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THE ENERGY DOUBLER DESIGN STUDY

A Progress Report

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PREFACE

The material of this physics note was prepared as a progress report on the Energy Doubler design effort for submission to the Universities Research Association and the Atomic Energy Commission, reflecting the state of that effort as of this past February.

Many members of the Laboratory staff have contributed to the Doubler work; it would be inappropriate to list the subset of those who have prepared this particular paper on the title page. However, since papers probably should not be completely anonymous, we list below the individuals who provided the draft copy on the various chapters.

Chapter 1	R. R. Wilson and E. L. Goldwasser
Chapter 2	D. A. Edwards
Chapter 3	W. B. Fowler
Chapter 4	P. C. Vander Arend
Chapter 5	B. P. Strauss
Chapter 6	G. Biallas and W. B. Hanson
Chapter 7	D. F. Sutter
Appendix 1	P. J. Reardon
Appendix 2	W. B. Fowler

Insofar as possible, I have attempted to confine the editing to matters of format and elimination of some of the inevitable redundancy.

D. A. Edwards

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Chapter 1
Introduction

Background

The design parameters of the NAL accelerator were set primarily by the funds available for construction. There was no sharp guideline of an energy threshold at which some crucial physics hypothesis could be tested. There was no limit, dictated by accelerator technology, to the energy that could be achieved. In the exploration of the world of the proton and the neutron, the higher the bombarding energy, the more minute can be the exploration. Furthermore, in the search for hitherto undiscovered particles which might hold the key to important new insights into the structure of matter, the higher the available energy the broader can be the region that is searched. Thus there have always been substantial pressures to go to higher bombarding energies, and in the design and construction of the NAL accelerator a major effort was made to build in a potential for higher energies and to conserve funds so that that potential could be realized within the initial $250 million construction authorization.

A doubling of the originally specified energy has already been achieved. Furthermore, it has been achieved at a cost which, to date, is significantly less than the appropriated funds. Now it appears that through the construction of a superconducting "Energy Doubler" another doubling may be possible.

It would be consistent with the initial philosophy of the Joint Committee on Atomic Energy toward this project for the Laboratory to strive for the highest energy achievable within the funds available. That approach has become even more attractive as the first experiments have shown that, due to the granular structure of the proton, the new phenomena become more pronounced at the highest energy. Still more exciting are the possibilities that would be aided, by the existence of the Energy Doubler, for studying really high energy collisions through the use of intersecting beams. At the same time, it has become evident that operating funds will be less than anticipated, and that the energy shortage makes it imperative that new ways be sought to reduce power requirements.

Chronology

About eighteen months ago a half-dozen people started discussions, on an informal and voluntary basis, to explore new ideas, inventions, and designs that might make the Doubler feasible. The progress of that group was enough so that a year ago the URA and AEC authorized the expenditure of $1.5 million of construction funds to be used for a more intensive study of the problems. This report is the result of that work. It describes the first steps in a sequence of feasibility tests which, if successful, could lead to the realization of an operating Energy Doubler. Naturally, the emphasis of the study has been on the superconducting magnets and their associated refrigeration systems. So far, many of the short-range technical goals have been successfully achieved. No serious challenge to the feasibility of the project has been uncovered. However, significant problems still await resolution. A more detailed statement of the chronology and organization of the design study is presented in Appendix 1 of this report.

The Energy Doubler Concept

The NAL proton synchrotron was originally specified to reach an energy of 200 GeV. It now regularly operates at 300 GeV, and has occasionally produced protons at 400 GeV. As built, it has the potential of reaching 500 GeV.

It was recognized early in the project that a higher energy or a better duty cycle (pulse-stretcher mode) might be achieved with more economical operation by adding a ring of small superconducting magnets in the same tunnel as the Main Ring of the present accelerator. Indeed, space in the tunnel and in the service buildings has been saved for just such a possibility. Because superconducting bending magnets might be expected to reach a field strength of 45 kG, compared with 22.5 kG for the present, conventional magnets at 500 GeV, and since the energy that could be achieved in such a ring would be 1000 GeV, the concept has been designated an Energy Doubler.

The present, conventionally built Main Accelerator raises protons in energy by a factor of up to fifty. Although a superconducting magnet ring with such a cycle is, perhaps, still just beyond the state-of-the-art, it is anticipated that implementation of the Doubler concept may already be within reach, because injection would be at a higher energy and, hence, at a higher magnetic field. Thus, the Doubler would likely be the first feasible application of superconducting magnets to high-energy accelerator construction. The existence of the present, conventionally built machine alleviates many of the difficulties anticipated for a superconducting magnet ring at low injection fields where frozen-in fields and eddy current effects during acceleration could be devastating.

The Energy Saver Concept

For operation of the present accelerator system at 300 GeV with a 6-sec repetition rate, an average power of more than 40 MW is required. More power would be required to achieve a higher average intensity by using a shorter acceleration cycle. Similarly, more power would be needed to support the longer flat-top required for a better duty factor at the present 6-sec cycle. In either case, the power requirement for the most effective operation of the accelerator at 300 GeV might be increased to over 50 MW; for 400 GeV it could exceed 85 MW.

The energy doubler ring just described could also be used as an "energy saver." In that mode, for 400-GeV operation, for example, the conventional accelerator could be run as a 300-GeV injector into the superconducting magnet ring. For that use, the present accelerator could be operated without a flat-top and with a 2-sec acceleration ramp. The final 100-GeV acceleration and extraction flat-top would be provided by the Energy Doubler. Such a cycle would consume about 20 MW of average power instead of the 85 MW that would be required to run the present accelerator at an 8-sec repetition rate at 400 GeV.

The Energy Doubler would provide about the same number of protons per pulse as would be available from conventional operation. The repetition rate could be about 12 sec with a 2-sec flat-top in place of the 1-sec spill used in the conventional operating mode. The time-averaged intensity would be about two-thirds that which could be obtained from the present accelerator. For 1000-GeV operation, the repetition rate would decrease to about 1.5 min but the power required would still be less than 15 MW due to the low repetition rate in the Main Ring. Interspersing 14 normal main-ring 300-GeV pulses between each pair of 1000-GeV doubler pulses could be accomplished, but would require an additional 35 MW.

Establishment of Feasibility

There are a number of questions to be answered in order to demonstrate the feasibility of the Doubler. For example: (a) Can superconducting magnets be built that ramp adequately fast? (b) Can the necessary accuracy of the magnetic field be achieved in mass production? (c) Can the design be reduced to such simple and reliable components, remotely adjustable, that the new magnet ring could be installed and brought into operation without serious interference with the expected experimental program? (d) Can the beam be extracted efficiently for use in external areas or for injection into a storage ring or into an even larger accelerator? and (e) Can all this be done economically?

Although a few years ago, when the Energy Doubler idea took form, there was no suitable superconducting wire available, now, in direct response to the possibility of a ring of such magnets four miles in circumference, we believe an adequate superconductor can be supplied to us. Seven small prototype magnets which have been constructed and tested, have satisfied the design goals set for them. Encouraged by these results, we have moved directly to the fabrication of full-scale 20-ft long dipole magnets in order to confront the construction problems which they pose. The first of these magnets has been tested in a very preliminary manner as described in Chapter 7 and is being readied for more complete tests. From the outset, the magnets have embodied the cold bore--warm iron principle. After the first few models, we settled on a shell-like conductor configuration, since our measurements indicated that this coil geometry was more likely to permit our ramp rate. Our full-scale prototypes incorporate the innovation that the magnets themselves serve as the liquid helium supply and return lines. The cross-section of the magnets is small--roughly an 8- x 12-in oval.

Parallel to the magnet effort, we have installed and brought into operation a large liquefier and helium-flow system to simulate a 400-ft section of the doubler refrigeration design. Initial tests of this system in the Protomain Tunnel have also been encouraging.

The next step -- the joining of the magnet and refrigeration system development -- is about to take place. Ten full-sized magnets will be built and inserted into the refrigeration loop in the Protomain Tunnel to build toward a true Doubler prototype; that is, a string of full-scale superconducting magnets linked by a common liquid helium path and powered in series.

Thus, we have begun to answer the questions above. But, with a new accelerator technology, there is no clear-cut point at which a guarantee of success can be made. We have projected the development of the Energy Doubler as a series of "go--no go" steps so that the major expenditure would be deferred to the last stage. This philosophy is outlined below.

Approach Toward an Energy Doubler

The design process, and if carried out, the construction of the Doubler, builds upon our experience at NAL. We have not proceeded on the basis of deciding what is readily practicable, designing to that, adding up the cost, and accepting the result. Instead, we have set a cost goal and keep designing, redesigning, haggling, and improving until we have done what we set out to do. Occasionally, we are forced to admit that we are not clever enough to achieve our cost goal and admit defeat, but not without a struggle.

In the case of the Doubler, our cost goal is "about $20 million" for the magnets and refrigeration equipment. At present, our best estimate for completing the whole Doubler is about $25 million, but we shall work to reduce that figure. There has always been the hope that some ingenious invention or lucky circumstance (a "Deus ex machina") might reduce the cost significantly. That is what happened in the case of our present accelerator. The refrigeration might perhaps be supplied, in part, by surplus equipment from the space program. Or perhaps an energy storage device might supply or share the refrigeration. Should some such windfall materialize, so much the better, meanwhile we continue to explore ways in which costs may be kept to a minimum by exploiting our existing facilities.

Our plan for the Energy Doubler is that it be installed in the same enclosure as the present Main Ring. The doubler magnet current is set by the availability of spare main-ring power supplies which thereby can be used interchangeably between the two accelerators. This latter consideration immediately determines the dimensions of the superconducting wire.

We have briefly described a series of small steps toward the realization of an Energy Doubler. The initial steps have been completed or are underway: the small prototype magnets, the first full-scale magnets, the large helium flow system, the installation of magnets in the helium-flow system.

The next big step which we would now like to start is the construction of a portion of the Energy Doubler inside the enclosure of our present Main Ring. We would have to learn to do this without serious interference with the present accelerator operations. If we could, we would then want to extract the proton beam from the Main Ring at about 100 GeV and inject it into the chain of superconducting magnets. We would then have an overall test which would fully demonstrate the feasibility of the Doubler; i.e., whether we could actually install the magnets without interference, whether we could line them up on the beam, and whether reliable operation could be achieved. In the course of carrying out this Proto-Doubler project, we would also arrive at a firm estimate of the cost for the full Energy Doubler.

CHAPTER 2

ACCELERATOR ASPECTS OF THE ENERGY DOUBLER

INTRODUCTION

The scope of our design effort as outlined in Chapter 1 indicates that emphasis is placed on the development of superconducting magnets and their cryogenic system. In the following chapters, the progress of the design study to date is summarized. In this chapter, we will provide a brief description of the Energy Doubler as an aid in visualizing the complete device. We also will identify a number of problems appropriate for further study.

