Concepts for Cooling Small Superconducting Devices Using Closed-Cycle Regenerative Refrigerators

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The use of regenerative type refrigerators to cool small superconducting devices requires solving the following problems:

. difficulty of cooling below 10K
. isolation of the refrigerator vibration
. cooling by conduction rather than liquid or gas
. maintaining constant temperature

Air Products and Chemicals, Inc. as a manufacturer of small regenerative type cryocoolers, JT coolers, helium transfer cryostats, and small helium liquefiers which are sold for use in laboratory research, has had appreciable experience in solving many of these problems. This paper describes some of the concepts that have been developed which include:

. three stage regenerator type cryocoolers for 7K operation
. 4.2K JT loop attached to 10K cryocooler
. refrigerated helium dewars with low boiloff rates
. flexible low loss helium transfer lines
. convective gas heat transfer to isolate vibration
. temperature cycle attenuators
. automatic temperature controllers.

In addition, the characteristics of the Air Products' modified Solvay cycle cryogenic refrigerator are described.

Key words: Helium dewar; JT loop, regenerative cryocooler; temperature control; three stages; two stages; vibration isolation.

1. Introduction

Most of the research work done to date on superconducting devices has utilized liquid helium as a refrigerant. Liquid helium has the characteristics of providing a constant temperature independent of heat load at its boiling temperature of about 4.2K, and an absence of vibration. Good heat transfer is obtained by immersing the object being cooled directly in the liquid or surrounding it with cold gas. Flexibility of orientation and portability are possible by using small light weight dewars that can hold enough liquid helium to operate for several hours or days.

In order to reduce the operating cost and eliminate the need for handling liquid helium, closed-cycle refrigeration will be required as superconducting devices move from the research laboratory to commercial applications. Claude cycle refrigerator/liquefiers are most commonly used for producing the liquid helium used today and some small units built by Air Products and Chemicals, Inc. are in use as Maser coolers [1]; however, most of the small closed-cycle cryogenic coolers presently in use are of the regenerative type operating on cycles related to the Stirling or Solvay cycles. They are used for applications above 10K, because they have proven to be most economical and reliable for long term operation.

When closed-cycle regenerative type refrigerators are used, then one must consider the following:

. operation at temperatures above 4.2K
. temperature control (short and long term)
. refrigerator vibration
. heat transfer mechanism to refrigerator
. size of refrigerator
. need for electrical power and heat rejection

Many of these problems have been addressed in adapting regenerative cryocoolers to a wide range of applications. The concepts that have been employed in solving these problems are described in this paper. These concepts can be considered to be the building blocks that are presently available to utilize regenerative cryocoolers in cooling new small superconducting devices. The paper also describes the characteristics of the refrigerators manufactured by Air Products and Chemicals, Inc.

2. Two Stage Displex[R] Refrigerator

Figure 1 is a photograph of the CS-202 Displex refrigerator [2] which consists of the expander, separate compressor, and interconnecting gas and electrical lines. The helium compressor is a modified oil lubricated air conditioning compressor with an oil removal system which includes an adsorber.

The expander, which is shown disassembled in Figure 2, produces refrigeration by a modified Solvay cycle. It consists of a two-stage displacer with regenerator heat exchangers packed inside the displacer body. Pressure cycling is set by a rotary valve disc which sets the cycle rate at 144 rpm on 60 cycle power. Piston motion is controlled by a pneumatic dash pot which also dissipates the work energy produced in the refrigeration cycle. It is the lack of mechanical linkages that enables long life and high reliability to be achieved. The cycle timing is such that the unit runs smoothly and is quiet; however, the reciprocating inertia of the piston must be considered in applications that are extremely sensitive to vibration. Recommended maintenance consists of changing the expander piston seals and valve disc, and compressor adsorber at 9,000 hour intervals.

Figure 3 is a curve showing the cooling capacity of the CS-202 refrigerator. If the refrigerator is operating in a vacuum with no heat load, the first stage will operate at about 35 K and the second stage at just under 10 K. The rated capacity of the unit is two watts at 20 K plus seven watts at 77 K. As the curve shows, there is a slight influence of the first stage heat load on the second stage temperature for first stage temperatures below 80 K. Temperatures above 80 K cause a significant reduction in second stage performance.

Two larger refrigerators are also presently available. The CS-208L has a capacity of ten watts at 20 K and the CS-227 has a capacity of fifty watts at 20 K. It is possible to operate a multiplicity of small expanders with one of the larger compressors.

3. Minimum Temperature of Regenerative Type Refrigerator

Work on reducing the minimum temperature of regenerative type refrigerators has followed several paths. Work on optimizing the design of a conventional lead shot regenerator and the cold end heat exchanger was pursued by Gifford [3] which resulted in a temperature of 6.8K being achieved on a two stage Gifford-McMahon unit.

Several efforts have been directed at improving the thermal storage capacity of the regenerator matrix. The use of rare earth materials has been studied by Moore [4]. Fleming [5] considered using helium adsorbed on charcoal, stored in small glass spheres, and stored in a surrounding cylinder. The third concept was tried on a Gifford-McMahon unit which operated at 7.6K vs. 7.7K with standard lead shot.

The most successful efforts to reduce the minimum temperature have consisted of adding a third stage of expansion. Stuart et. al. [6] reported a temperature of 6.5K in a Gifford -McMahon cycle unit. Daniels and duPre [7] reported on testing of a three stage Stirling cycle unit with three different regenerator materials. A temperature of 9.0K was reached with a conventional lead regenerator, 8.5K was reached with charcoal, and 7.8K was reached with europium sulfide. Daniels and DuPre expressed the opinion that the higher pressure ratio at which the Gifford-McMahon (and Solvay) cycle units typically operate compared with Stirling cycle units accounts for their lower temperatures. Cowans [8] built a three stage Vuilleumier Cycle refrigerator with a stored helium regenerator; however, internal leaks prevented successful operation.

There has been essentially no commercial market to date for small 7K refrigerators; thus it is premature to say which if any of the approaches that have been tried is best.

