AN EXAMINATION OF A LIQUID HELIUM REFRIGERATION SYSTEM FOR SUPERCONDUCTING MAGNETS IN THE 200 GEV EXPERIMENTAL AREA*

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I. INTRODUCTION

It has been suggested that the dc experimental area transport magnets for the 200 GeV machine be superconducting. The primary advantages of dc superconducting magnets are the elimination of large power supplies and cooling towers, and a drastic decrease in the consumption of electric power and cooling water. Although the need for power and cooling water is drastically reduced, capital and operating expenditure is required to maintain the superconducting magnets at liquid helium temperature (4.2°K).

The first analysis of this refrigeration problem was done by Strobridge, Chelton and Mann[1] of the National Bureau of Standards in Boulder, Colorado. A second more detailed report on the refrigeration system was published[2] in June 1968 by 500 Incorporated, a subsidiary of Arthur D. Little, Cambridge, Massachusetts. This second report is summarized in this paper. The second report differs considerably from the first in several respects. First, a specific experimental area model is analyzed; second, the refrigeration systems analyzed are all helium systems (no liquid nitrogen is used); third, simplicity, reliability, and flexibility are important considerations in the study; fourth, gas compression, storage, and purification are centralized; finally, the cost reduction resulting from quantity production is considered.

Three basic refrigeration concepts are analyzed in the second report[2]: 1) central liquefier, liquid delivery, 2) central refrigerator, cold gas supply and return, and 3) many small refrigerators with warm gas supply and return from central compressor stations. Several versions of the small refrigerator concept are investigated.

II. THE EXPERIMENTAL AREA

The experimental area model used is a modified version of one found in the National Accelerator Laboratory design report.[3] The approximate dimensions of the experimental area are 300 m by 1600 m. The over-all design is divided into three smaller areas, one for each of the three target stations.

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*Work performed under the auspices of the U.S. Atomic Energy Commission.

1. T.R. Strobridge, D.B. Mann, and D.B. Chelton, NBS Report 9259 (1966).
2. M.A. Green, G.P. Coombs, and J.L. Perry, 500 Incorporated Report (1968).
3. National Accelerator Laboratory Design Report (1968).

TABLE I. The parameters of secondary beams used in the LRL-500 Inc. refrigeration study.

	Beam length (m)	Number of beam magnets	Beam life (yr)	Radiation shielding required
Beams off Target A (Fig. 1)				
Beam A-1a	55	9	< 1	Moderate
Beam A-1b	230	14	< 1	Moderate
Beam A-2	120	18	< 1	Moderate
Beams off Target B (Fig. 2)				
Beam B-1	140	10	< 1	Moderate to heavy
Beam B-2	233	14	< 1	Moderate to heavy
Beam B-3	232	12	< 1	Moderate to heavy
Beam B-4	463	24	1 - 3	Light
Beams off Target C (Fig. 3)				
Beam C-1	1590	64	> 3	Light
Beam C-2	1590	68	> 3	Very heavy
Beam C-3	746	19	1 - 3	Moderate

Two hundred and fifty-two magnets are to be found within the experimental area. A future complication is the constant change in the experimental area beam layout. The model used in the 500 Incorporated report[2] only exists at one point in time. Table I presents detailed parameters of the beam lines found within the experimental area model used for the refrigeration study.

Several types of secondary beams are not represented in the experimental area model. The elimination of these beams does not affect the validity of the model because many of the beams will be similar to beams that were included in the model.

III. THE MAGNETS AND THEIR CRYOSTATS

The dipoles and quadrupoles housed in the magnet cryostats are assumed to have field strengths at the windings of the order of 40 kG. The dipole central fields are assumed to be 35-40 kG, the 4 in. quadrupole gradients 6-7 kG/cm, and the 8 in. quadrupole gradients 3-3.5 kG/cm. The length of the quadrupole and dipole fields given in the 500 Incorporated report is based on the above numbers.

The helium temperature mass is assumed to be 250-500 kG. The magnet stored energy will vary from 3×10^5 J for a 4 in. quadrupole to 2×10^6 J for an 8 in. dipole. It is assumed that a magnet quench is an infrequent phenomenon.