LOCATION AND MAGNET DISTRIBUTION

The Doubler is intended to share the same enclosure as the existing Main Accelerator. In order to provide access to both rings with a minimum of interference, it is proposed that the Doubler be placed near the apex of the tunnel; its orbit would then be some 3 ft inside and 4 ft above the main-ring beam trajectory. Once one has settled on using the main-ring enclosure, then only limited variation from the disposition of magnets in the present accelerator is possible for the doubler lattice. The distribution of bend centers in the Main Accelerator is such that the tunnel center line varies in distance from the center of the ring by 30 ft through each of the six superperiods. A limited degree of flexibility remains, however, and may be exploited to advantage for injection and extraction (see Page 8). Nevertheless, the doubler geometry must duplicate the six long and six short straight-sections of the Main Ring.

We have adopted a length of 20 ft for our superconducting dipole magnet prototypes - the same length as the conventional dipole magnets in the Main Accelerator. A total of 774 such magnets would be required. Our design field of 45 kG corresponds to 1000 GeV. A duplication of the main-ring lattice implies the use of 192 normal-cell quadrupole magnets and 48 long straight-section matching quadrupole magnets. If the tune (number of betatron oscillations per revolution) of the Doubler is to be the same as that of the Main Ring*, the product of field

*The tune of the Main Ring has recently been lowered from the neighborhood of 20.20 to the region of 19.28 to avoid certain non-linear structure resonances. For the present, we are using the new main-ring tune for the doubler design.

gradient and length for the normal-cell quadrupole would be 1260 kG at 1000 GeV, and just over 60% of that figure for the matching quadrupole magnets. Thus, 1014 superconducting magnets are needed for the Energy Doubler.

Repetition Rate and Intensity

In its basic form, the Energy Doubler is a slow-cycling machine, with a period of approximately 100 sec. This figure was selected as a compromise between the increasing costs of refrigeration and, to some extent, superconductor associated with more rapid cycling, on the one hand, and the decreasing average extracted intensity that accompanies longer cycle times on the other. Today, the typical operating intensity of the NAL accelerator lies in the range of 3 to 4 x 10^{12} protons per pulse, with a 6-sec cycle at 300 GeV. If, by the time the Doubler is functioning, the accelerator has achieved its design goal of 5 x 10^{13} protons per pulse and if this charge can be conveyed to, accelerated in, and extracted from the Doubler without significant loss, then the average intensity (number of protons per second) delivered to the external beam lines from the Doubler would be the same as the accelerator produces at present.

One might consider raising the average intensity by stacking several main-accelerator pulses in the Doubler before acceleration. At this stage, the field quality and beam manipulation requirements associated with this technique lead us to think of it as a remote possibility. For the present, we favor the approach of leaving open the option of adding refrigeration capacity to reduce the cycle time once the Doubler is operating.

For definiteness, we have been talking of a "trapezoidal" 100-sec cycle consisting of 10 sec at low field, 10 sec at high field, and 40-sec ramps for field increase and decrease. There is no deep significance in this particular division of the cycle. With single-turn injection, injection would be made into a rising magnetic field for simplicity, hence the time spent at low field could be as short as is found to be consistent with power-system regulation characteristics.

Of course, for internal target experiments causing negligible diminution of the circling beam current, the effective intensity is independent of cycle-time.

Dynamical Questions

Since the Energy Doubler as pictured here closely resembles the Main Accelerator in number and disposition of magnets, some of the aperture arguments are the same for the two machines so we need not detail these all here. Finding and improving a closed orbit, provided a suitable beam position-monitoring system is available, is a well understood problem. Given reasonable magnetic measurement data, a careful survey, and a means for beam steering, it is likely that a circulating beam can be obtained without unusual difficulty insofar as magnetic length and placement effects are concerned.

Efficient extraction imposes a more severe aperture requirement. In a resonant extraction scheme, the aperture has to be large enough in the extraction plane to permit a betatron oscillation of sufficient amplitude to develop so that the amplitude-dependent step-size becomes sufficient to jump an extraction septum with high efficiency. The extraction system currently used in the Main Accelerator utilizes about 2-in of aperture in which the unstable betatron oscillation builds up and another 3/4-in space for the particles that will enter the extraction channel upon encountering the septum at the proper phase of their oscillation. At present, extraction efficiency is typically 95% and is limited by effective septum thickness.

The full-scale prototype dipole magnets described in Chapter 6 have an aperture in the horizontal (extraction) plane of just under 2.2 in. Although the fundamental ground rule in the Doubler proposition is the acceleration of protons to the 1000 GeV range at minimum cost, clearly their effective delivery to external experimental areas is a most desirable feature, and the determination of whether or not improvements in the extraction scheme can be made to compensate for the smaller aperture considered herein remains a subject for future study.

The second main dynamical question associated with our magnet design development concerns non-linear effects. Interpretation and correction of non-linear resonances in the Main Accelerator has proved to be a difficult and time-consuming process. The measurement on field quality in superconducting magnets reported in Chapter 7 at high magnetic fields resemble those of our main-ring magnets at injection field. The cost trade-off between increasing the coil aperture to improve field quality versus employing an elaborate correction system remains to be assessed. One may also consider a reduction of the period length of the lattice to shorten the betatron oscillation wavelength, thereby reducing the influence of amplitude-dependent resonance effects.

Injection and Extraction Geometry

Two extensions of the basic concept which will greatly enhance the utility of the Energy Doubler are the capabilities of using it as a "beam stretcher" at energies between 200 and 500 GeV and of extracting from it into the existing switchyard complex at energies up to 1000 GeV. As a spill stretcher, the Doubler would operate at a constant field corresponding to the operating energy of the Main Ring. At the peak of each main-ring cycle, beam would be single-turn injected into the Doubler and then slow extracted over the intervening period before the arrival of the next main-ring pulse. For this mode, the doubler-injection system would have to be capable of transporting protons at energies up to 500 GeV. Use of the present switch-yard tunnels is important to minimize duplication of facilities even though many beam-line magnets would have to be replaced by superconducting magnets, and new beam lines to new experimental areas (e.g., by extension of the existing, so-called Q-stub) might be developed.

The simplest magnet lattice for the Doubler would be one which exactly duplicates that of the Main Ring, bend-for-bend and quad-for-quad. Slight departures from this scheme (moving the azimuthal location of some bending magnets) would facilitate injection and extraction without, at the same time, leading to excessive excursions of the Doubler from the tunnel center line. Two such modifications are proposed.

First, the medium-length straight-section in each period would be moved downstream by 40 ft. This will aid in vertical injection into the Doubler at this position. Second, a bending magnet would be shifted from the cell upstream of the upstream long straight-section doublet to a position at the other end of the long straight-section. This change will have two beneficial consequences. The space in the Doubler for installation of an extraction septum would be increased to 40 ft as opposed to the 20-ft gap in the Main Ring. By moving a bend-center from the upstream end to the downstream end of the long straight section, the doubler long straight-section would be rotated toward the direction of the external beam lines, thus reducing the bends required in the extraction channel. The combination of these moves would lead to a total radial excursion of 29 in. (+17 in, -12 in) from the tunnel center line in the neighborhood of the long straight-section in each superperiod.

The injection system would consist of pulsed orbit-manipulation magnets in both rings, an extraction Lambertson in the Main Ring to bring the beam out vertically at the upstream end of a long straight-section, a pulsed injection septum in the Doubler, fast kickers in each ring, and a superconducting transport connecting the rings. The superconducting transport would be constructed, for the most part, of energy-doubler magnets operating at the same excitation as the Doubler. The exceptions are two high-field magnets at either end of the transport.

Although there are dynamical questions requiring examination with regard to extraction from the Doubler as mentioned in the preceding section, the basic design of the transport has little to do with the method of obtaining slow spill and can be looked at separately.

The extraction line bends away from the Main Ring at an angle of 22 mrad; the lattice changes mentioned above would reduce this angle to 14 mrad for the Doubler. Nevertheless, since the Doubler would be above and inside of the Main Ring, a substantial offset will need to be made by the beam leaving the Doubler. The same lattice change that will pitch the doubler orbit direction outward with respect to the Main Ring will leave space for an electrostatic septum twice the length of the main-ring septum but having the same field gradient at the doubled energy. This septum would be followed by a Lambertson magnet to bend downward so that the first of a pair of superconducting dog-leg magnets could be placed so as not to interfere with the Doubler. These dog-leg magnets would be oriented so as to bend both horizontally and vertically; the second of them would be placed just upstream of our present Enclosure B. It would be followed by a conventional vertical bending magnet to provide the final deflection into the existing switchyard line. This last magnet would be turned on and off to act as a switch between beam coming from the Main Ring and Doubler. This arrangement would require the construction of only some 150 ft of small (2- to 3-ft in diameter) tunnel between the Transfer Hall and Enclosure B.

Both the injection and extraction transport outlined briefly above require the stable operation of superconducting magnets in systems with which high background radiation is traditionally associated. The feasibility of this remains to be demonstrated, although it is our understanding that recent tests at Brookhaven have been encouraging. In the near future, we will install the dual dipole magnets discussed in Chapter 7 in the main-ring extraction channel in order to gain some insight into this question.

OTHER ACCELERATOR SYSTEMS

A number of the other accelerator systems are more or less conventional, and have not been subjects of detailed study thus far. The power system will resemble that of the Main Accelerator; the interesting new problem presented by the Doubler is quench protection of a large number of magnets powered in series. We will be turning to this problem in the immediate future. An average pressure of $\sim 3 \times 10^{-8}$ Torr (at 4° to 5°K) in the cold-bore tube should be adequate to keep nuclear interaction and multiple scattering losses at the level of a percent or so for our duty cycle. Calculations indicate that pressure buildup from ions striking the wall, then producing neutrals which are subsequently ionized to produce yet more neutrals, should not be a problem at our beam currents even though the desorption coefficients are very high. For our slow acceleration cycle, the radiofrequency system requirements are, of course, modest.

CHAPTER 3

THE REFRIGERATION SYSTEM

INTRODUCTION

In order for the energy-doubler superconducting magnets to give the desired magnet field, they must be cooled to liquid helium temperature levels, i.e. 4° to 5°K, so that the Niobium-Titanium (NbTi) becomes superconducting. In addition to this "cooldown" from room temperatures, the refrigeration system has to have sufficient capacity to compensate for heat dissipated in the magnets during pulsing due primarily to eddy currents and hysteresis losses in the superconducting material. Also, various fault conditions have to be handled with minimum upset of the cryogenic and magnet system.

Working from the guidelines established for the Doubler of maximum utilization of existing facilities, a cooling concept was developed. Calculations were performed on fluid flow, pressure drops, and heat transfer as magnet designs were generated.

Since there are 24 service buildings located at approximately 240-meter intervals around the Main Accelerator, and these buildings are only partly occupied with equipment, we have planned the installation of the refrigeration equipment in each of these buildings and have investigated the feasibility that each refrigerator service at least 240 meters of energy-doubler magnets. Because there might be some improvement in reliability and some lower cost, we have also considered using 12 refrigerators of approximately twice the capacity installed in every other service building as an alternative.

In order to develop concepts for the refrigeration system we used as a guide studies conducted in Europe concerning the modification of the SPS at CERN for 1000 GeV operation.

Using the energy-doubler rate of one pulse per minute and the best estimates for the various heat loads, we believe that the refrigeration requirement for each of the 24 refrigerators is 720 W. A unit of similar size manufactured by Cryogenic Technology, Inc., is shown in Figure 1. Since faster pulse rates may be desirable sometime in the future, attention has been paid to how to increase refrigeration capacity, if this is deemed necessary (see Figures 2 and 3).