Certainly there is room for improvement in terms of minimum temperature and efficiency. It is unlikely that the efficiency of regenerative type refrigerators near their minimum temperature will be as good as Brayton cycle machines; thus their use will be limited to applications that require less than a few watts at temperatures below 10K.

4. 4.3K JT Loop

Figure 4 is a flow sheet of the Model CS-308 presently being built by Air Products and Chemicals, Inc. which shows a helium JT (Joule-Thomson) loop which is precooled by a CS-208L expander that produces 10W @ 20K plus 30W @ 77K. In addition to providing refrigeration at 4.3K, it has the advantage of having a stream of cold gas which can be used to transport the refrigeration that is available at each temperature level to remote points where it can intercept heat leak. This feature can also be used to separate the refrigerator from the object being cooled by transferring the cold gas through a flexible vacuum jacketed transfer line, thus helping to isolate the vibration inherent in the refrigerator.

The compressor that supplies gas to the cold end is a multi cylinder oil lubricated air conditioning compressor. One cylinder compresses the JT return flow from 15 psia to 75 psia where it joins the return from the expander to be compressed to 275 psia.

The Jet Propulsion Laboratory has been operating 1 watt 4.3K systems similar to this for more than ten years with a very good record of reliability. It is hoped that W. Higa, who is scheduled to attend this meeting, will give an updated report on their experience.

5. Other Cold Stages

Other methods of bridging the gap from the 15K temperature level where regenerative type coolers have reasonable efficiency to 4.2K that have been or are being tried are Simon Cooling and Dielectric refrigeration. Gifford et. al. [9] reported on a Simon expansion device used with a Gifford-McMahon cycle refrigerator that produced about .25 L of liquid helium after precooling gas at about 2,500 psi to less than 12K. This produces liquid in batches, but presumably a dual system could provide continuous refrigeration. From a manufacturing standpoint it does not appear as attractive as the JT loop because of the switching mechanisms required and because another high pressure stage of compression is required.

Development of a Dielectric cold stage was initiated by Lawless [10] and work continues today at Los Alamos. It is hoped that W. A. Steyert will give a report on this work during the present meeting.

6. Refrigerated Helium Dewar

Figure 5 is a schematic drawing showing a two stage Displex refrigerator mounted on a helium dewar to reduce the boiloff rate [11]. A dewar similar to this but with a warm bore tube extending all the way through and having the refrigerator direct mounted was built and tested. With six 30 Ga instrument leads in one of the neck tubes the boiloff rate was 10.1 ml liquid/hr. When the wires were removed the boiloff rate dropped to 3.8 ml liquid/hr, which enabled the customer to operate for more than ten months before adding more liquid helium.

During the test program it was demonstrated that the expander piston could be removed from the cold cylinder, serviced, and reinstalled without warming the piston. A total of 50 ml of liquid helium vented as a result.

This concept is most attractive for applications where there is no heat generated at 4.2K and where there are no lead wires to the liquid helium. If the heat loss at 4.2K is more than a few mw, then the boiloff rate of helium is high enough that the sensible heat intercepts heat leak and the refrigerator is not needed.

In addition to providing a constant temperature bath, the liquid helium dewar has the advantage of having an inventory of stored refrigeration. If a cold stage is added to a regenerative machine such as a JT loop that is cold enough to recondense the helium, then one can combine the advantages of liquid helium with those of a closed-cycle refrigerator and, at the same time, have built in a high degree of reliability.

7. Vibration Isolation

Some low temperature devices are sensitive to the vibration of regenerative coolers which all have reciprocating displacers. Figure 6 is a photograph of a Heli-Tran[R] refrigerator unit which has a flexible helium transfer line [12], [13]. By having part of the helium stream make a return pass through the transfer line to intercept heat leak, it is possible to maintain 4.2K with less than 1 L/hr liquid helium consumption. The technologies of this transfer line can be used to transfer refrigeration in a closed-cycle cooler and, at the same time, provide vibration isolation.

A second concept for isolating vibration is shown in Figures 5 and 7. The unit shown in Figure 7 has been successfully used to conduct Mossbauer experiments at 10K. The principal that is employed is to mount the refrigerator on a separate base from the cryostat and thermally couple the two with a cold helium gas convective circulation loop [14]. There is a loss of about 25% of the refrigeration produced with a modest sized heat exchange loop.

Figure 8 is a drawing of a gas well cooled by a two stage Displex refrigerator which is used with a Faraday balance. The cold gas provides good heat transfer while keeping the object being cooled both mechanically and electrically isolated from the refrigerator.

8. Temperature Control

Temperature fluctuations in a regenerative cycle cooler are both short term and long term. The short term cycle corresponds to the reciprocating rate of the expander, 144 rpm on 60 Hz and 120 rpm for 50 Hz power for the Displex refrigerator. The low specific heats of the refrigerator materials at 10K result in a temperature change of about 1K each cycle at the refrigerator cold tip. Long term temperature changes are due to changes in heat load, ambient temperature, and wear of the refrigerator. Experience has shown that refrigerator wear results in temperature changes of several tenths of a degree within recommended maintenance intervals.

Two adapters have been developed to reduce short term temperature cycle. A one inch long rod of pure lead attenuates the fluctuation at 10K by a factor of 10. This has the desirable characteristic of having a very high thermal conductivity, but it has the disadvantage of adding 30 minutes to the cooldown time of the refrigerator. The second adapter that has been developed is multiple layers of indium and mylar. This is compact and has a relatively small thermal mass. It reduces the short term temperature cycle at 10K to about .005K, but one pays the penalty of losing half the refrigeration that is produced at temperature between 10K and 20K.

Control of temperature over a long period of time requires an active temperature controller. Most commonly used is one which employs Au .07% Fe vs. Kp thermocouple and has a 24 hour stability rating of $\pm$ 0.2K. For more precise requirements silicone diode sensors are commonly used in conjunction with a controller that has a 24 hour stability of $\pm$ .02K.

