after Kays and London Fig. 24 [5]. It is seen that the heat exchanger has higher heat transfer efficiency for a given pumping energy than typical plate fin heat exchangers.

3.3 Magnetic Effects

Studies were made of the effect of operating in magnetic fields in terms of the effect of the fields on the refrigerator expander and the effect of the expander on the homogeneity of the field. It was found that the valve motor can only operate satisfactorily in fields of 0.08T and that the 1Kg of iron in the valve motor contributes the only significant amount of inhomogenity to the field [6].

3.4 Test Cryostat

A double-walled cryostat was built for the CS304 which simulates the neck tube of a large liquid helium cryostat and has room to accumulate 1L of liquid. It has an 89mm (3.5") bore and a second stage receptacle to mate with the tapered plug on the second stage of the refrigerator. It has no first stage heat station. This cryostat was used to measure heat transfer characteristics of the second stage thermal coupling, temperature stability, serviceability and long-term operation.

3.5 Cool Down

Figure 5 shows the cool down data collected and plotted on an HP3497/HP87 data acquisition/computer system for the CS304 in the double-walled cryostat. The temperature scale is folded at 30K so the second and third stage temperatures show scale changes at 30K. The first and second stages cool down relatively fast, but the third stage takes a long time because of the thermal mass of the test pot, the cooling of the 1L volume of helium (which is maintained at 1.1 atm pressure), and the low flow rate of helium in the J-T loop during most of the cool down. When operating in a vacuum with no applied heat loads or extra mass attached both refrigerators reach 4.2K in 4 hours.

3.6 Temperature Stability

Despite the lack of a precooling heat exchangers on the CS304 first and second stages the unit condenses 1L of helium overnight. After accumulating liquid in the pot, the feed valve is closed and pressure in the cryostat monitored. Over a period of a week the cryostat pressure is typically maintained in the pressure range of 700 to 720 Torr. Most of the variation is due to changes in barometric pressure which is normally 760 Torr.

3.7 Thermal Coupling

Studies of the heat transfer characteristics of the thermal coupling showed that heat is transferred primarily by gas conduction in the gap and metal-to-metal contact contributes only a small amount. The weight of the refrigerator is sufficient to maintain good contact. A temperature of 1.1K was measured for a heat load of 3W at 16K.

3.8 Serviceability

The refrigerator is designed to be easily serviced. During the testing phases, the refrigerator was removed from the cryostat and reinstalled a number of times to demonstrate that this procedure could be accomplished with no undo problems (such as air inclusion, ice, etc.), as well as to establish service instruction data. On one occasion, for example, the refrigerator was removed using the flexible sleeve to preclude air in-leakage, and warmed to room temperature, a different size J-T orifice was installed, the J-T heat exchanger was purged, and reinstalled in the cryostat in 45 minutes. The unit cooled back to 20K before the last of the 1L liquid helium evaporated.

3.9 Reliability

In order to assure long-term reliability, a considerable effort was expended to determine the most efficient means to clean up the system initially and keep it clean, in order to avoid accumulating contaminants in the gas stream which could have the potential to block the J-T heat exchanger. After initial experimentation, the last 9,000 hours of cumulative operation on several CS304 units, most of it at subatmospheric pressure, have resulted in no indications of contaminant freeze out in these systems.

4. Summary

Compact 4K refrigerators have been developed and tested, primarily to be utilized in superconducting magnet and electronic applications. A simple compact J-T heat exchanger, has been developed which can be mounted on a two-stage G-M type refrigerator, providing a small, efficient, three-stage machine. Extensive testing has been completed on initial prototype and preproduction machines, which has included in-house performance and life testing. Field testing has included the successful cooling of the cold radiation shield and recondensing the helium in an MRI magnet and cooling of a small superconducting electronic device.