The cryostat design will be as simple as possible. It is assumed that the magnet cryostat will have only an inner vessel and an outer vacuum jacket which are separated by multilayer superinsulation and a tension-rod support system. The 1000 A electrical leads are assumed to be gas cooled. The total heat leak into the Dewar is assumed to be 5 W. The liquid storage capacity of the Dewar varies from 70 to 2000 liters depending on the type of refrigeration system used.

The simple high heat loss cryostat design seems to be contrary to normal cryogenic practice. However, the elimination of intermediate temperature shields and retractable leads has several important advantages, which are: 1) the Dewar design has less plumbing to fail, hence the Dewar will be more reliable; 2) the amount of money saved on the cryostat construction more than compensates for the increased refrigeration cost (reduced total system cost); 3) operational simplicity — there is no nitrogen filling process, a simple orifice at room temperature regulates the lead cooling gas flow. Considerable development work is required on the magnet cryostat before the simplified low-cost cryostat becomes a reality.

IV. THE REFRIGERATION SYSTEMS AND THEIR COST

The 500 Incorporated study[2] presents a number of cases for providing $4.2^{o}K$ refrigeration to the experimental area superconducting magnets. Three basic types of systems are presented: 1) a central liquefier providing liquid in portable Dewars with warm gas return (Case 1); 2) a small number of central refrigeration units providing cold gas through transfer lines and cold gas return (Case 2); 3) a large number of small refrigerators run off a small number of large compressor stations with gas transport at ambient temperature (Cases 3a, 3b, 4a, 4b, and 5). The small-refrigerator concept has a number of cases represented because it appears to be feasible from both an economic and operational standpoint. Table II presents a comparison between all of the refrigeration concepts studied in the 500 Incorporated report.

The large-liquefier concept (Case 1, see Fig. 4) has a number of advantages as follows: 1) high "process plant" reliability can be achieved in the liquefier, 2) storage and distribution Dewars can be made with a long life and little required maintenance, and 3) replaced magnet can be changed and cooled quickly. There are a number of important disadvantages that cannot be overlooked: 1) clear access to the magnet Dewar fill line must be provided at all times, 2) the system has a high labor input, and 3) gas storage is a problem during a liquefier failure.

The advantages and disadvantages of the central refrigeration system (Case 2, see Fig. 5) are as follows: Advantages — 1) large refrigerators are more efficient and less costly per watt than either liquefiers or small refrigerators; 2) less labor is required during operation; and 3) less space is required on the experimental area floor either for refrigerators or for fill vehicles. Disadvantages — 1) transfer line reliability is questionable today; it is difficult and expensive to move and install helium temperature transfer lines; and 2) when one refrigerator fails a large amount of liquid must be provided to a large number of magnets.

The advantages and disadvantages of each of the small-refrigerator cases (Cases 3a to 5, see Figs. 6 and 1) are discussed in detail in the 500 Incorporated report.[2] The following general statements can be made: Advantages — 1) the systems are flexible; warm compressed gas piping is easy to move and is reliable; 2) the refrigerator design can be simplified — mass production techniques can be used; and 3) the systems have a low operating labor output. Disadvantages — 1) the system reliability goes down because of a large number of small refrigerator units; regular maintenance will increase reliability; and 2) the refrigeration efficiency goes down as the size decreases and refrigerator cost per watt is increased.

TABLE II. A comparison of various 4.2°K refrigeration systems for the 200 GeV experimental areas.

Case	System description	Location of refrigerator	Refrigerator or liquefier size	Number of refrigerators	Number of compressor stations
1	Central liquefier, portable Dewar, liquid distribution and warm gas return	A location accessible to all three target areas	2200 liters/h	1	1
2	Central refrigerators with cold gas supply and return	Four locations near the three target areas	800 W, 1800 W, 2100 W, and 2300 W	4	4
3a	One refrigerator per magnet Dewar, central compressor station, warm gas supply and return	On top of the magnet Dewar inside shielding	10 W	252	4
3b		Near the magnet outside the shielding	10 W	252	4
4a	Two magnet Dewars per refrigerator when possible, central compressor station, warm gas supply and return	Near the magnet pair inside the shielding	20 W	140	4
4b		Near the magnet pair outside the shielding	20 W	140	4
5	Mixed 80 W and 20 W refrigerators, central compressor station, warm gas supply and return	Near the magnets outside the shielding	20 W and 80 W	7 - 80 W 115 - 20 W	4

The central compressor station concept is an important one. The central compressor station has the following advantages over individual compressors: 1) the gas storage and purification is removed from the experimental floor; 2) the central compressor station costs less than many small compressors; 3) the over-all system reliability increases because the largest cause of failure in today's small refrigerators is their compressors; 4) a number of types of refrigerator, including helium II and supercritical helium, can be run off the same compressor station.