We have also used the concept of self-sufficient independent modules with the interconnection between modules limited to a vacuum pipe for the proton beam. This will facilitate the sequential manufacture, installation, and check-out of the 24 units.

Cooling Concepts

The most difficult problem of the cryogenic design of the superconducting Energy Doubler located in the NAL accelerator tunnel is the transport of refrigeration from the refrigerators to the ~ 1000 magnets located over ~ 6000 meters. A basic system might consist of supply and return transfer lines from a central refrigerator (carrying liquid helium and cold helium gas) entering the tunnel and running in parallel with the accelerator. Each magnet would be connected into the low-temperature distribution system much as the present magnets are connected into the water-cooling system. Examination of this system leads quickly to the conclusion that the cost of such a system is too high. An alternate at the other end of the spectrum from the single refrigerator is small refrigerators for each magnet located in the tunnel which eliminates the transfer line system. Again, the cost of such a system is too high and the operational reliability is not adequate on the basis of the reliability of present day refrigerators.

We investigated using the magnet system itself as the transport system for the cryogenic fluids. A system in which supercritical helium is pumped around the complete length of the accelerator with heat exchangers and pumps located at the service buildings to remove heat from the liquid was calculated. The system depends on the specific heat of supercritical helium for removal of heat from the magnet system. This requires a temperature rise along the path of fluid flow. If the temperature rise is to be kept at a value sufficiently below the critical temperature for NbTi, flow rates need to be extremely high. This, in turn, means a large pressure drop and a relatively large amount of heat generated by the pumps moving the supercritical helium. This increases the size and cost of the helium refrigerators. The concept was abandoned because it is difficult to isolate parts of the system in case of magnet failure. Also, the temperature rise of the liquid helium flowing through the magnets limits superconductor capability at the warm end and results in rather short distances between adjacent refrigerators.

After several months of study, a new cooling system was invented by Peter Vander Arend. The schematic flow arrangement of a module of the new system, which eliminates the disadvantage of a rising liquid-helium temperature along the path of flow is shown in Figure 4. A helium pump compresses liquid helium from a liquid-helium reservoir of the refrigerator. The subcooled helium flows through and around the windings of the magnet over a distance of some 120 meters. At the end of the path (halfway between service buildings), the liquid helium flows through a valve and becomes boiling liquid helium. The boiling helium is returned through an annular space around the magnet vessel to the liquid reservoir of the refrigerator. A fraction of the liquid helium is vaporized through heat transfer. Part of the heat transfer takes place between the subcooled helium in the magnet vessel and the boiling helium in the annular space. Heat arriving from the environment also vaporizes part of the low-pressure helium.

This system has a number of advantages:

a. With a large surface area for heat transfer between supercritical and boiling helium, it is possible to maintain an almost constant temperature in the magnet vessels independent of distance from the refrigerator.

b. The heat flowing in from the warm environment never enters the liquid helium surrounding the coils of the magnets.

c. It is possible to reduce the temperature of the magnets by reducing the pressure of the boiling liquid helium. For instance, maintaining a pressure of 0.5 atm in the boiling helium system, a boiling temperature of 3.7° to 3.8°K may be possible.

The combination of (a) and (b) reduces the flow required for maintenance of a constant temperature to a minimum. This minimum is determined by the total heat flux to the 4°K temperature system divided by the heat of vaporization of liquid helium.

The preferred design also incorporates a thermal shield which surrounds the 4°K system and which is maintained at 15° to 20°K. Heat is removed from the shield by helium gas (at approximately 20 atm) flowing from the refrigerator through two tubes attached to the shield. The helium gas is returned through another two tubes to the refrigerator. The helium gas flowing through the shield removes the bulk of the heat entering from the warm environment. This reduces the required flow rate of 4°K-helium and improves the thermodynamic efficiency of the cryogenic system markedly.

The selected cryogenic system was examined in more detail to determine whether the advantages as described above can be realized in practice.

Heat Transfer

In order to maintain the temperature of the magnets at the lowest possible constant temperature, heat needs to be transferred efficiently from the magnet windings to the subcooled helium and then from the subcooled helium to the boiling helium. It is believed that the heat can be removed from the magnet windings by the subcooled helium present in cooling channels which are incorporated in the windings. As soon as heat is added to the helium from the windings, its density decreases. On the other hand, helium located outside the windings is cooled by the boiling liquid helium in the annulus surrounding the magnet vessel. Its density increases. The change in density of the two columns of helium sets up convection currents and helium starts to circulate. Calculations have been made to determine the flow rates obtainable as a function of channel dimensions and temperature rise of the fluid flowing through the channels of the windings. If the heat to be removed is of the order of 1 W per meter of magnet length, the temperature of the windings may be maintained at a temperature 0.1° to 0.2°K above the bulk fluid temperature outside the windings. The bulk fluid outside the magnet windings is cooled by the boiling liquid helium surrounding the magnet vessel. The heat transfer coefficients have been determined for the present configuration of energy-doubler magnets. Although the wall of the magnet vessel is made of stainless steel, the surface area available for heat transfer is so large that the temperature difference between the boiling liquid and subcooled helium can be maintained at 0.025°K. The mass flow rate in the boiling liquid helium channel is an important parameter in determining the type of flow in this channel.

The various types of flow which may be expected in a channel when a mixture of liquid and gas is present have been analyzed as a function of two parameters determined by fluid properties, fraction of liquid and gas, and dimensions. For good heat transfer it is necessary that the type of flow in the channel carrying the two-phase helium is "bubble" or "froth." It can be concluded that with the design flow rate of 115 lb/hr^2 with approximately 50% of the liquid helium vaporizing in passing through 120 meters of channel, the type of flow is always bubble or froth.

Pressure Drop

After the minimum flow rate required for satisfactory heat transfer was determined, pressure drops in the flow system were calculated. The pressure drop of the high pressure flow in the magnet vessel and the boiling helium in the annulus surrounding the magnet vessel for a distance of 120 meters is:

Flow rate of liquid helium	115 lb/hr
Pressure drop of subcooled helium	1.65 psig
Pressure drop of boiling liquid helium	0.56 psig

Refrigerator Requirements

Magnet supports and insulation have been determined with sufficient detail to permit a reasonably accurate estimate of refrigerator requirements. The various heat loads at the 4°K and 20°K temperature level for a refrigerator serving a module with a total length of 240 meters are as follows:

Refrigeration at 20°K		650 W
Refrigeration at 4.4°K		
Pump work	120	
Heat in magnets (ac)	240	
Heat from 20°K environment	20	
Miscellaneous	60	
		440 W
Liquid helium for leads		50 liter/hr

This is equivalent to a helium refrigerator with equivalent capacity of 720 W at 4.4°K.

Backup Information

The main refrigeration system design work for the Energy Doubler was subcontracted to Cryogenic Consultants, Inc. (CCI), of Allentown, Pennsylvania, beginning in November 1972. This is the same group that worked on the NAL 15-ft bubble chamber refrigeration system design from July 1970 through 1972. Their report "Refrigeration System for the NAL Energy Doubler" of April 26, 1973, was widely circulated with a request for critical comment. In addition to carrying through a complete preliminary design, they also performed a cost analysis of the system which was separately reported to NAL. Research and development effort was identified and pursued as can be seen from the discussion in Chapter 4.

As a part of its design activity, Magnetic Corporation of America (MCA) performed some calculations on radiation losses and pressure drops which served as a partial cross-check of the work of CCI.

In December 1973, NAL contracted with the Cryogenics Division of the National Bureau of Standards to develop and evaluate information from the large helium refrigerators used in the Kansas gas fields for helium extraction from natural gas. Their report, "Operating Experience - He

Extraction and Liquefication Expansion Devices" of January 1974 covers a total of 35 years of high capacity helium refrigerator operation.

Also in December 1973, NAL hired R. B. Jacobs Associates of Boulder, Colorado, to independently check all the heat transfer, pressure drop, and capacity calculations of CCI. This work is to be completed by February 1974.

The most active commercial helium refrigerator manufacturer is Cryogenic Technology, Inc. (CTI) of Waltham, Massachusetts. Various design studies, including cycle design, compressor investigation, reliability studies, and cost schedule estimates, have been carried out by CTI. This work is summarized in their report of January 25, 1974.

These activities are described in more detail in Appendix 2, Page 76.

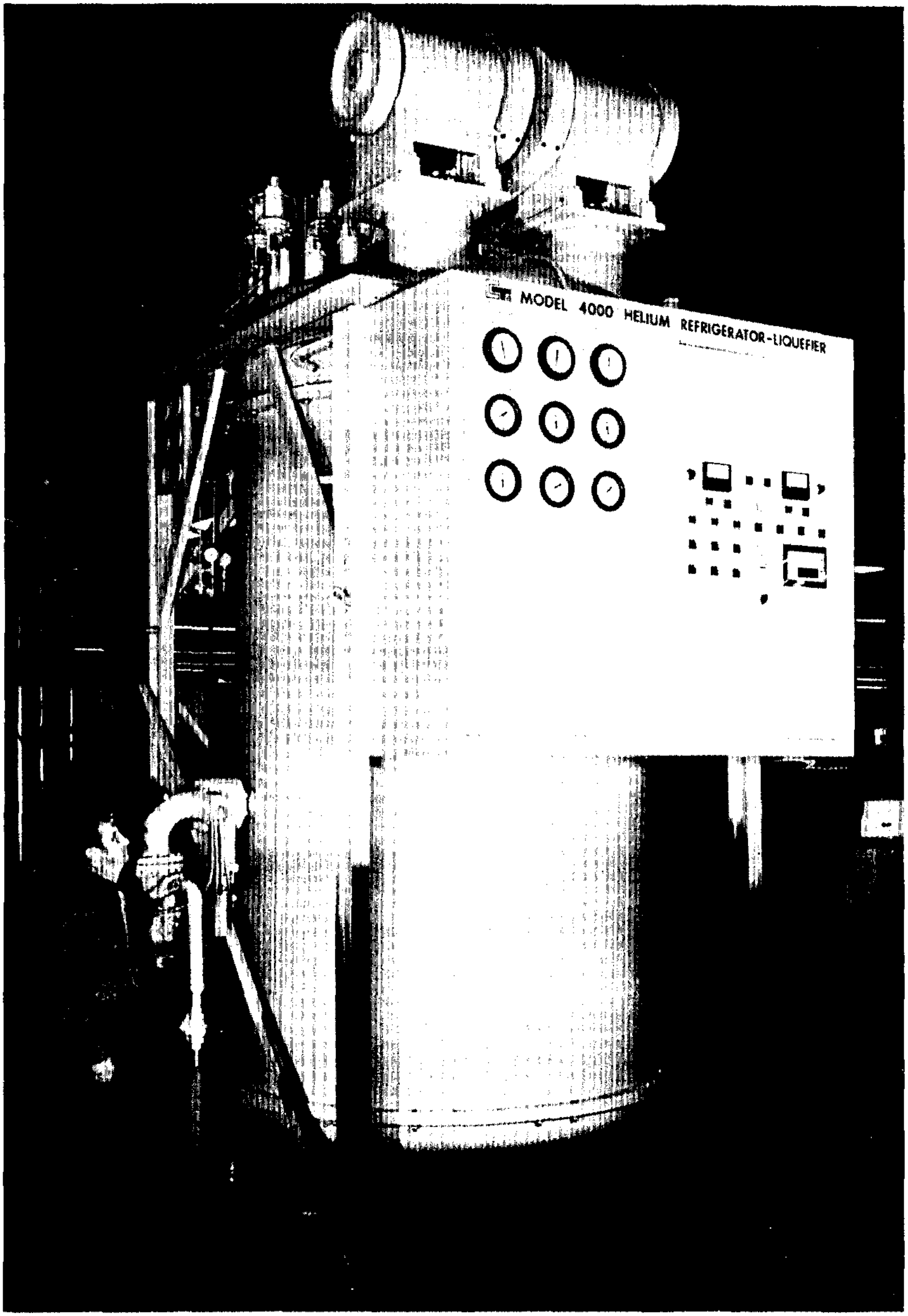

Figure 1. 700-Watt, 4.5°K Refrigerator, Brookhaven National Laboratory. Manufactured 1972.