For applications which use the JT loop, the temperature can be controlled by regulating the vapor pressure. A controller of this type with vacuum as an absolute pressure reference has been successfully employed to maintain a stability of $\pm$ .01K at 3.9K to 4.2K in the small Claude cycle Maser coolers built by Air Products and Chemicals, Inc. [1].

9. Summary

The task of matching a refrigeration system with a given application starts with understanding the requirements of the application and the characteristics of available refrigeration systems. It is hoped that this paper will help potential users of closed-cycle regenerative coolers to generate a list of requirements and, at the same time, suggest the concepts that are presently available to solve certain problems.

In the long run the best refrigeration system for a given application is the one that meets performance and reliability requirements at minimum capital and operating cost.

10. References

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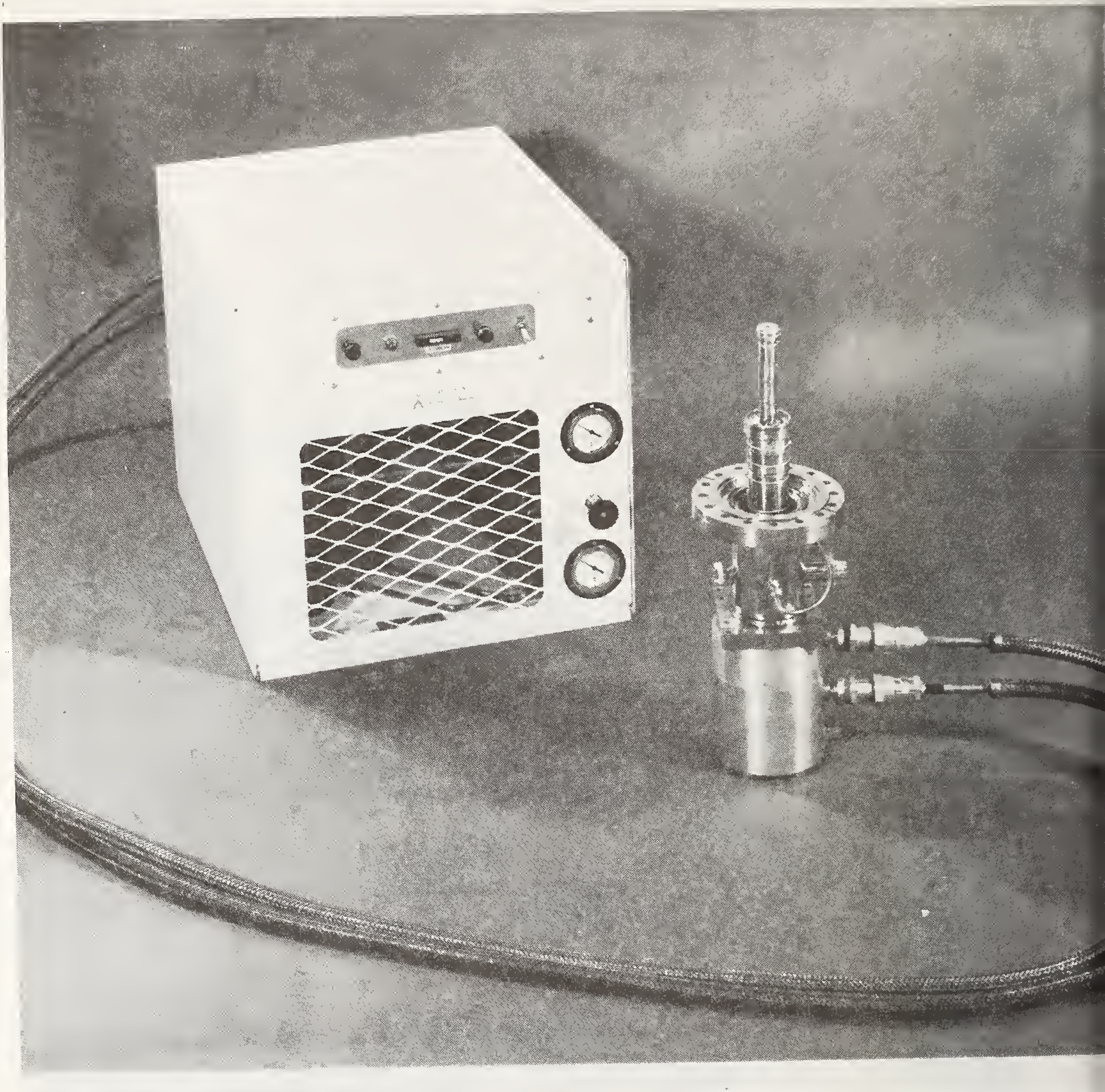