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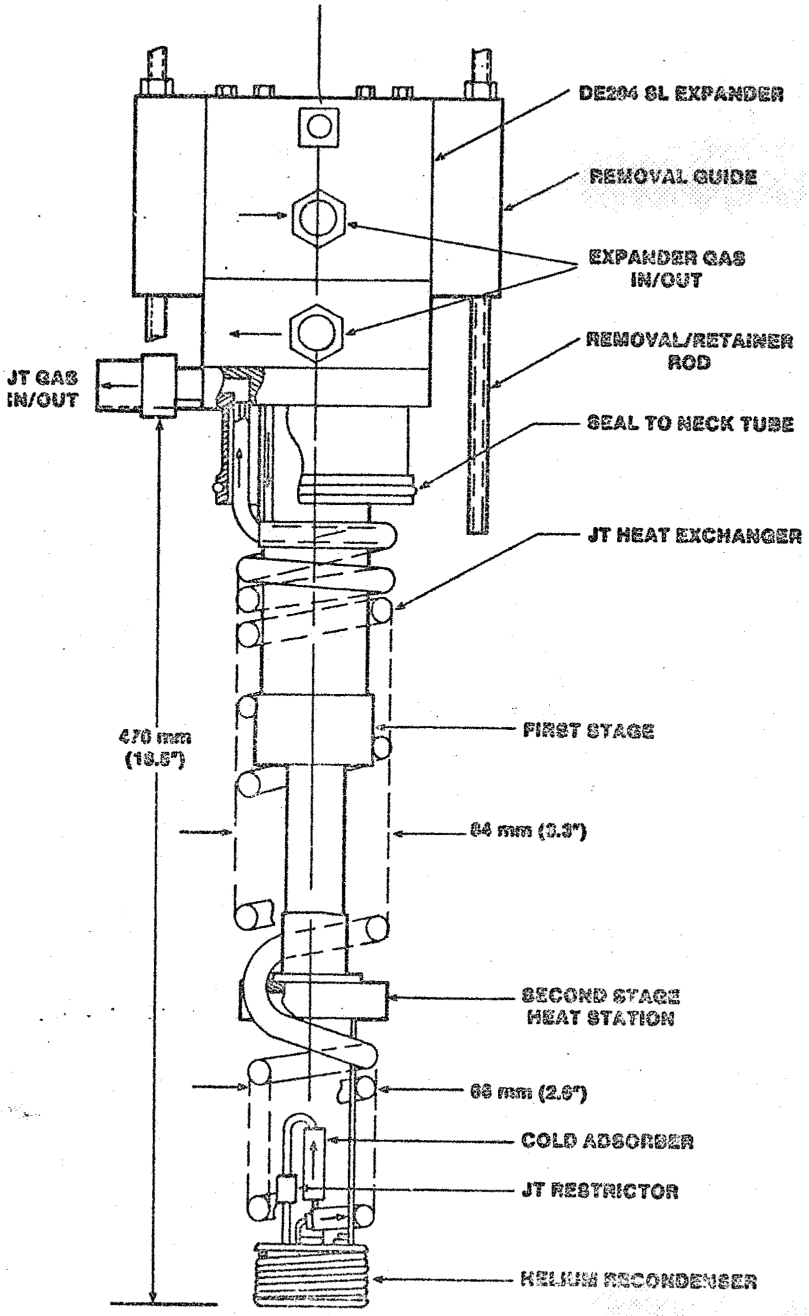

Figure 1. CS304 Refrigerator, Two Stage Expander with Concentric Spiral J-T Heat Exchanger