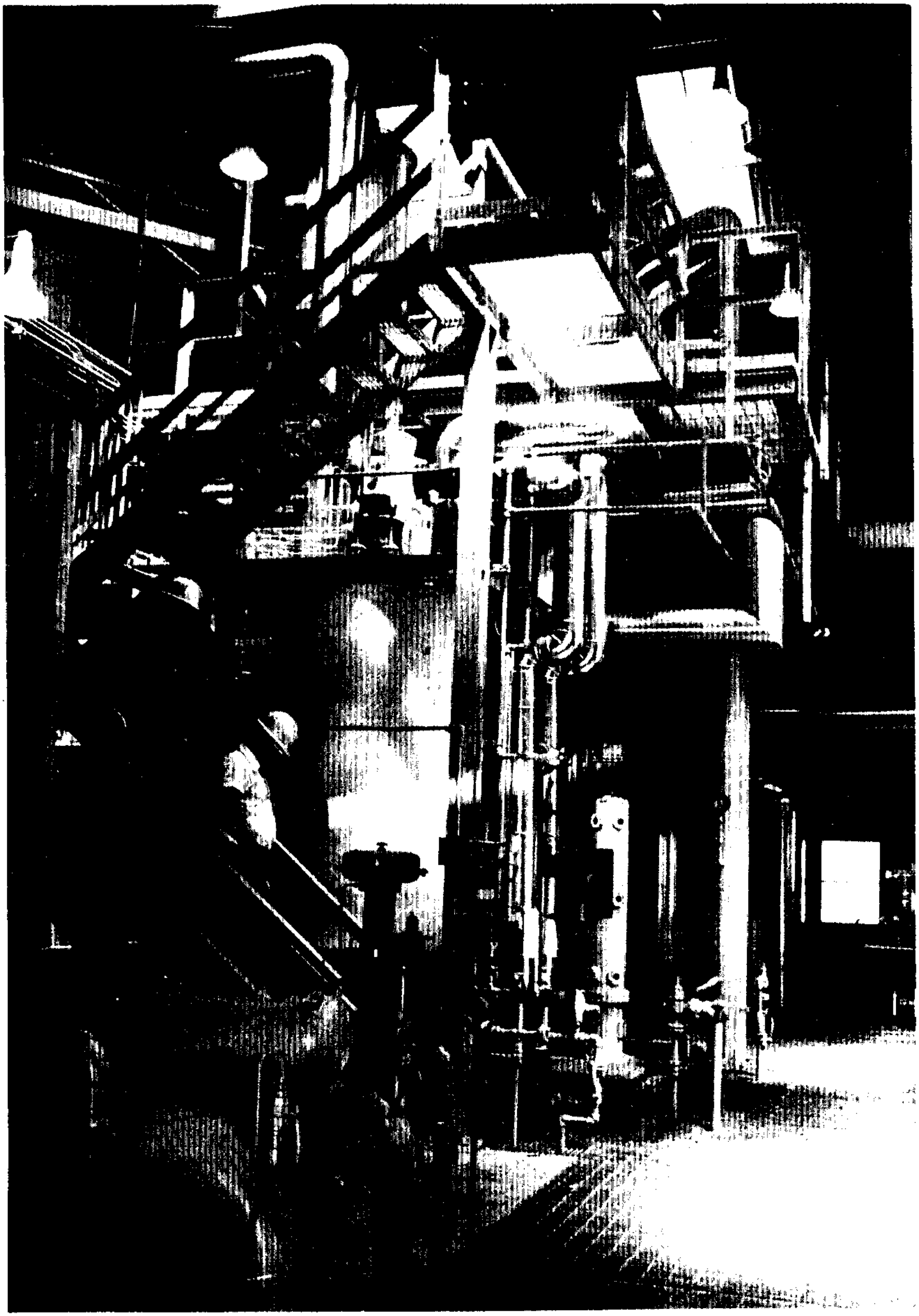

Figure 2. Cities Service Helium Liquefication Plant, Ulysses, Kansas (6 KW capacity).

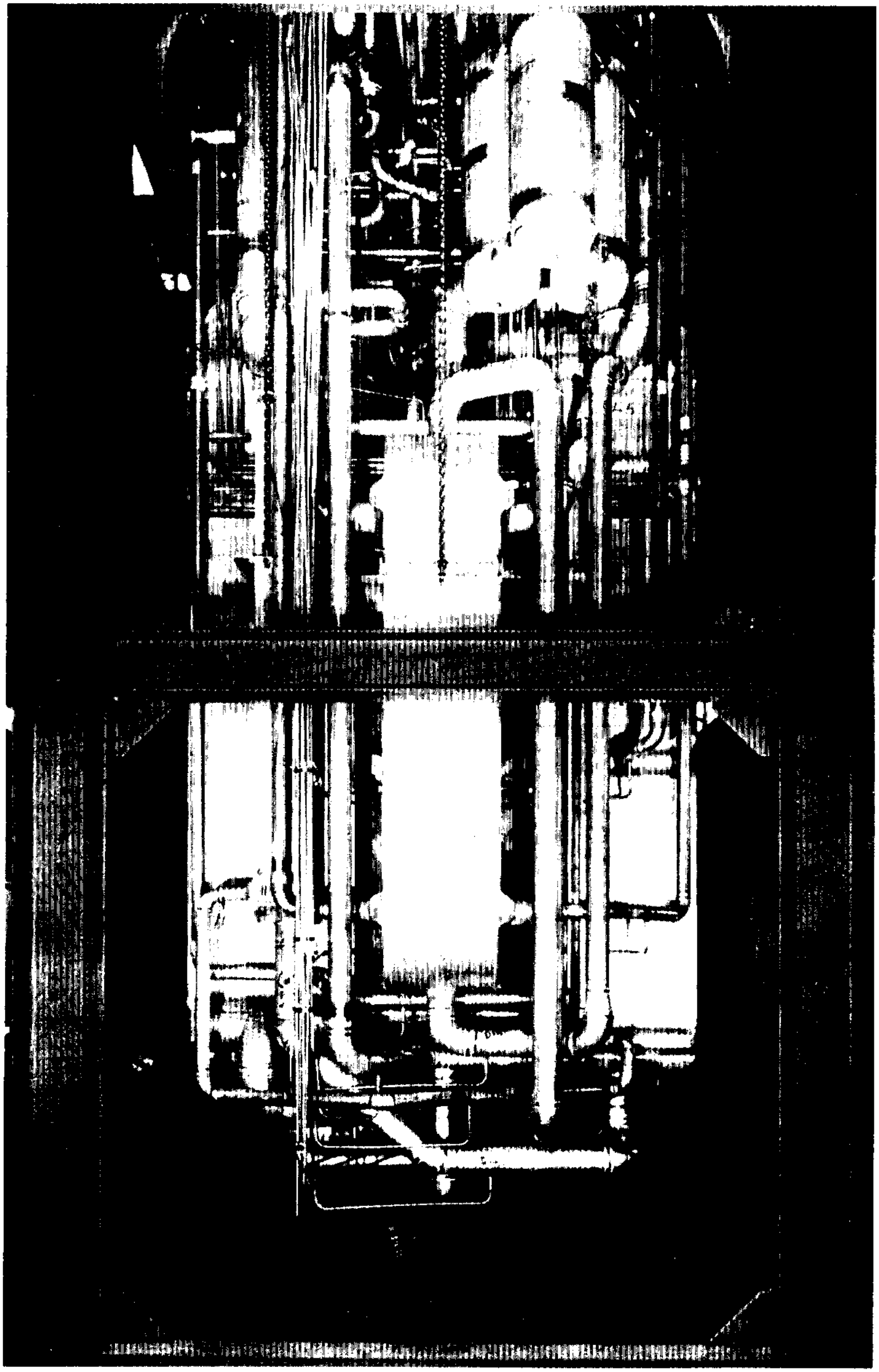

Figure 3. Cold box of Cities Service Plant.
Manufactured 1972 by C.T.I.

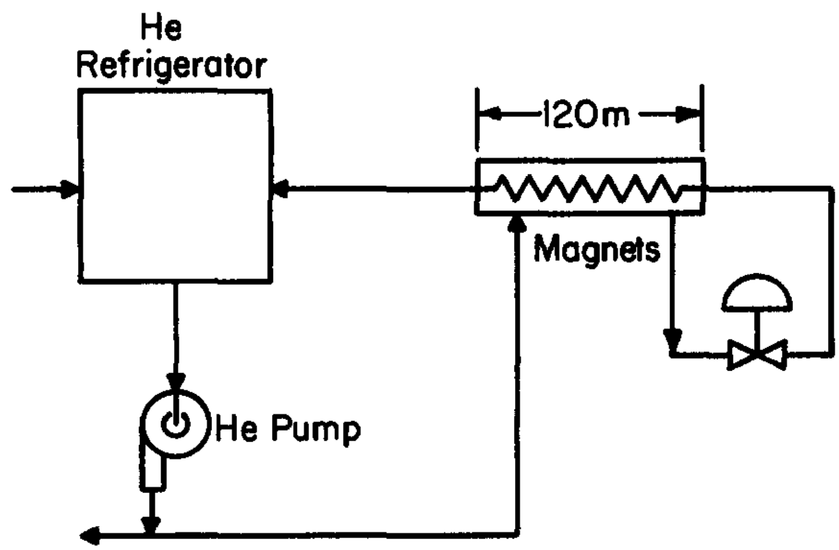

Figure 4. Schematic flow arrangement of one module of a cooling system devised by P. Vander Arend. See text, Page 14.

CHAPTER 4

LIQUID HELIUM PUMP LOOP

INTRODUCTION

The discussion describing the refrigeration system of the Energy Doubler points to a number of parameters which are important for proper functioning of the system. Large pumped helium systems of this sort have not been built; accordingly, a significant effort in the design study is the construction and testing of a liquid helium pump-loop on a scale large enough to provide experimental verification of energy-doubler refrigeration concepts.