Figure 1. CS202 Displex Refrigerator

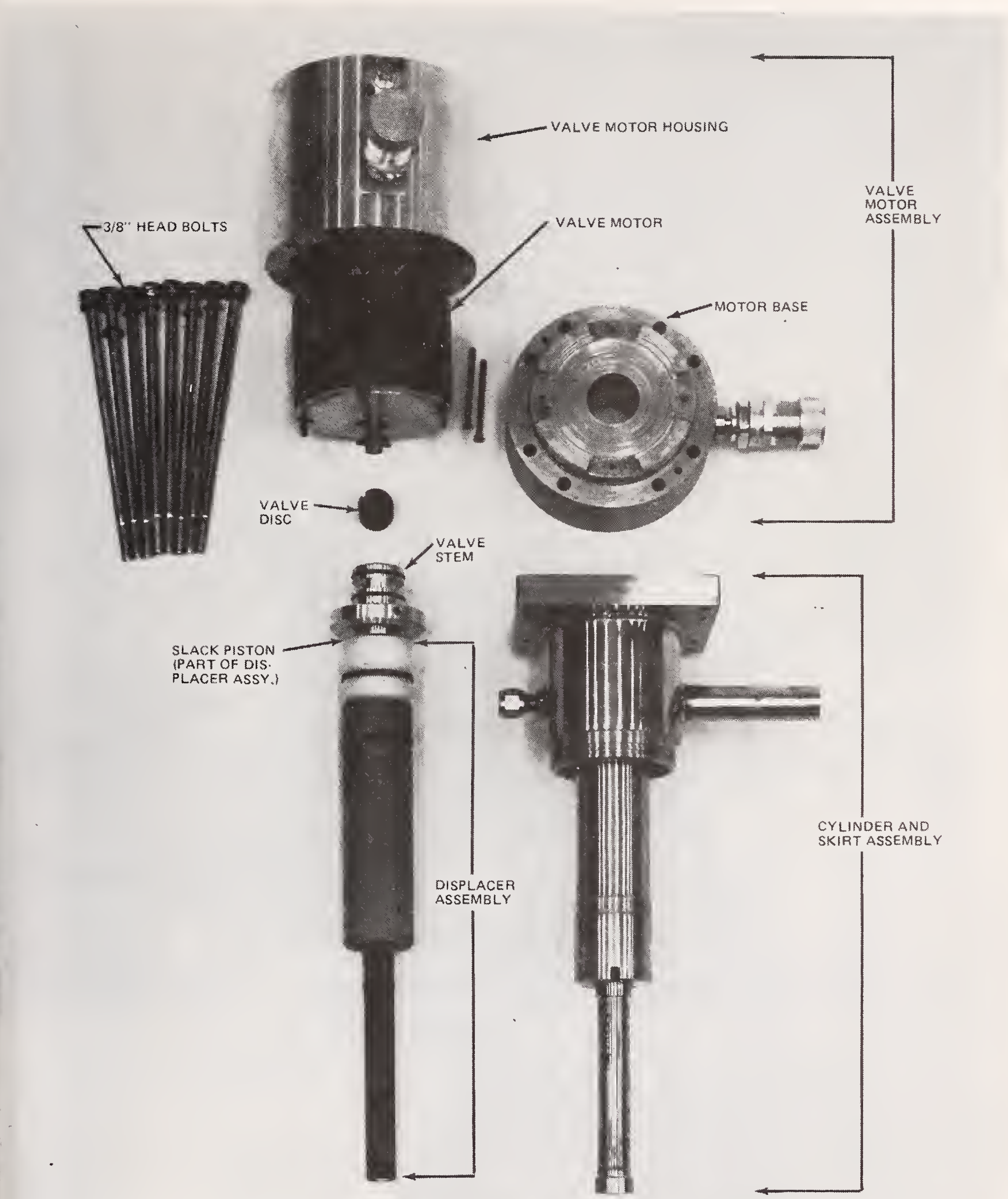


Figure 2. CS202 Expander Components

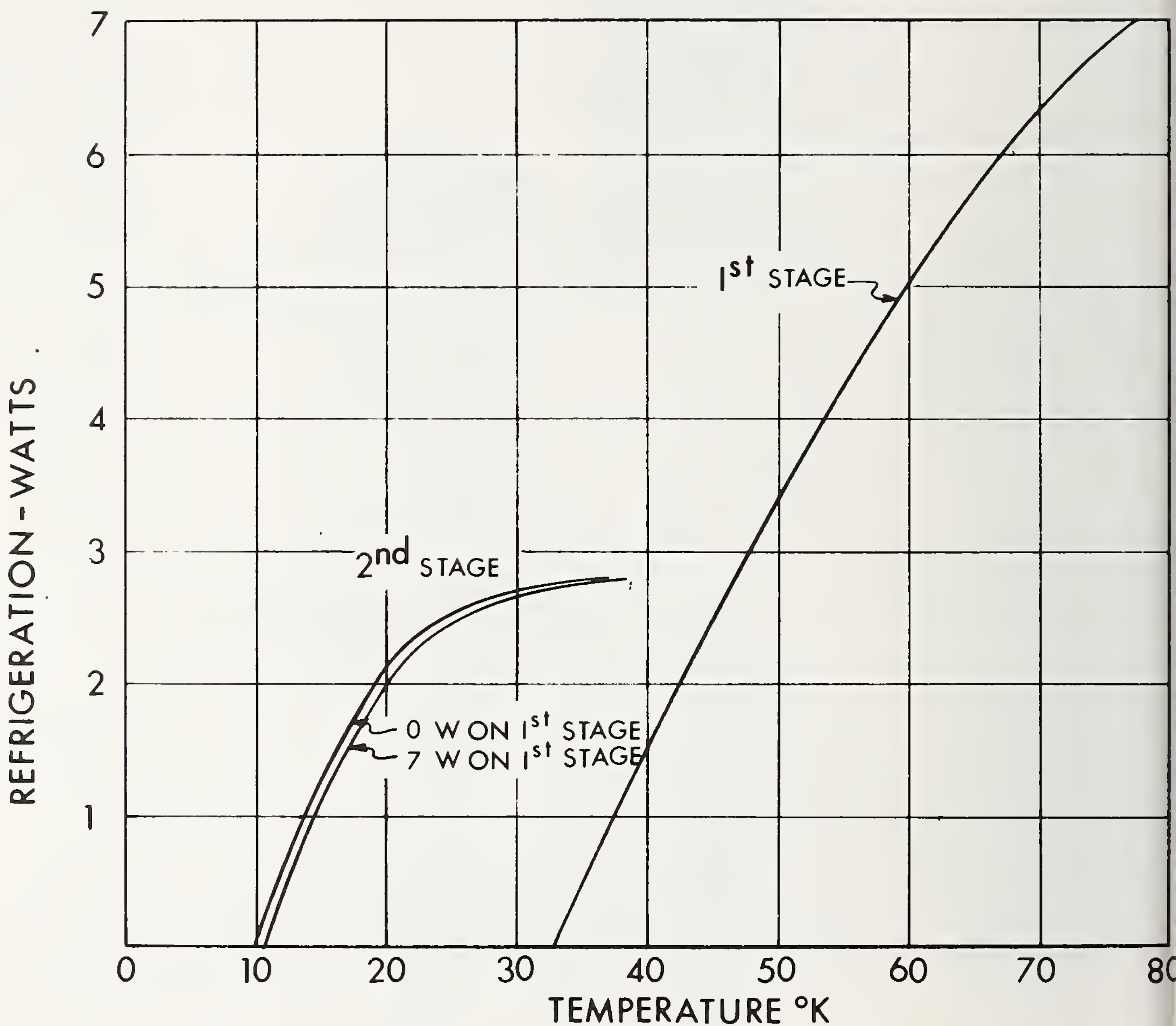


Figure 3. CS202 Refrigeration Capacity Vs Temperature.