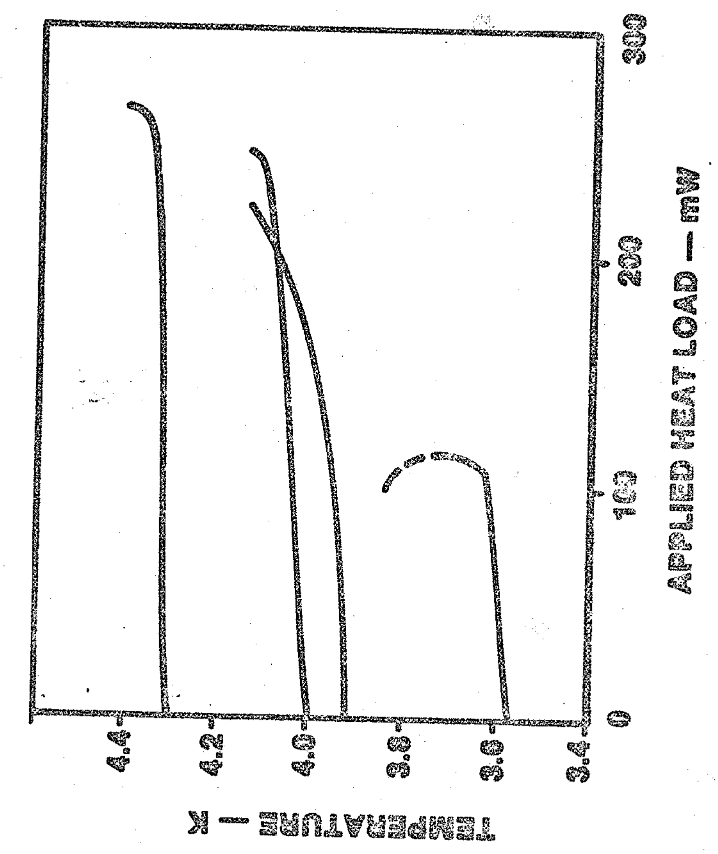

Figure 2. Temperature vs. Applied Load on CS302 for Different Settings of the J-T Valve

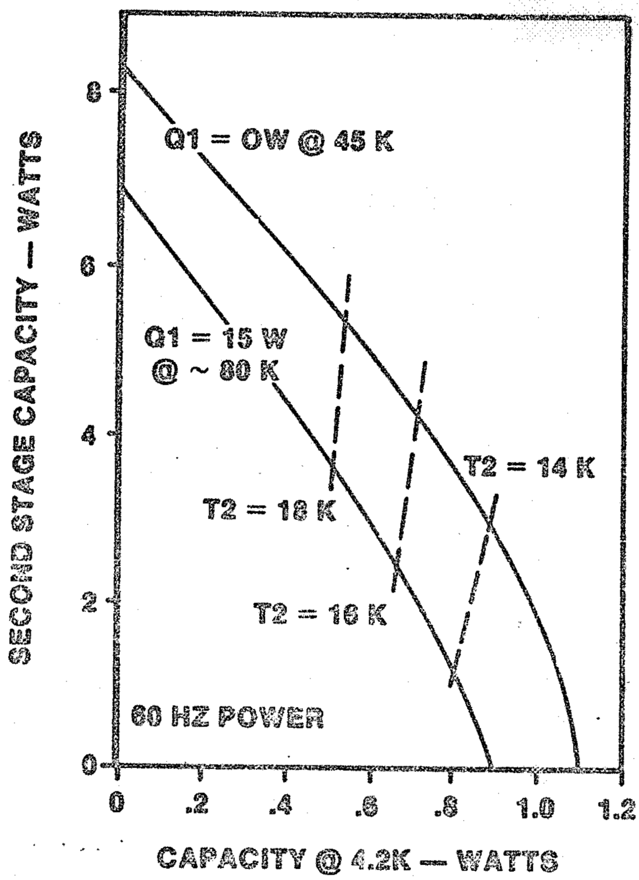

Figure 3. CS304 Maximum Refrigeration Capacity @ 4.2 K vs. First and Second Stage Heat Loads