Experimental work is in progress on the liquid helium pump-loop to investigate the following specific items of the energy-doubler magnet refrigeration system:

a. Pressure drop of a stream of subcooled liquid helium flowing through a series of magnet dewars and connections.

b. Pressure drop of a stream of boiling liquid helium flowing in an annulus around the magnet dewars.

c. Heat transfer between the streams of (a) and (b) above.

d. Pump characteristics of a liquid helium pump which circulates liquid helium through the system. Included in this is the heat input by the pump under various operating conditions. It should be realized that, so far as we know, there are only two centrifugal liquid helium pumps of this capacity in operation.

e. The possibility of thermal oscillations occuring in pipes or tubes connecting the liquid helium system with the ambient temperature environment.

f. Pressure and temperature stability of a magnet system consisting of a number of magnets in series.

g. Venting capability of the system when one or more magnets "goes normal," i.e., it loses its superconducting property.

h. Operation of magnets at temperatures below 4.2°K.

Helium Pump Loop Description

The basic pump-loop system is shown in Figure 5. Refrigeration is provided by a 150 to 200 liter/hr helium liquefier (equivalent to 600 W of refrigeration at 4.5°K) which makes liquid into a reservoir. The reservoir contains a liquid helium pump which circulates helium through the pump loop.

In addition to the liquid helium pump, the liquid helium reservoir contains a heat exchanger, which (together with a vacuum pump added to the system) makes it possible to operate the helium pump-loop at temperatures as low as 3.6°K.

The pump loop in its basic form consists of two lengths of 200 ft of coaxial pipe (1.315-in outer diameter inside a 2.245-in inner diameter pipe). The two systems are connected in series. The helium pump forces liquid to flow through the inner tube. At the end of 400 ft the liquid is expanded through a valve, and low-pressure liquid helium returns through the outer annulus to the liquid helium reservoir. The low-pressure helium in the annulus boils and cools the inner supply pipe and the liquid helium inside it. The boiling helium also intercepts heat from the environment passing through the insulation of the loop. Typical temperatures of the supply and low pressure return streams are 4.6°K and 4.4°K, respectively. Pressure difference between the two streams is 5 to 15 psig. The pump loop is equipped with temperature, pressure, and flow indicators; electric heaters may be inserted in the inner pipe of the loop.

It is intended that energy-doubler magnets be installed in the loop by removing sections of pipe and replacing these with energy-doubler magnets. Until magnets become available, an interesting and useful test program is being carried out with the loop.

Test Program Without Magnets

The following parameters may be evaluated before magnets are installed in the loop:

a. Pressure drop of a stream of subcooled liquid helium.

Temperature indicators (helium vapor pressure thermometers), together with pressure indicators will verify that the liquid in the 1-in inner stainless steel line is subcooled. Flow rate and pressure readings will provide data for verification of pressure drop calculations of the 1-in inner line.

b. Pressure drop of a stream of boiling liquid helium.

The pump loop as is will generate qualitative data on the pressure drop of the boiling liquid helium stream. The addition of a liquid nitrogen-cooled shield and the addition of controlled amounts of heat will better control the relative amounts of liquid and gas in the fluid. This will enable us to more accurately evaluate the pressure drop of the boiling liquid stream.

c. <u>Heat transfer</u>.

The arrangement for evaluating heat transfer between the streams of subcooled and boiling liquid helium is shown in Figure 6. Heat is generated uniformly in the electric heater and transferred to the flowing subcooled helium. TI-1 and TI-2 are helium vapor pressure thermometers. The flow rate is measured at the pump discharge. The rate of heat transfer between subcooled liquid helium and boiling liquid helium is equal to the amount generated, when TI-1 equals TI-2.

d. <u>Pump characteristics</u>.

The liquid helium pump, shown in Figure 7, was purchased from Sunstrand Aviation, and was developed for our application based on their experience with liquid hydrogen pumps. The pump performance may be evaluated by measuring flow rate versus head developed. To illustrate, a typical operating condition would be a flow of 3 gal/min with a pressure rise across the pump of 8 psi. Power input may be measured by reading the temperature of the fluid downstream of the pump.

e. <u>Thermal oscillations</u>.

It is well known that liquid helium systems which are connected to ambient temperature systems through long and narrow tubes may show oscillation phenomena. These thermal oscillations are intolerable in the energy-doubler magnet system. If they occur, large amounts of heat may be transported into the low temperature fluid and local hot spots might develop. In addition to this, mechanical vibration of appreciable magnitude may be generated. A set of experiments which show under what conditions thermal oscillations may occur and may be suppressed is described in References 1 and 2. These data will be verified with the pump loop.

Test Program with Magnets

As soon as energy-doubler magnets become available for installation in the loop, data will be obtained for the following:

a. Heat transfer from magnet subcooled helium to boiling helium.

b. Pressure drop of the liquid helium streams.

c. Thermal oscillations.

d. Pressure and temperature stability of the magnet system.

e. Venting capability of the system when one or more magnets go normal.

f. Operation of the system at temperatures below 4.5°K.

Test Results to Date (January 24, 1974)

The system has been operated for two runs: one of 109 hr and one of 70 hr duration. These tests were very valuable in gaining operating experience with the system, and some progress was made in carrying out the program of measurements described on Page 22. Further runs, with improved instrumentation, to complete the initial phase of the test program are scheduled for the near future; our preliminary results are summarized below.

a. Pump characteristics.

The flow rate versus developed head curve is in agreement with the predictions of the manufacturer. Power input to the helium stream will be studied in the next run.

b. Pressure drop.

Under all flow conditions, pressure drops in both helium streams were quite low (in the tenths of a psi range). Comparison of the measured and calculated performance is in reasonable agreement for our present instrumentation.

c. Heat transfer.

Calculated and measured heat transfer coefficients between the two helium streams are in good agreement. Quality of the fluid in the return flow aperture has not yet been studied.

d. Thermal oscillations.

In the initial run, thermal oscillations, sometimes of magnitude sufficient to cause visible motion of the entire pump loop, were frequently observed. In the second run, oscillations were suppressed completely at pressure differentials below 8 psi between the two streams, after the system had been modified to incorporate cold check-valves. Mild oscillations at higher pressures are believed to be associated with a leak in one of the check-valves.

e. <u>Dumping of energy</u>.

Heat was added to the subcooled helium of the inner pipe at a rate of 6 kW for 4 min (1.44×10^6 J). The pump loop handled this energy dump with surprising ease, without exceeding the design pressures of the system.

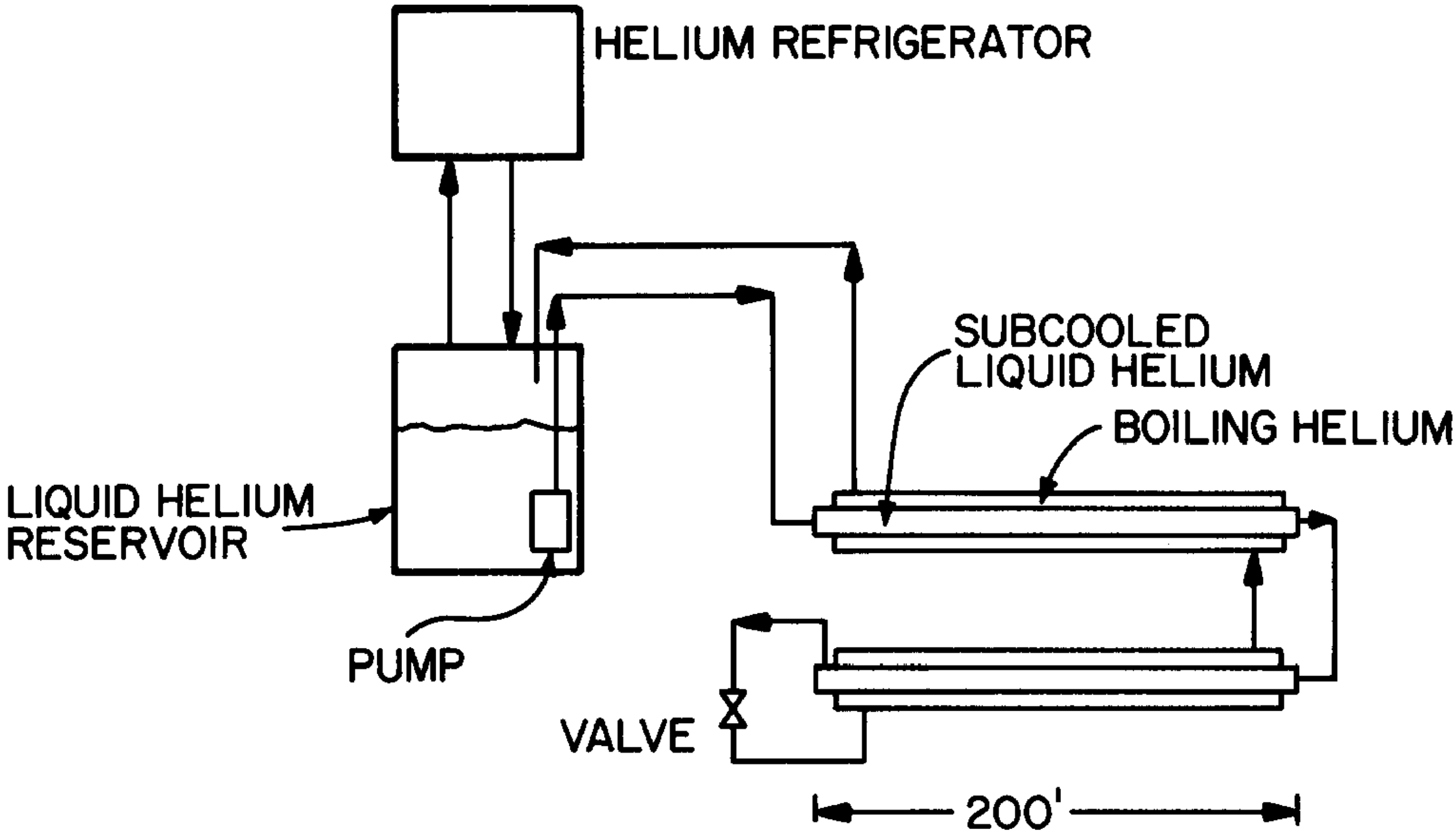

Figure 5. The basic pump-loop system.

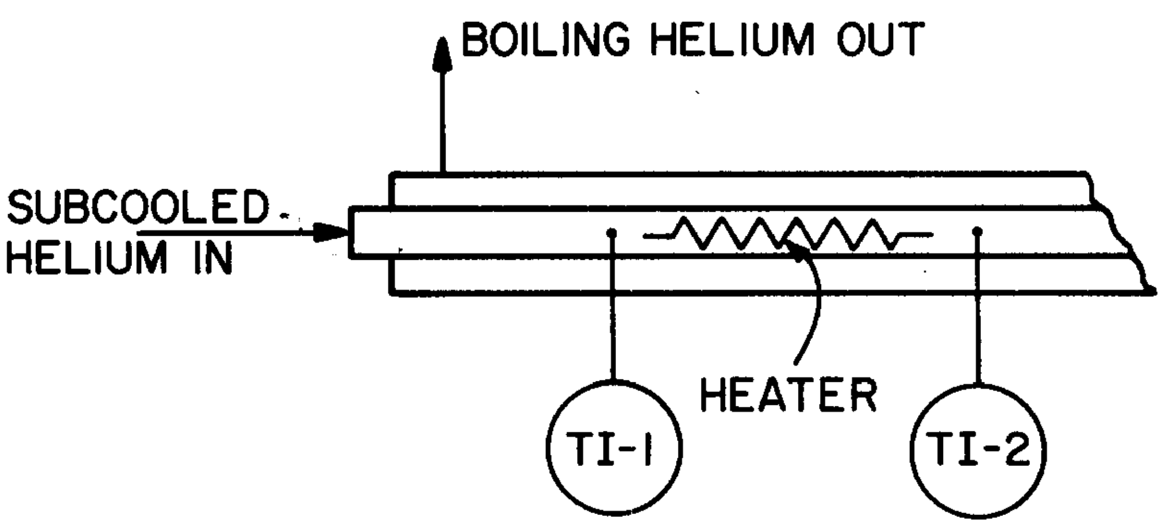

Figure 6. Arrangement for evaluating heat transfer between the streams of subcooled and boiling liquid helium.