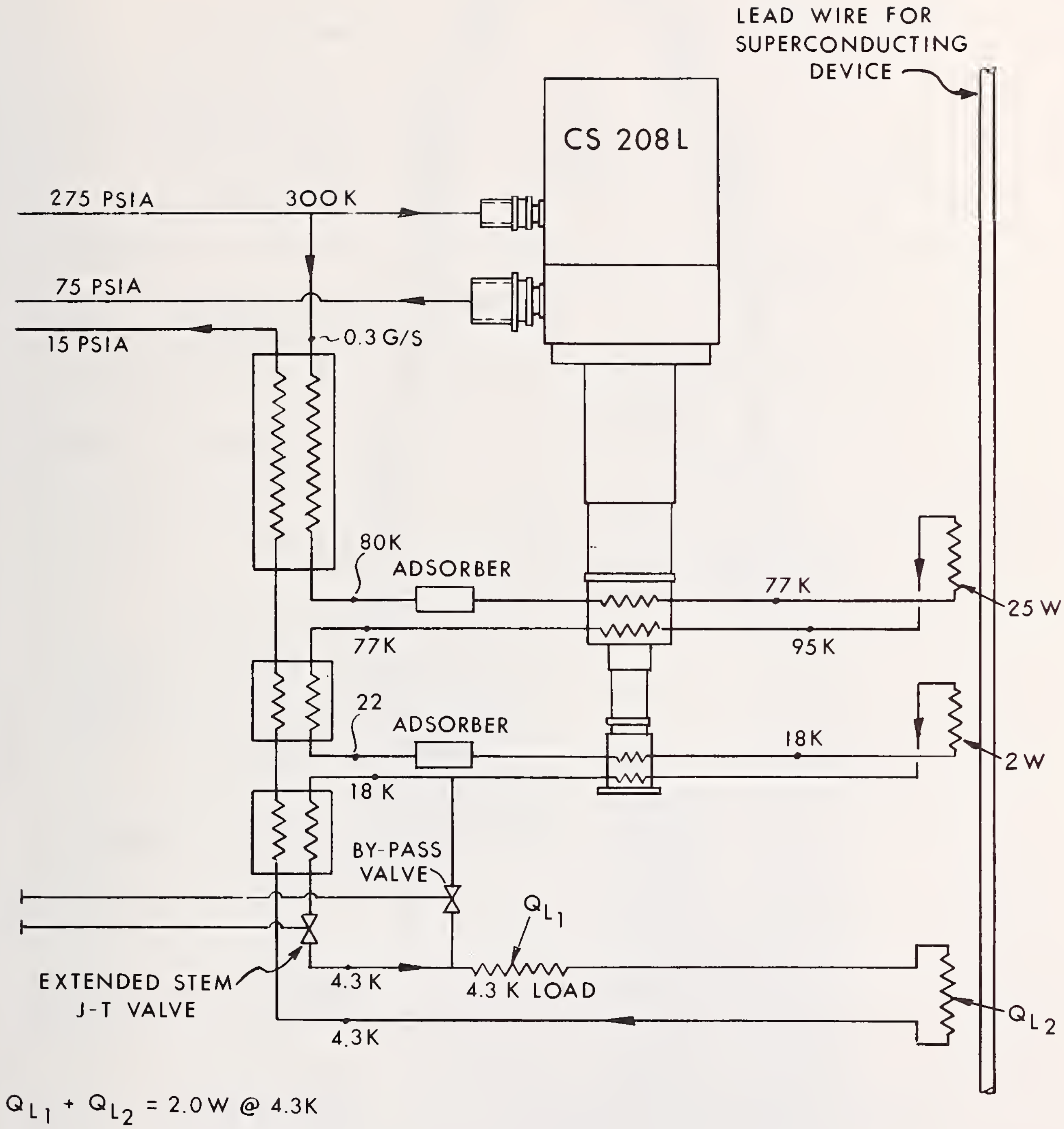


Figure 4. Flow Schematic of Two-Stage Displex Refrigerator with 4.3 K. JT Loop, Model CS-308