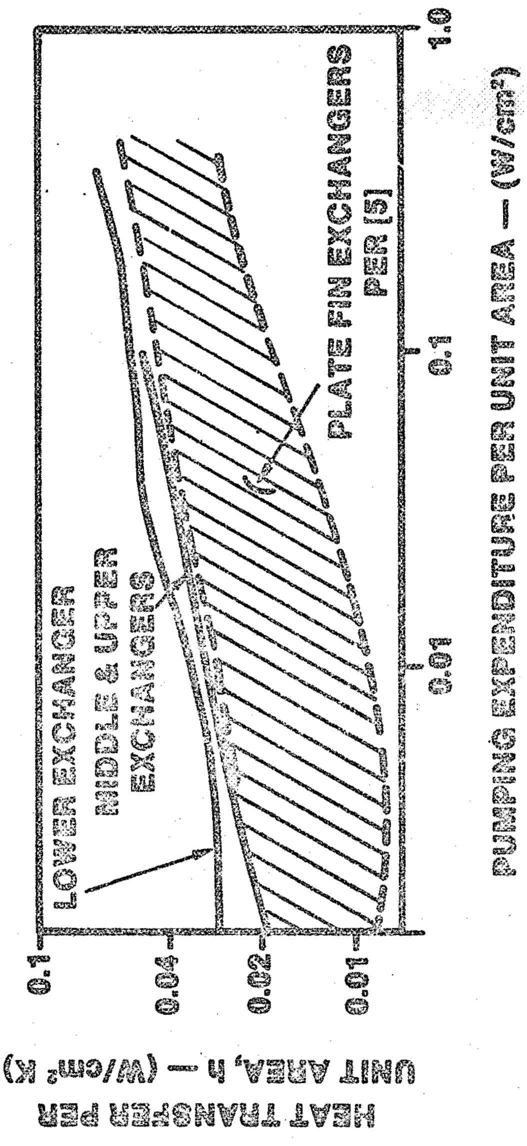

Figure 4. Heat Transfer Coefficient, h. vs. Flow Friction Energy Loss Per Unit Area for APCI Coiled Tube J-T Heat Exchanger and Typical Plate F in Surfaces

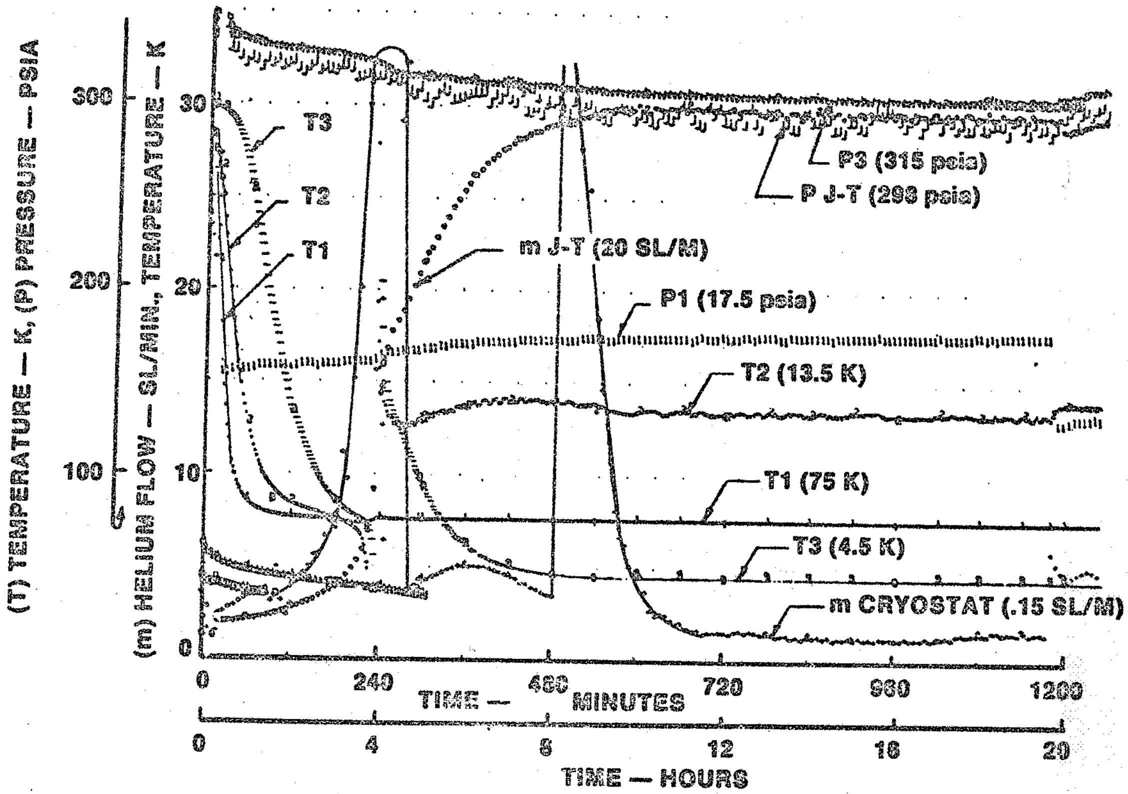

Figure 5. Cooldown of CS304 .5 W 4 K Refrigerator with Experimental Heat Exchanger in Helium Filled Cryostat