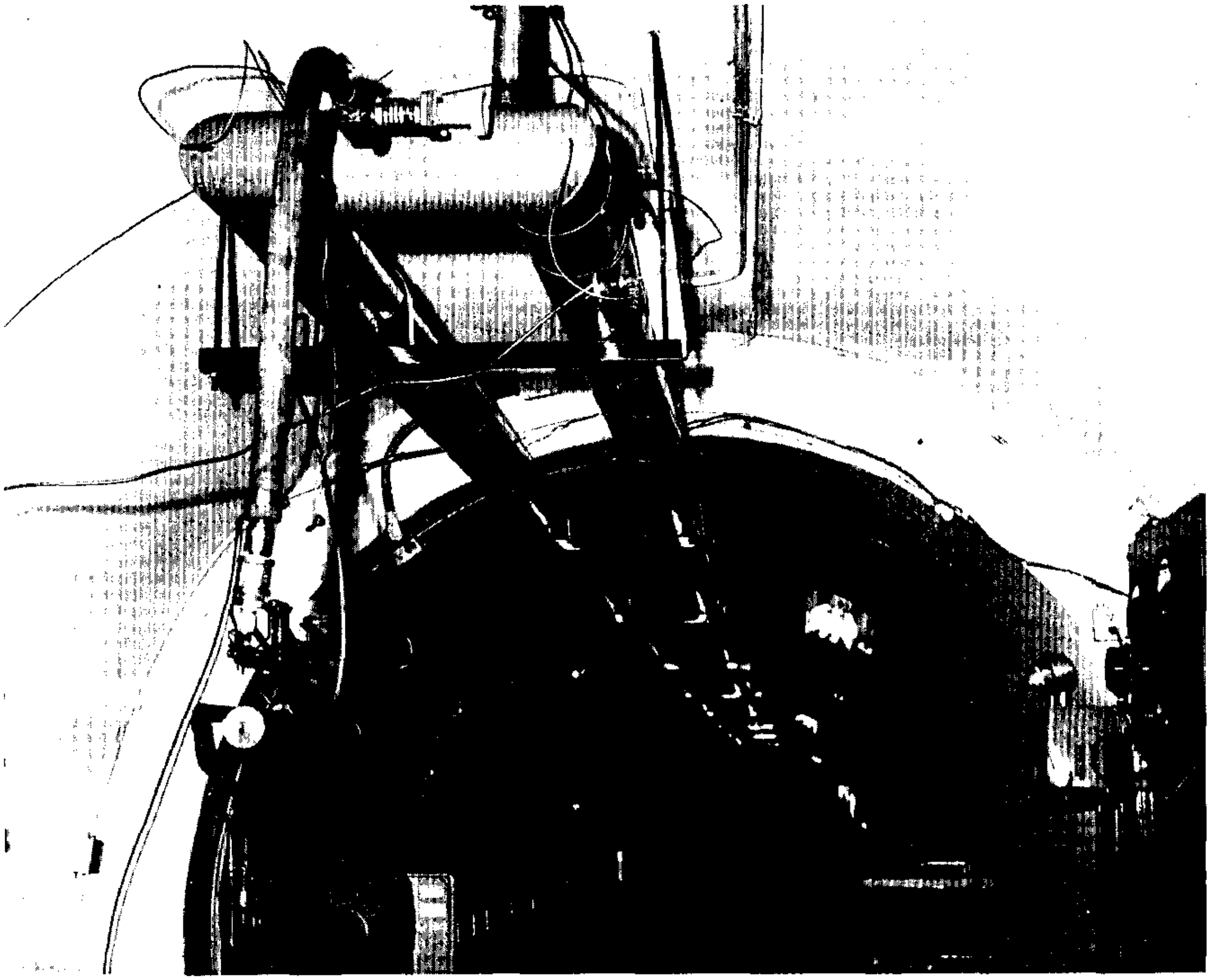

Figure 7. Helium pump loop suspended from ceiling of Protomain enclosure. Liquid helium enters at far end of 200-ft tunnel. Prototype main accelerator magnets are visible at lower left.

CHAPTER 5

WIRE SELECTION FOR THE ENERGY DOUBLER

INTRODUCTION

In view of the high cost for the superconducting magnet wire for approximately 1000 magnets, we are interested in obtaining a high current density wire which will operate at a reasonably high over-all current. We would expect to attain this goal, however, only if the wire could be reliably and economically produced and if the splicing problems for higher currents continue to present few problems. With the present design concepts, we have a requirement for about 6 million ft of superconducting wire. We expect that for these lengths of conductor, production economics of scale should set in and cost should come down to some asymptotic level which may be substantially less than half of present costs. In addition, the cost difference between a relatively sophisticated small filament cable and a larger filament wire should also be small and in fact the cost difference, if any, may be wiped out by the savings in refrigeration. Needless to say, an order of this size will have a major impact in the superconductor industry and our price assumptions are based to some degree on this perturbation. Our expected cost per foot as a function of total length is shown in Figure 8.

Our initial concepts for the Doubler were for an accelerator which would pulse at a rate of once every 100 sec and would have total ac losses of about 1 W/meter. Magnets were developed with approximately 5-cm bores using a graded conductor concept which allows us to operate the conductor at higher current density in lower field regions of the windings with a possible savings in wire costs. At a field of 45 kG, the conductors are to operate at a transport current of 2815 A corresponding to a current density of 42.6 kA/cm^2 for the large size and 64.8 kA/cm^2 for the smaller size. As a result of these requirements and the responses to our invitation for bids, two conductors from two manufacturers were chosen. Their characteristics, listed in Tables I and II, will be discussed later.

CONDUCTOR CHARACTERISTICS

Although superconductors have zero resistivity when operated in the dc mode, movement of flux throughout the winding may cause high thermal losses. Even worse, losses or heat fluctuations resulting from mechanical movement might cause the conductor to revert to the normal state. We are faced with the problem then that the severe heat transfer restrictions and the difficulty of restraining the conductor motion will lead to a reduction of the maximum current density obtainable. To reduce the sensitivity of the conductor to these phenomena, it is "stabilized" by various techniques.

Methods of stabilization can be classified into the following three categories:

a. Cryogenic stabilization, which, in essence, is the provision of an alternate path of high conductivity material to shunt the superconductor. The heat flux per unit area of conductor with all of the current in the shunt must be less than a certain critical value, the pool boiling limit. For small passages the engineering limit is 0.3 W/cm^2 or a local temperature rise of less than 0.5°K.

b. Enthalpy or adiabatic stabilization, in which attention is concentrated on the superconductor itself and heat transfer is neglected. The stability criterion is determined by postulating a small change in flux, computing the temperature rise, and determining whether the resulting temperature, associated with the flux change, is compatible with the ambient operating conditions.

c. Dynamic stabilization, which is obtained by the presence of enough low resistance filler to impede flux flow into the superconductor, thus damping any magnetic instabilities that might exist. Any heat generated in the filaments is carried away by the high thermal conductivity matrix, and a thermal steady state may be reached.

Due to the high over-all current densities that are required by the dipoles, the first method is of very little utility in our application. This method, however, is well understood and has been utilized and proven in many large magnet systems, particularly bubble chambers. We must rely on a combination of the other two methods.

The second criterion may be expressed as an upper limit on filament size; for NbTi the filament diameter must be less than 40 μ. The third implies that our desire for a high current density is linked to the purity of the matrix material.

But effective dynamic stabilization will lead to unacceptable eddy current losses in the time-varying fields associated with an accelerator unless counter measures are taken. These so-called coupling losses may be reduced by twisting the conductor, so that the eddy current circuit linking two superconducting filaments is reduced to a distance of the order of the twist length.

For our conductor, this condition implies a twist pitch of about one per inch. Additional reduction of coupling losses may be effected by introducing barriers of high resistivity material in the cross-section of the conductor. We will discuss ac losses in more detail in the next section.

In our first specifications for the wire, it was assumed that the magnets would be operated in subcooled liquid helium at about a temperature of 4.6° to 4.9°K. This imposes a degradation on the conductor performance of some 20% compared with 4.2°K. It was also assumed that the conductor would be operated at 80% of the short sample current for a given ambient temperature and field. Our present concepts for refrigeration indicate that it may be possible for us to operate at temperatures of 3.8° to 4.2°K.

LOSSES IN TIME-VARYING FIELDS

Care must be given in the choice of wire in order to minimize the ac losses which are proportional to the diameter of the individual filaments, the twist length, the peak field, the ramp rate, and the over-all conductor size. The losses are also inversely proportional to the effective resistance of the composite which depends on the resistivity of the normal metal matrix as well as on other construction, metallurgical, and geometrical factors.

The dominant sources of conductor ac losses in the Doubler are hysteresis and eddy current losses. Hysteresis losses are caused by the fact that type II conductors above the Meissner limit exhibit a "resistance" whenever the field is changed. An estimate of this loss can be obtained by equating the power loss to the product of the electric field, caused by the changing magnetic field, times the current flowing along this field. Eddy current losses are caused by a changing magnetic field passing through the normal conductor which induces a voltage across the non-superconducting matrix material. Currents driven by this voltage are dissipated as in ordinary joule losses.

Hysteresis losses in a superconductor are independent of field change rate and only depend on the peak magnetic field B_{max}, the critical current density J_c, the volume of superconductor V_{sc}, and the filament diameter, d_{sc}.

$$W_H = 10^{-8}\ B_{max}\ J_c\ d_{sc}\ V_{sc}\quad \text{(J/cycle)}$$

For our cycle, the loss can be approximated at one-half of the above.

On the basis of eddy current losses in transverse laminae, we can formulate the losses for an accelerator pulse in the conductor as:

$$W_E = \frac{\pi^2}{4} B_{max}^2 d_{cu}^2 f V_{cu} K\rho^{-1}$$

where

W_E = loss in joules per accelerator cycle

ρ = matrix resistivity

f = equivalent accelerator frequency

V_{cu} = volume of copper

K = empirical coefficient with $1 \leq K \leq 2$

d_{cu} = width of laminae

Taking K = 1 and postulating equivalent round diameters for the rectangular conductors, the values in Table III were calculated. These values provide a comparison of the contribution of these two types of loss to the total conductor loss for various conductors that might be used in the present design for doubler dipole magnets. It can be seen that the present conductor is adequate for a machine with a 100-sec repetition rate, but that at any faster rates we would be advised to go to smaller filaments, cabling, or the use of cupro-nickel in the matrix.