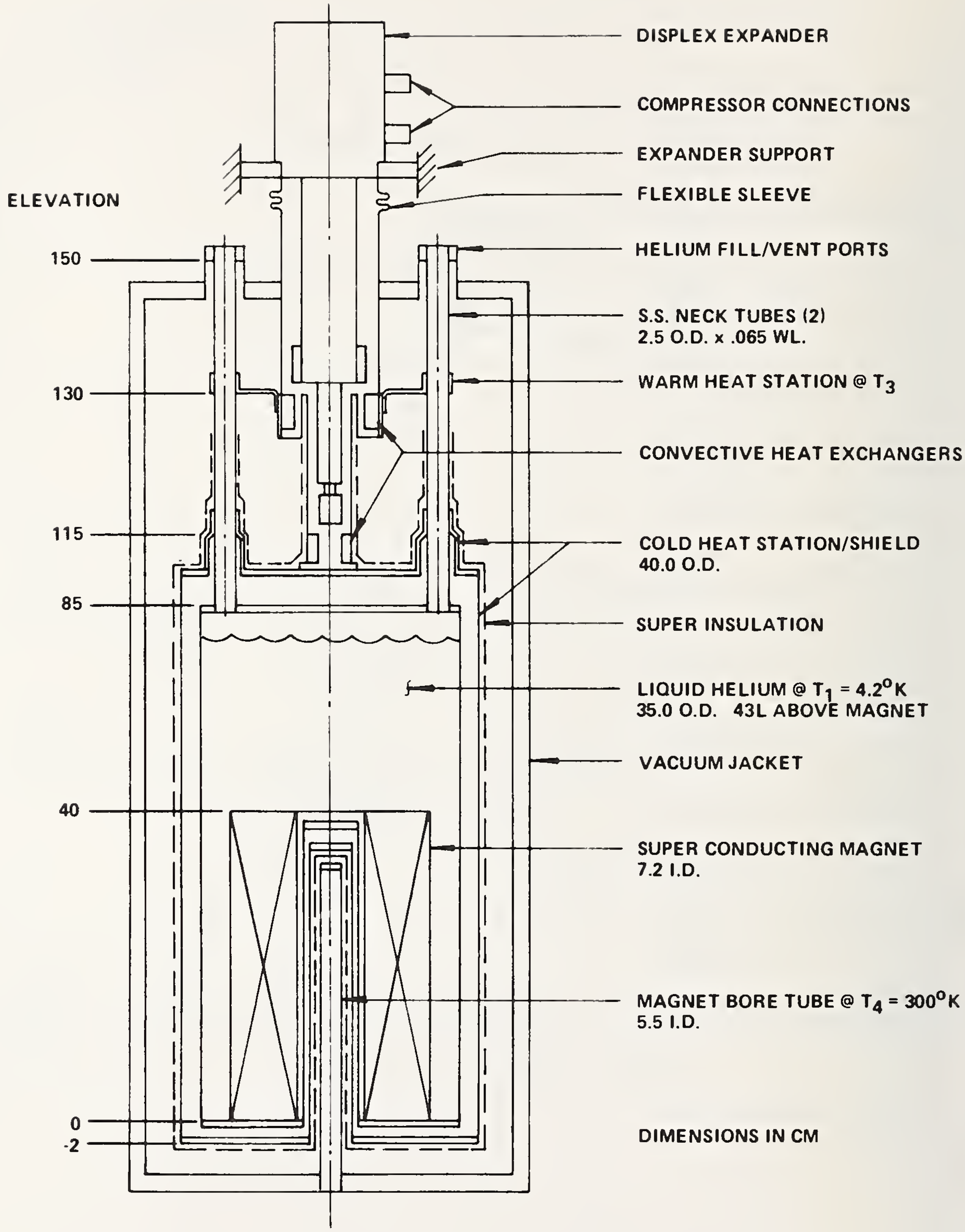


Figure 5. Helium Dewar with Displex Refrigerator to Reduce Boiloff Rate

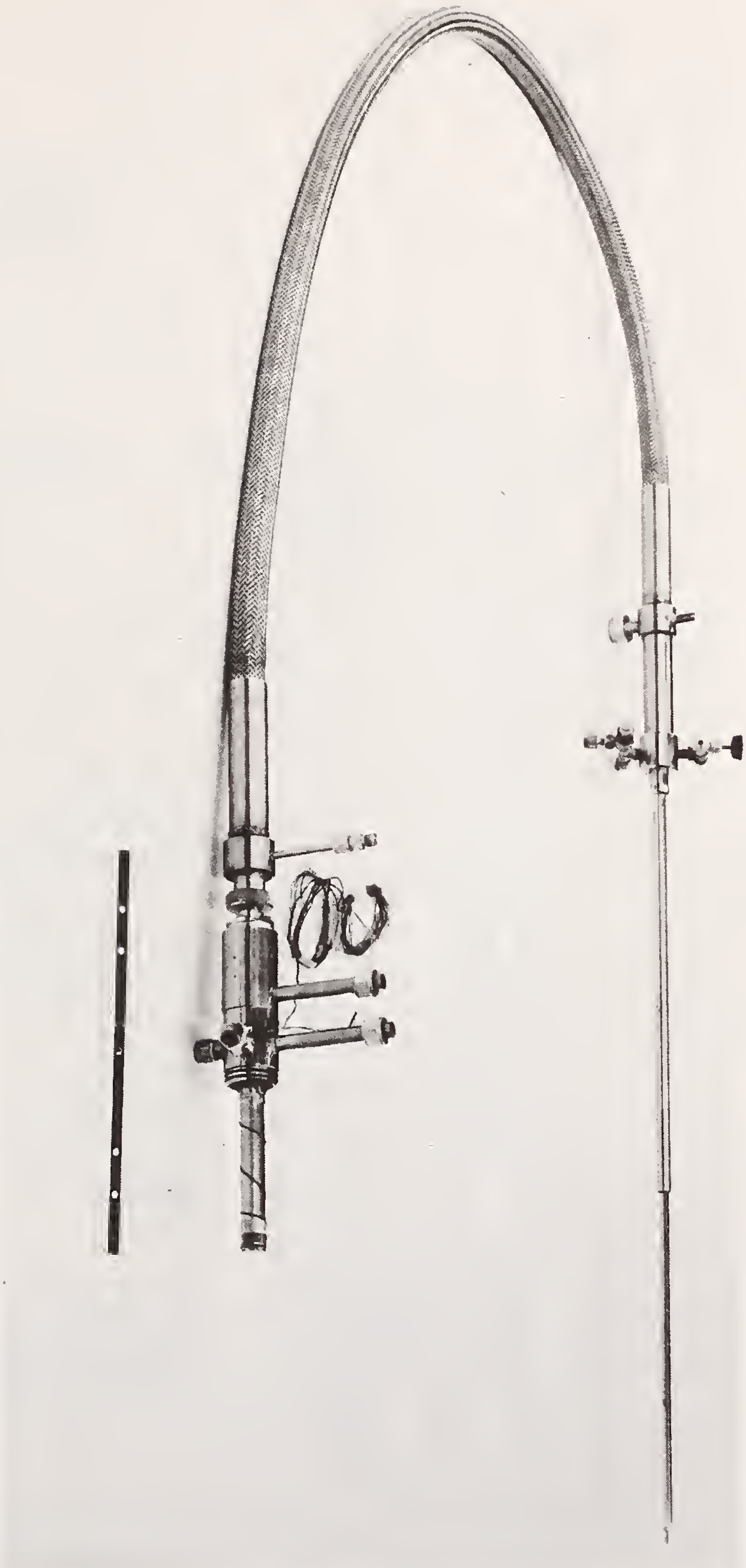


Figure 6. Heli-Tran Refrigerator