A detailed cost analysis of each of the cases can be found in the 500 Incorporated report.[2] The cost factors used to calculate refrigeration may be found there also. Table III presents a summary of the capital and operating costs for each case.

TABLE III. The refrigeration system cost summary (costs in thousands of dollars).

	Refrigeration system capital cost	Refrigeration system 10-yr operating cost (continuous operation)	Total system cost
Case 1	2980	13 405	16 385
Case 2	5200	6590	11 790
Case 3a	5400	4090	9490
Case 3b	5575	4090	9665
Case 4a	5015	3890	8905
Case 4b	4835	3890	8725
Case 5	5125	3885	9010

There is approximately a 12% variation in capital cost in Cases 2 through 5. Case 1 has a low capital cost but is extremely expensive to operate. The costs given for Case 2 will change considerably with changes in transfer line technology. It is clear that careful design work is required if the small refrigeration systems are to be reliable.

The capital cost of the refrigeration system will be 25-30% of the total magnet system cost. Over half of the system operating costs will be associated with the refrigerators.

V. CONCLUDING REMARKS

A few concluding remarks can be made about the following concepts: 1) the no-nitrogen simplified-Dewar concept, 2) the small refrigerator vs large refrigerator, and 3) the central compressor station vs small individual compressors.

The no-nitrogen simplified-Dewar concept is valid when the following conditions apply: 1) small refrigerators are used to supply helium to the Dewar; 2) large refrigerators are used, but the Dewar heat leak is not the major part of the refrigeration load; and 3) many Dewars are widely separated. The no-nitrogen simplified-Dewar concept may not be valid under the following conditions: 1) when a laboratory Dewar is used; 2) when cooling is supplied by liquid (both nitrogen and helium transfer can be made at the same time); and 3) when large refrigerators are used and the Dewar heat leak is the major part of the heat load.

Many small refrigerators supplying a helium system appear to be attractive when: 1) the loads are scattered over a wide area, 2) transfer line losses exceed Dewar losses in a large system, and 3) flexibility of the system is required. Large refrigeration units become attractive when: 1) the loads are concentrated in a small area, 2) the loads greatly exceed the transfer line losses, and 3) when the system position is fixed. Many small refrigerators appear to be attractive for an accelerator experimental area, but large refrigerators would clearly be best for a large superconducting synchrotron.

Central compressor station seems to be most attractive when: 1) the refrigerator and load contain a large volume of helium, 2) piping is not the major part of the compressor station cost, and 3) system reliability is important. The small compressor is useful for temporary machines and machines that would require large amounts of piping if they were tied into a central system.

The transformation of superconductivity from a laboratory to a useful tool for the high energy physicist requires an extensive analysis of the whole system. There appear to be a number of refrigeration systems which can apply to the experimental area of the 200 GeV accelerator. Changes in technology will affect the final solution to the problem.