Conductor Procurement

Based on the above criteria, a repetition rate of about 1 min, and conductor losses of about 1 W/meter of a magnet, an order was placed for conductor sufficient to fabricate the magnets for our prototype program. Because our goal was to build magnets that could be easily fabricated in industry, a solid conductor, resembling "stiff" copper wire was chosen. This presented some problems at the over-all current densities we required in the superconducting alloy. Most conductors offered at that time optimized the critical current density by cold-working the wire. This would not have been possible with our combination of parameters. The response by MCA proposed using superconducting alloys that would optimize the critical current by the solid precipitation of submicroscopic normal particles within the filaments. All of the conductor they supplied has met our specification with regard to critical current and has provided current densities in the superconductor 30 to 50% above those available previously. With few exceptions, the windability (ductility) of this conductor has been excellent. Since we felt that the more important goal was to first establish the attainability of the high current density in a solid conductor and that, later, industry would be able to develop a similar wire but with much smaller filaments to reduce the losses, we feel that this procurement has been most successful. In fact, a resolicitation of all manufacturers for 1000 pounds of the same conductor for use in beam line magnets resulted in replies from an international representation of manufacturing concerns all proposing this type of high-current density wire. A cross-section of the wire, containing some 2000 filaments of 35-μ diameter is shown in Figure 9.

As shown in Table III, we were less than conservative in our initial choice of filament size if we wish to leave open the possibility of higher repetition rates at a later stage. We realized this, of course, at the outset and ordered a back-up cable conductor described in Table II. This cable is to be made up of seven individual wires, each with a cupro-nickel shell and with filaments smaller than 20 μ. After cabling, the wires will be rolled to the same shape as the solid conductor and filled with a high resistivity conductor before insulation with mylar tape. The break-up of the matrix with the cupro-nickel and solder should significantly reduce the superconductor loss by 50%. Because of production problems in the extrusion stage, we have not received delivery of this conductor at the present time. Upon delivery, we expect to fabricate two full-size magnets and compare losses.

As a result of our test program, we intend to resolicit all manufacturers on the basis of a new specification. Obviously, the filament size will be smaller, and we hope to obtain filaments on the order of 5 to 10 μ in diameter. We will probably choose either a mixed copper/cupro-nickel matrix or cabling to reduce the eddy current losses. We are considering participation in a cooperative development program with Los Alamos Scientific Laboratory and several manufacturers. This program has the goal of optimizing all phases of production of composite wires. Particular attention will be paid to the high-risk extrusion stage as well as to the adapting of large scale production techniques to the wire drawing stages. Quality control standards will also be generated. A secondary goal will be the development of techniques to use lower purity, less expensive, NbTi alloys by the addition of doping elements. Of course, benefits from such investigations are not likely to accrue immediately to the Energy Doubler effort.

For the immediate future, NbTi is the best choice for our application, since it can be fabricated into useful conductors and provides the highest critical current densities at our operating temperature. The use of high temperature, high current density β-W (A-15) type crystal structure conductors such as Nb_3Sn are not anticipated at this point. In the first place the only significant lengths of this type of material are manufactured as ribbons, a geometry that is neither optimum with respect to hysteresis, eddy current losses, or other magnetization losses. It is also quite brittle and hard to wind. Several attempts to fabricate a fine-filament stabilized conductor of this type have been reported; while seemingly successful in short lengths, lengths of sufficient quantity for our purpose have not been generated.

TABLE I

CONDUCTOR TO BE USED FOR FULL-FIELD, 1-METER MODELS AND FIRST 6-METER PROTOTYPE MODELS

Manufacturer	MCA, Inc.
Size 1	0.150 x 0.075 inches over-all
Size 2*	0.150 x 0.050 inches over-all
Asub/Asc	2/1
Number of filaments	2300
Filament size	35 μ
Twist	1 per inch
S.C. alloy	NbTi
Substrate	Copper
R300/R4.2	> 100
Insulation	Self-bonding polyvinyl formal (Formvar)
Minimum short sample currents	3500 @ 50 kG and 4.2°K
NAL specification	0428-090-52500

*This smaller cross-section wire will be obtained by drawing down the Size 1 wire bringing about an approximately 30% reduction in filament size.

TABLE II

CABLE CONDUCTOR FOR FULL-FIELD, 1-METER MODELS AND 6-METER PROTOTYPE MODELS

Manufacturer	Supercon, Inc., Natick, Mass.
Type	Cable of seven 0.036-in strands solder filled and rolled 0.150 x 0.075 inches over-all
Asub/Asc	2/1
Number of filaments	160/strand
Filament size	20 μ (0.0008 in)
Twist	2 per inch (strand)
S.C. alloy	NbTi
Substrate	Copper and cupro-nickel
R300/R4.2	> 100
Insulation	Wrapped mylar
Minimum short sample currents	3500 @ 50 kG and 4.2°K
NAL specification	As ordered under Subcontract No. 80110 dated 12/6/72

TABLE III

CONDUCTOR LOSSES PER METER OF MAGNET

	Present conductor (30 μ fil., 0.150- x 0.075-in)		
Cycle time	100.0	50.0	10.0
Hysteresis	0.55	1.1	5.50
Eddy current	0.0433	0.175	4.41
Total	0.5933	1.275	9.91

	Same matrix (5 μ-filaments)		
Cycle time	100.0	50.0	10.0
Hysteresis	0.11	0.22	1.1
Eddy current	0.0433	0.175	4.41
Total	0.1533	0.395	5.51

	7-wire cable rolled to fit 0.150- x 0.075-in envelope, 5 μ-filaments		
Cycle time	100.0	50.0	10.0
Hysteresis	0.11	0.22	1.1
Eddy current	0.0045	0.02	0.49
Total	0.1145	0.24	1.59

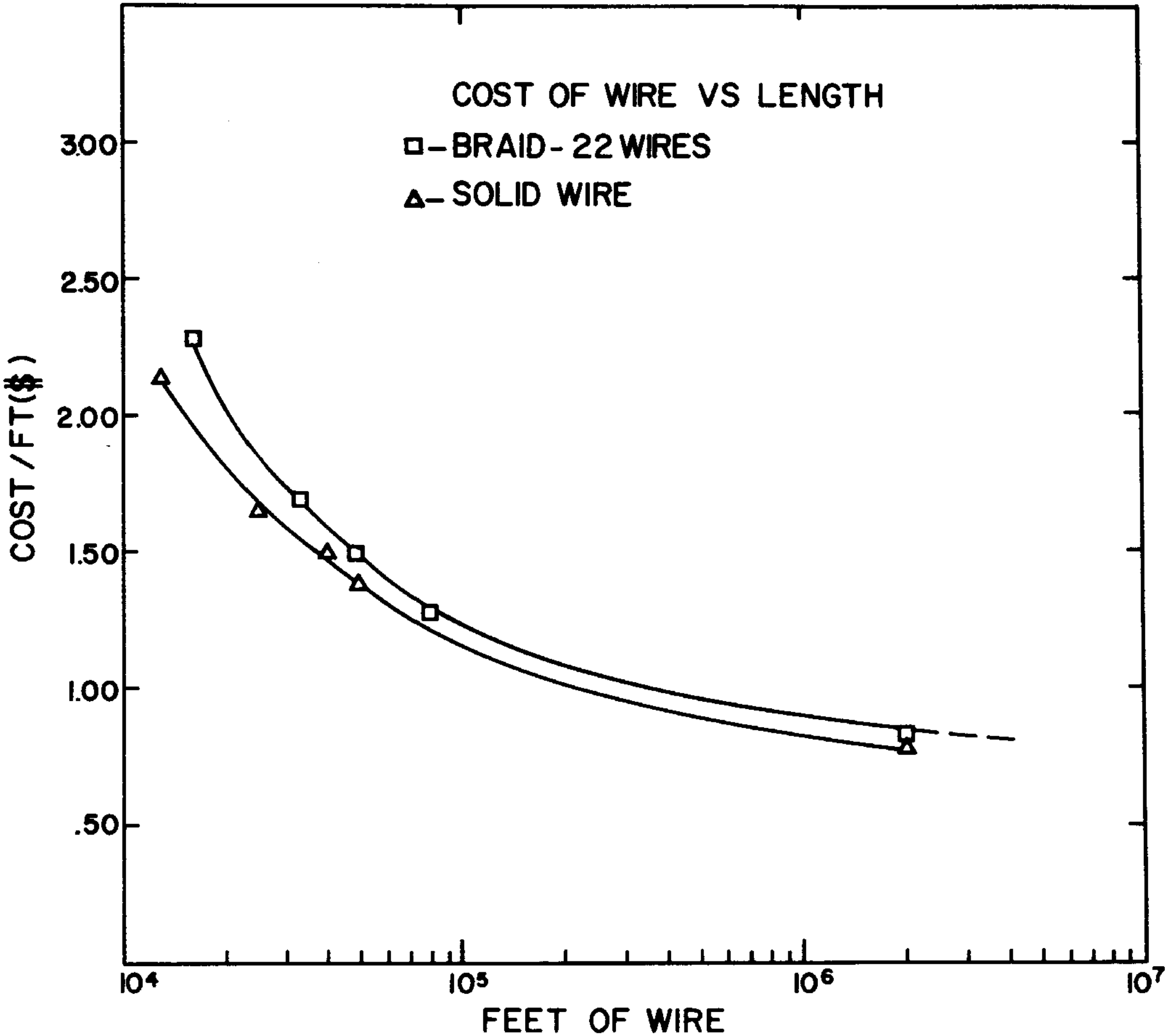

Figure 8. Expected cost per foot of superconductor, as a function of total length.