Employing Flexible Helium Transfer Line

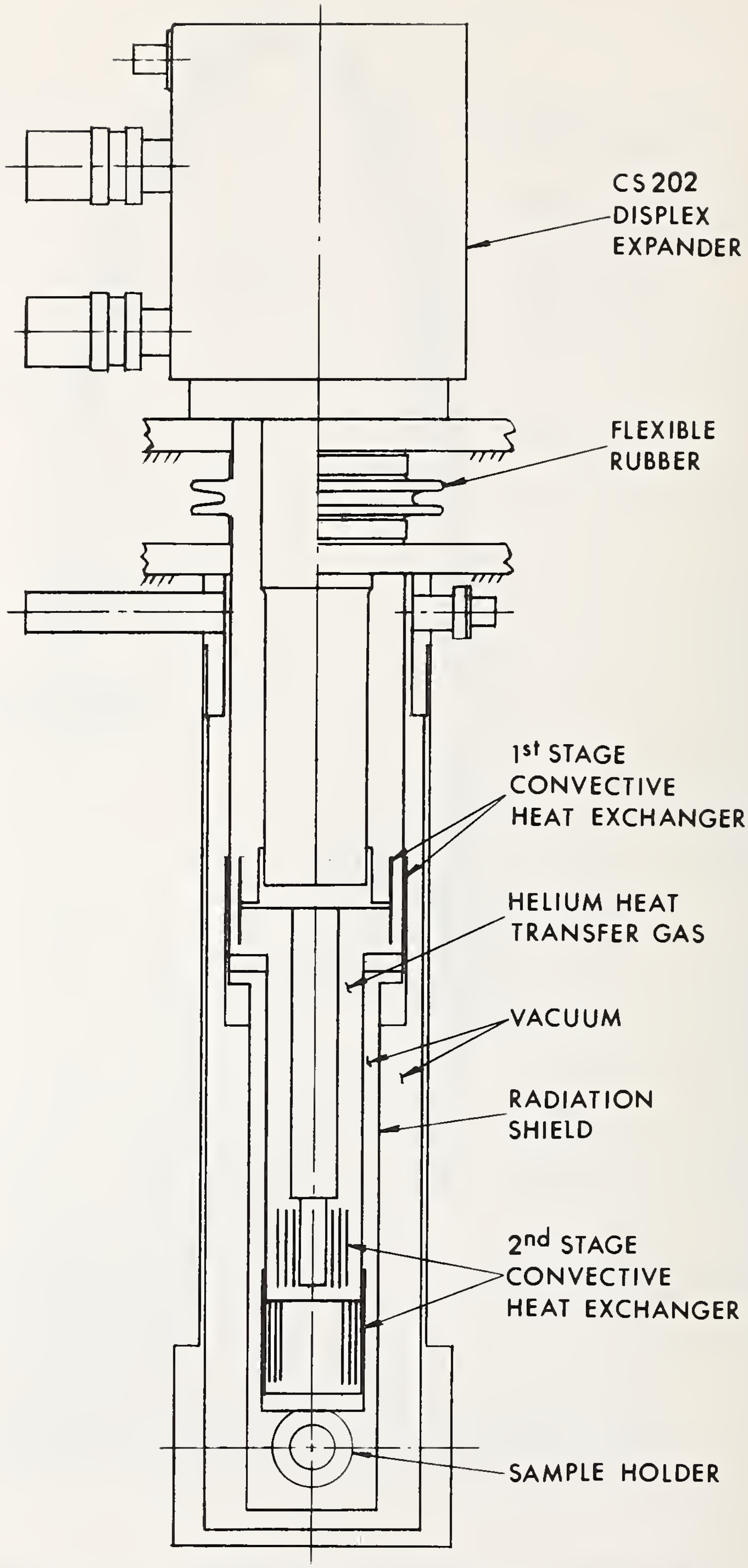


Figure 7. Model DMX-20 Interface for Mossbauer Spectroscopy Employing Cold Gas Convection for Vibration Isolation