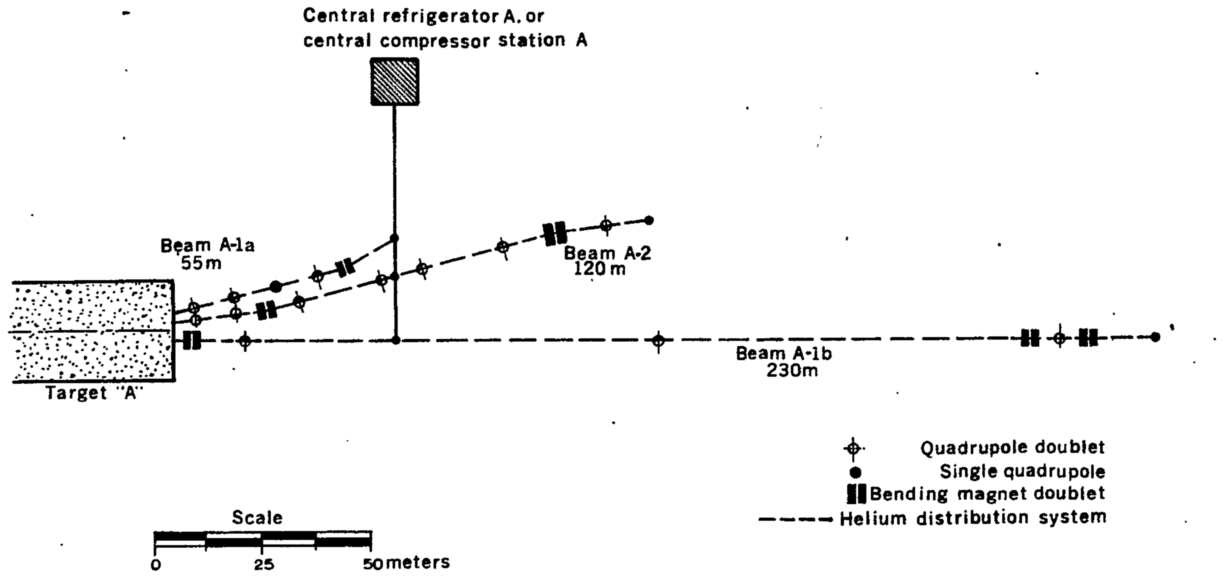

Fig. 1. Experiments from Target Station "A".

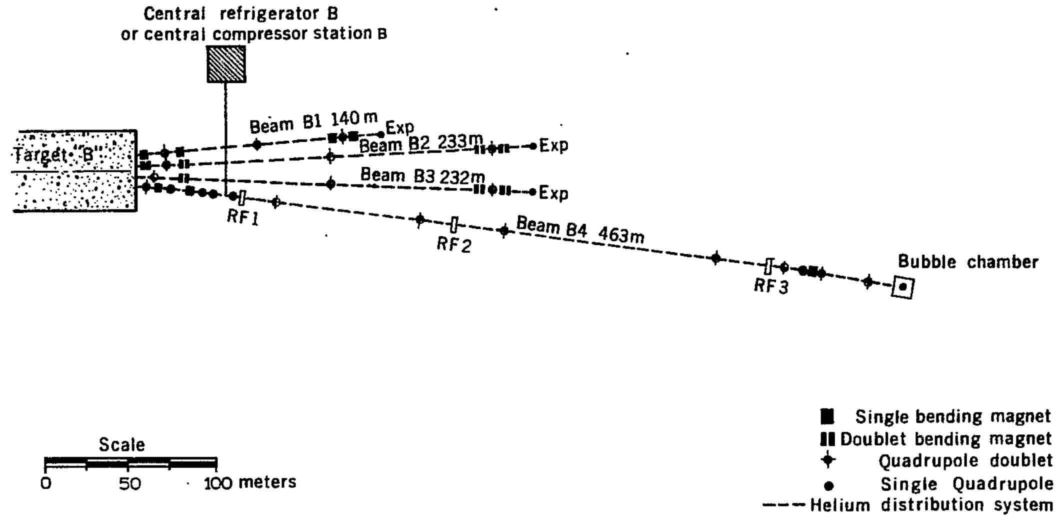

Fig. 2. Experiments from Target Station "B".