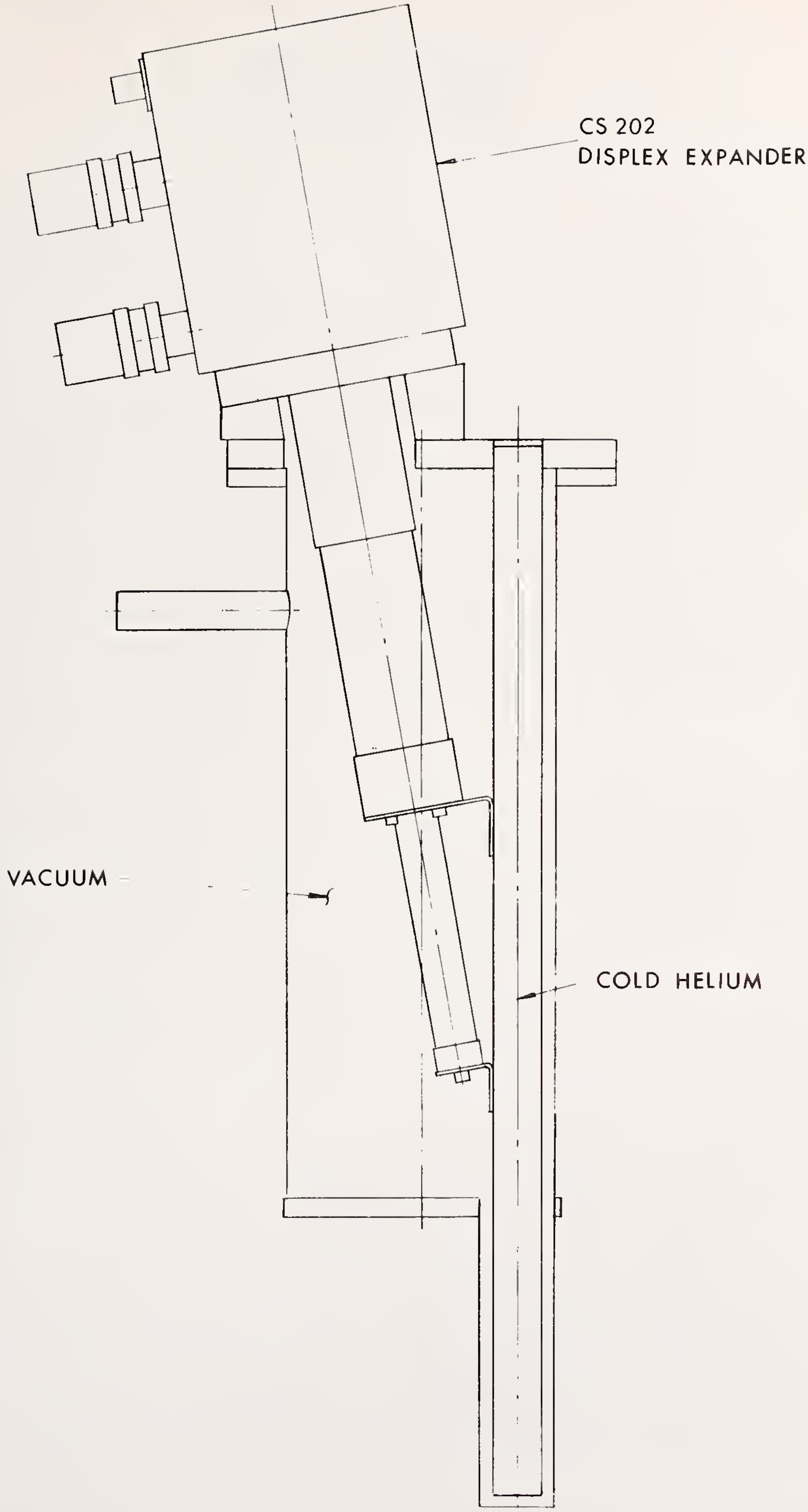
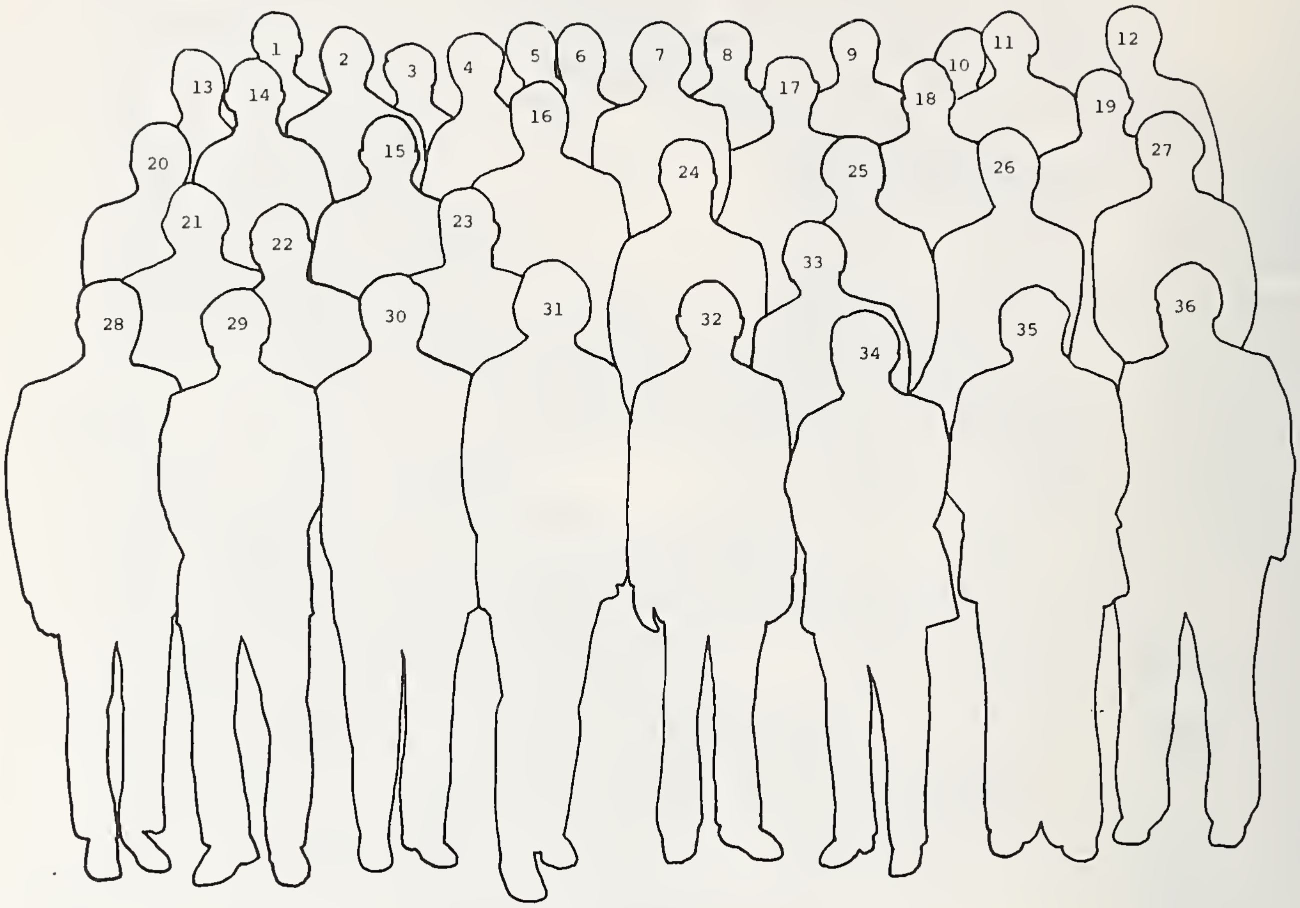


Figure 8. Cold Gas Well Cooled by Displex Refrigerator for Faraday Balance

Photograph of Delegates



IDENTIFICATION OF PHOTOGRAPH

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