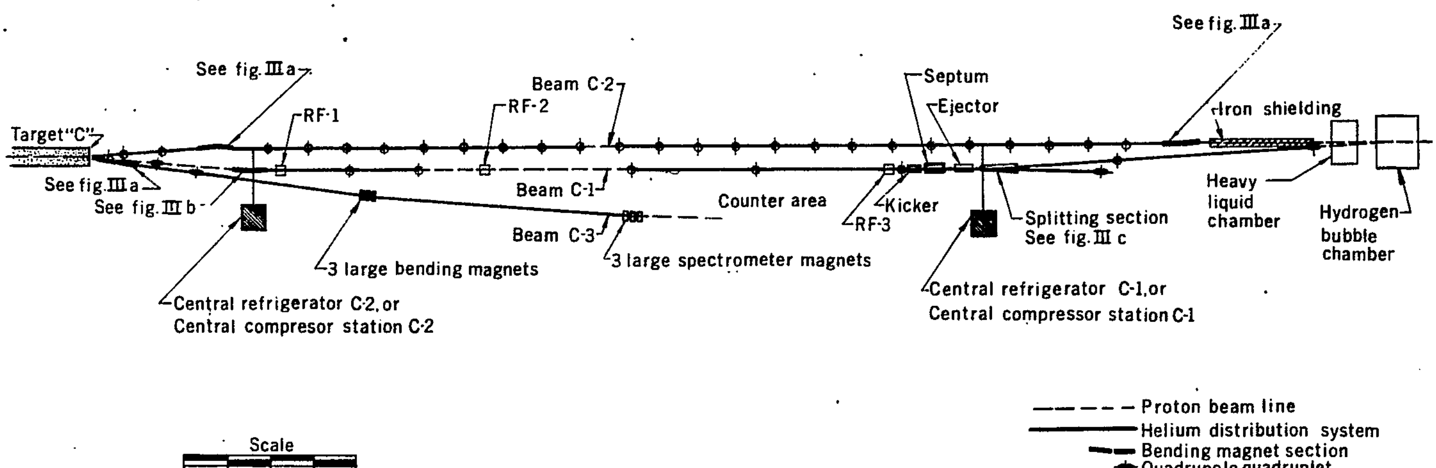

Fig. 3. Experiments from Target Station "C".

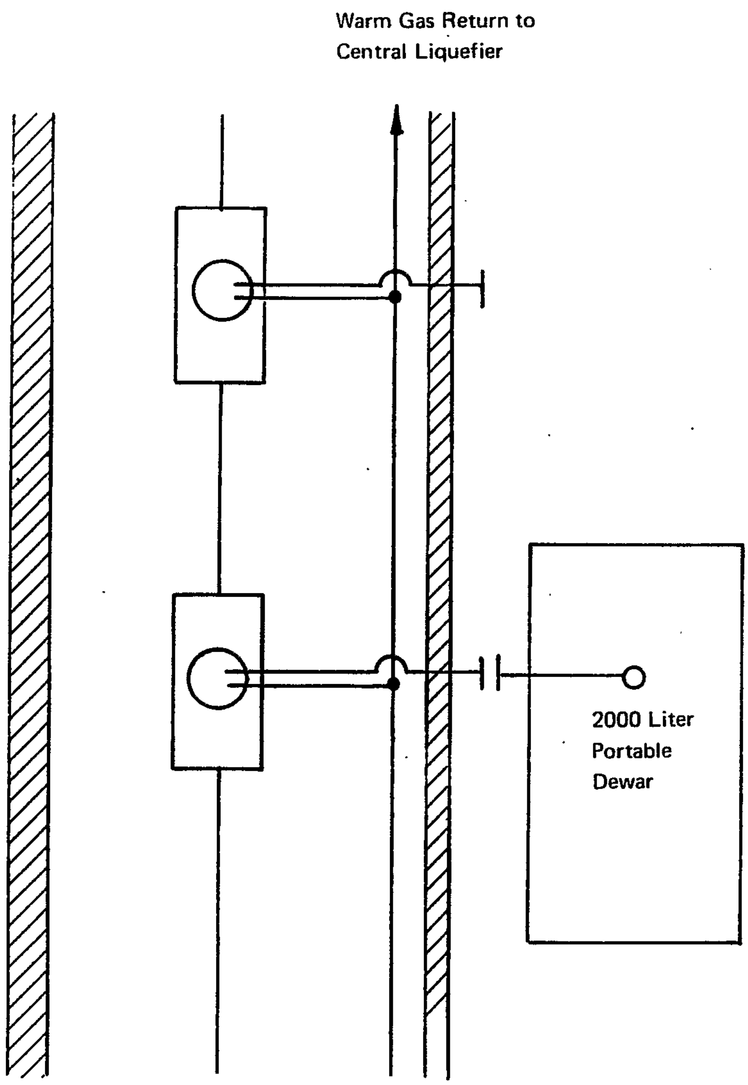

Fig. 4. Case 1 — central liquefier with transport of liquid in portable Dewars.

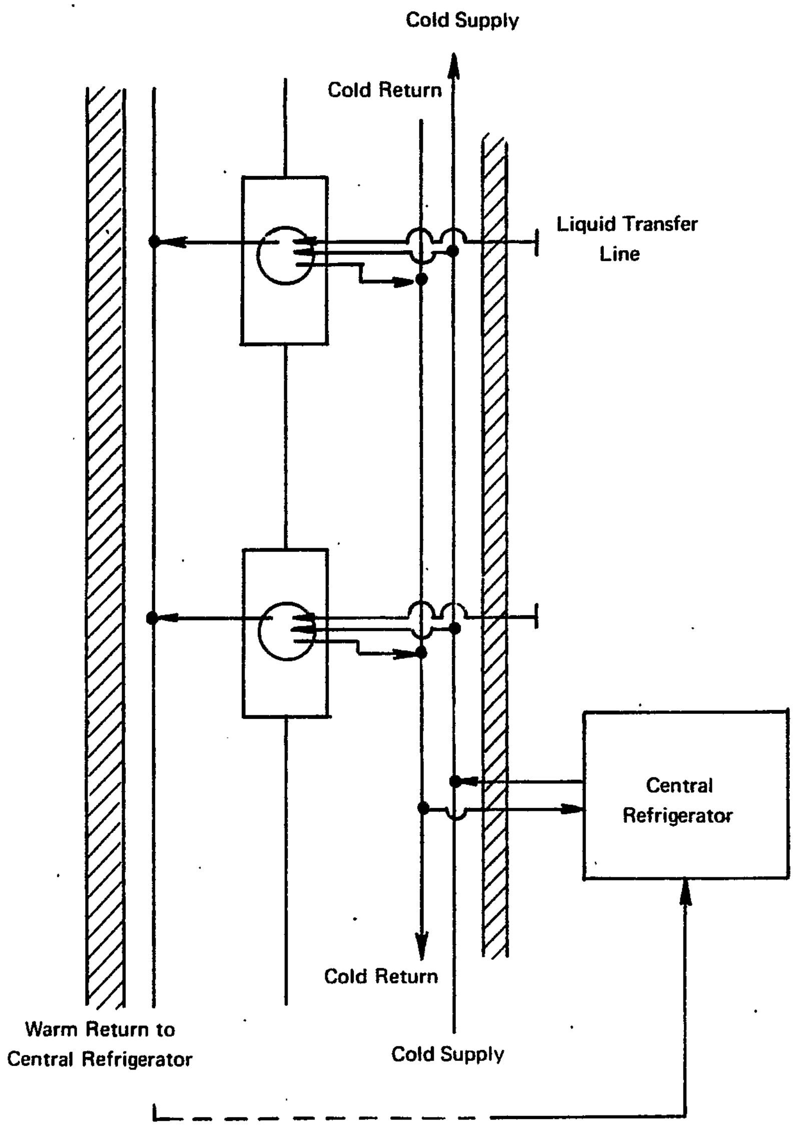

Fig. 5. Case 2 — four central refrigerators with continuous transfer of cold gas.

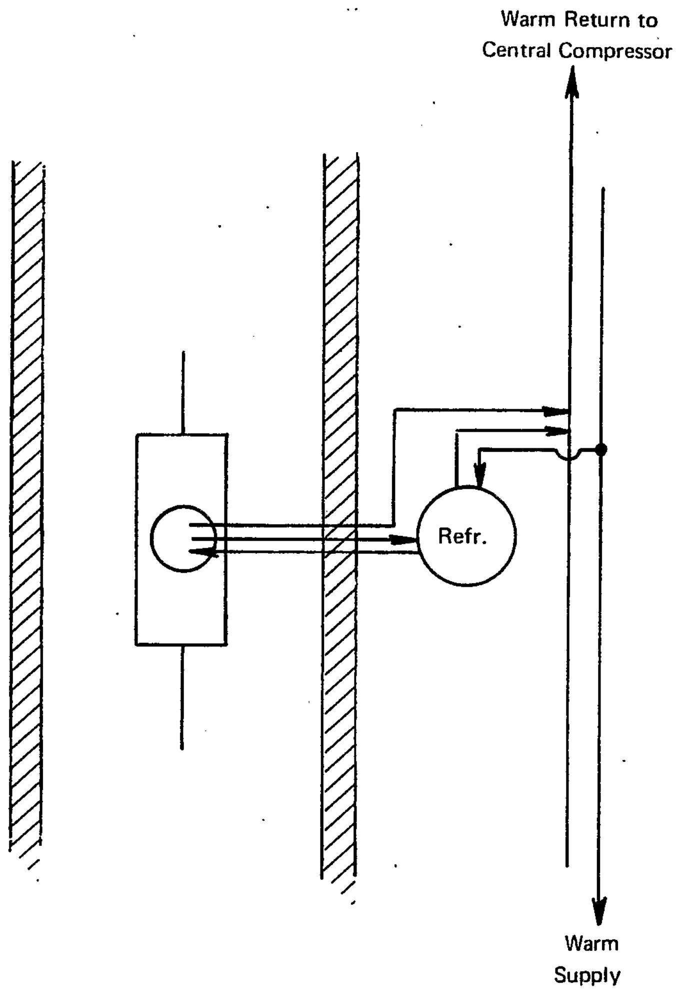

Fig. 6. Case 3b — individual refrigerator for each magnet; the refrigerator is located outside of the shielding.

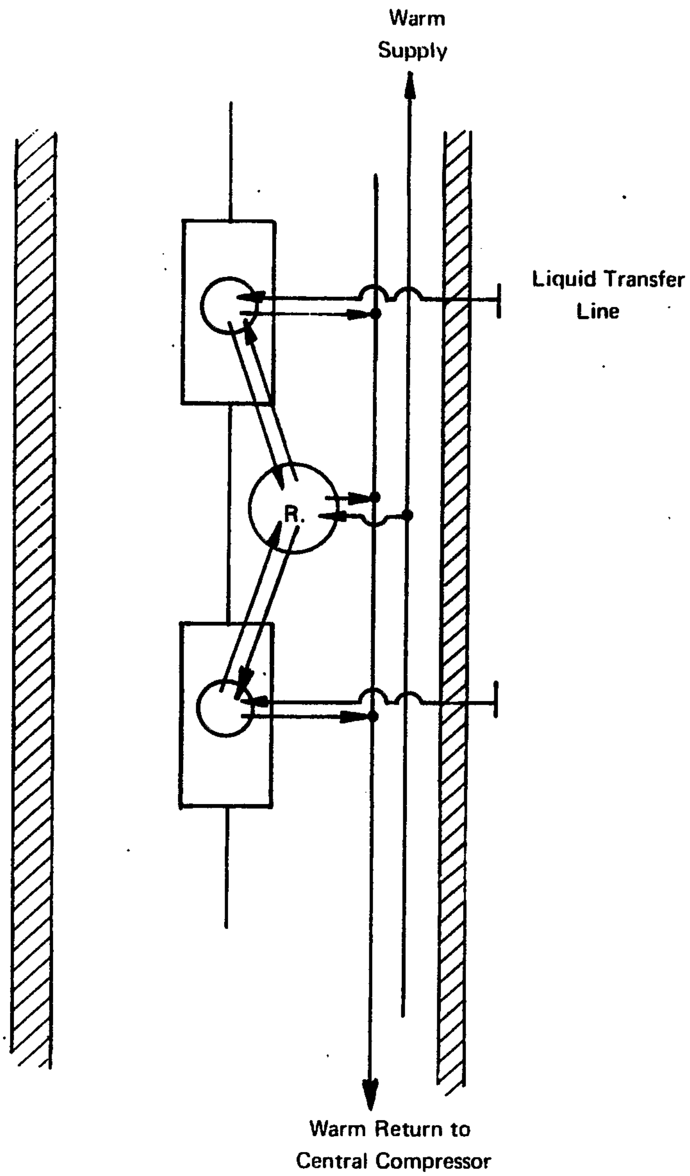

Fig. 7. Case 4a — small refrigerator servicing two magnets; the refrigerator is located within the shielding.