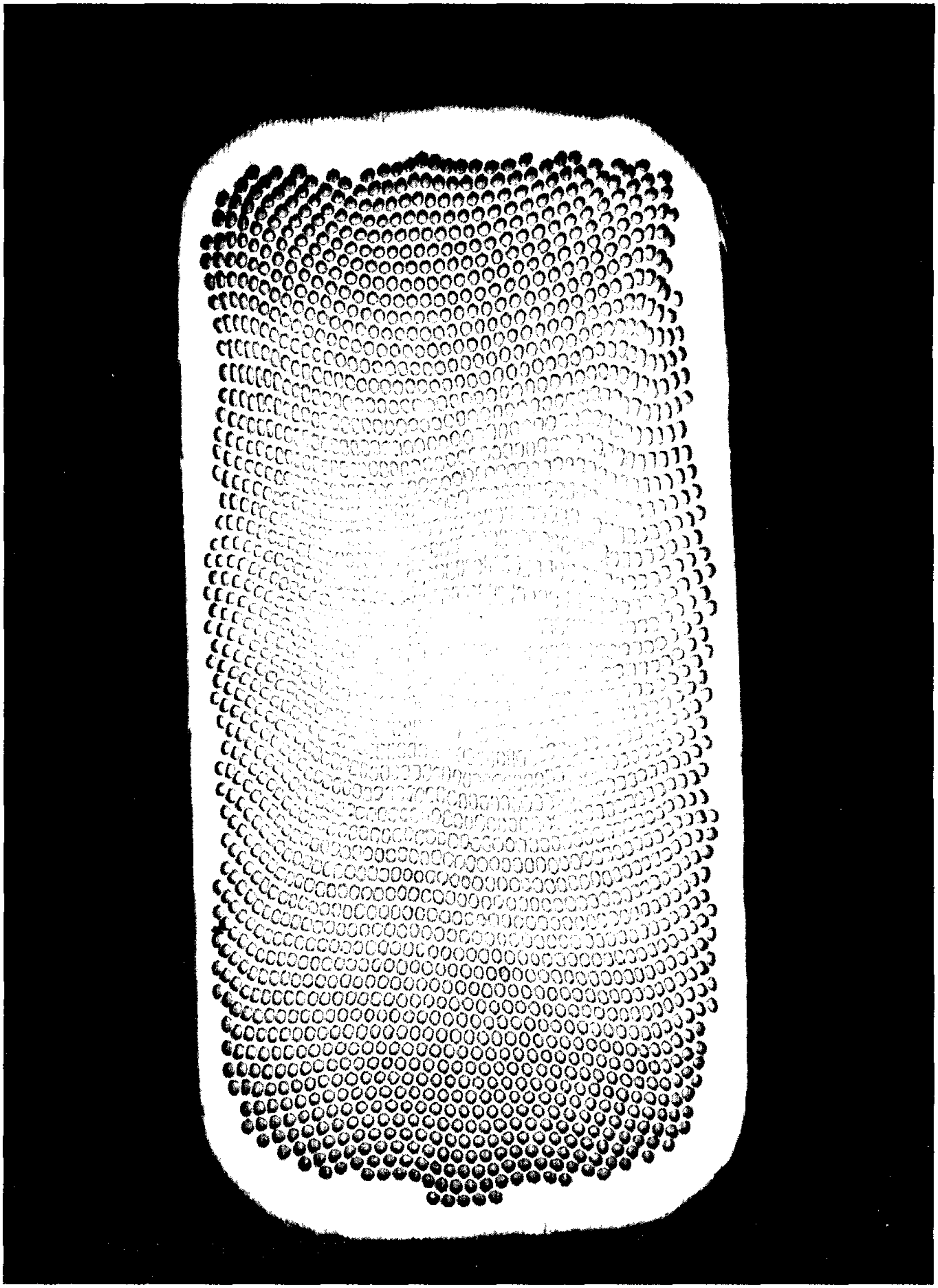

Figure 9. Cross-section of 0.075- x 0.150-in. superconducting wire magnified to show filaments of niobium-titanium superconductor embedded in copper matrix.

CHAPTER 6

MAGNET DESIGN AND FABRICATION

INTRODUCTION

In Chapter 1, we commented on criteria that were chosen as a basis for magnet design development. In the next section of this chapter, we will elaborate on these criteria and discuss their realization in current designs. Tooling and fabrication methods will then be treated. Thus far, most of our effort has been devoted to dipole magnets, and unless explicitly indicated otherwise the discussion in this chapter will be concerned with them.

Methods of field calculation are not described in this report, since the techniques are well known and appear in the literature. For the present, we are using as a design goal, the condition that the magnetic length not vary by more than one part in a thousand over a region similar in shape to the inner surface of the coil but 25 to 30% smaller in linear dimensions. In models constructed to date, this condition has been applied to the field in a transverse section only; calculations for magnets now under construction include end effects in arriving at a specification for conductor placement.

MAGNET DESIGN

It will be helpful to unfold Figure 10 while reading the discussion below. At the left in the figure, two transverse sections through the magnet are shown. The center part, a portion of a section in a plane containing the magnet axis, shows the force transfer scheme. An end design appears at the right-hand end of the drawing; we are currently re-examining this region of the magnet, but the drawing illustrates the functions associated with a magnet end and the magnet-to-magnet interconnection.

THE BEAM TUBE

Ideally, the beam vacuum tube should be as thin as possible to maximize beam aperture. However, the boundary of the good field region lies well within the inner surface of the coil and some of the intervening space is utilized to provide a stiff bore-tube as part of an elastic reaction system to the repulsive magnetic force on the conductors. This force amounts to 4200 lb/in at peak field. The reaction system will be considered in more detail under the heading "Banding System."

The beam tube is made of an inner vacuum tube of 0.032-in wall stainless steel surrounded with a molded epoxy-fiberglass coating to provide a quickly producible, stiff, accurate, and insulated base for the coils. Two central keys are molded along the tube's length. The first coil layer is butted to these keys; remaining coil shells are positioned with reference to the inner coil by additional key blocks placed in cutouts in the key.

THE COIL SYSTEM

The coils are made of three concentric shells. The conductor is graded in size for economy. The inner shell is wound from wire which prior to keystoning (see Page 44) is 0.150- x 0.075-in. in cross-section. Part of the second and all of the third shell are made of a smaller wire (0.150- x 0.050-in) usable in lower field regions. It is necessary to keystone the conductor from the rectangular shape supplied by the wire vendor in order to closely pack it into the shell configuration. The final size has to be held to $\pm$ 0.0003 in. in order to prevent excessive buildup of position errors in the larger conductor blocks. The bus conductor is an integral part of the coil bundle, taking the place of a missing conductor. It is isolated from other conductors with sufficient electric insulation to withstand voltages that may arise during a rapid de-energization.

The philosophy for cooling the coil is that 40% of one edge of every conductor is exposed to liquid helium. This is realized in a three-shell design by placing cooling passages between the first and second shells and on the outside of the third, between the mylar bands.

If the steel shield were to extend over the magnet ends, the highest field applied to the superconducting material would occur in the end region. To counteract this field enhancement, the steel shield stops somewhat short of the coil ends.

BANDING SYSTEM

The coils are held down to the beam tube with a series of pretensioned mylar bands. The system is designed to minimize elastic deflection of the coil bundle under magnetic load. The pretensioning works as follows. When the banding is applied, under tension, the coil-beam tube structure compresses slightly. As the magnet is energized, the reaction to the compressive force of the bands is provided to an increasing degree by the magnetic force on the coils and to a lesser degree by the high modulus bore tube as it expands. In the limit - the highest field at which the magnet will operate without excessive deformation - the bore tube is completely unloaded, and further field increase will result in the bands stretching according to their relatively low modulus of elasticity.

All the pretension formerly available to load and compress the tube and coils then is available to resist the magnetic load. Thus, very little coil movement results, even though the restraining bands are of low modulus.

An alternative would be to use a high modulus material as the outer banding. An appropriate fastening scheme and electrical insulation system have not been worked out but the idea may be considered for the future.

The advantages of mylar are ease of application, excellent mechanical properties at low temperature, positive differential shrinkage at low temperature to add to the pretension, and its insulation ability. As noted on Page 46, its application takes up an excessive proportion of the magnet production time.

HELIUM VESSEL SYSTEM

The magnet helium vessel system is formed by two concentric stainless steel cylinders. The inner vessel contains the coil and its single-phase coolant. The geometry of the oval coil bundle within the cylindrical vessel wall provides space above and below the coil which offers low impedance to liquid helium flow. An outer concentric two-phase helium vessel forms an annular space around the inner high-pressure vessel, which is sized to be consistent with the bubble or froth flow regime discussed in Chapter 3 of this report. Force transfer buttons are mounted in the annular space at 15-in intervals along its length to transmit forces to the exterior.

In the case of an over-pressure condition, a relief valve between the inner and outer vessels relieves one to the other. If the capacity of the outer vessel is then exceeded, its relief valve exhausts from the magnet.

SUSPENSION SYSTEM

The use of a room-temperature iron shield has a number of attractive features. At low temperatures the thermal mass is greatly reduced. Smaller surface areas for heat transfer from the environment are obtained. Within a given magnet cross-section, the warm iron shield is farther from the beam tube than a cold shield would be, resulting in reduced saturation effects. A disadvantage is that the iron cannot be called upon to directly counteract magnetic forces applied to the coil. Thus, the mylar banding system is required. But in addition, a displacement of the coil from the center of the shield leads to forces attracting the coil toward the shield. Accordingly, a strong but low heat loss suspension mechanism must be interposed between the helium vessels and the warm shield. The off-center force is the dominant factor in determining the conductive heat leak of the cryostat to the outside world.

The increase of off-center error force with distance is 0.711 lb for every thousandth of an inch off-center along every inch of length. Our suspensions are designed to have five times this spring rate. For example, for 15 in of length between suspensions and an initial error of 0.020 in. in centering, a suspension is initially subjected to 0.711 x 15 x 20 = 213 lb. The suspension reacts at five times this, or 1065 lb/in. Equilibrium is reached at 125% of the original position error. Thus, the additional elastic movement of the entire bundle is 0.005-in.

The suspensions evolved to date consist of two concentric rings separated from one another by yarn of Kevlar (a new DuPont material) acting as tension spokes. Kevlar has the highest ratio of tensile modulus of elasticity to thermal conductivity of the known commercial materials. The space between rings is filled with superinsulation to cut down radiant heat leak. The suspensions are made as independent units and slid into place using final shimming to center them on the cryostat. Cooldown shrinkage of the cryostat forces it to slide through the inner rings of the suspensions toward the center. The suspensions are fixed on their outer surface in contact with the steel and hence do not move.

The suspensions are part of the force transfer system designed to be stiff and to maintain its stiffness after cooldown. Starting from the coils, the force is transferred by force transfer blocks banded to the coils during assembly. The force is then transmitted through the force transfer buttons between cryostat vessels and hence to the suspensions through shims. Flexibility of the thin cryostat shells allows clearance takeup. From the suspensions, the force transmits directly through to the steel shield.

OUTER VACUUM SYSTEM

The vacuum space between the steel and the cryostat is formed by a split tube mounted over the suspensions and welded along its length. It is made to fit snugly between the steel laminations and the suspensions. The suspension outer rings are relieved at the weld point to prevent heat deterioration. The space between suspensions is filled with superinsulation to reduce the radiant heat leak. Vacuum pumping of the insulation space takes place through the threads of the suspensions and the layers of superinsulation. A shield cooled to 15° to 20°K can be threaded through this space as well as through the suspension. An intermediate heat shield of this sort will be included in our next set of prototype magnets.

IRON SHIELD SYSTEM

The iron shield is made of laminations because they are easily stamped and stacked to the tolerances required. It forms an approximate cosine distribution about a circular bore. It is split into two half cores along the vertical plane. The laminations are held into a pack by tie plates running the magnet length in the horizontal plane and welded to stiff end plates. There is no web to take the shear load if the magnet is supported at the ends. Thus the cores are to be impregnated with epoxy which substitutes for the web very adequately. The cores are stacked curved to a precamber to produce an eventual straight magnet under gravity load. In addition, it is possible to curve the magnet in the horizontal plane to approximate the 1/4-in sagitta correction necessary to increase beam aperture.

THE END JUNCTION BOX SYSTEM

At each end of the magnet, provision must be made for connection to its neighbor of (i) the beam tube, (ii) the two helium vessels, (iii) the two current leads (the internal bus conductor results in the magnet becoming a four-terminal device), (iv) the outer insulating vacuum chamber, and (v) the intermediate heat shield when this feature is incorporated into the design.

Referring to Figure 10, the outer vacuum insulation space is connected from magnet to magnet by a junction box on the magnet ends. It consists of an enlarged tube which acts as a bulkhead for utility feedthrough, such as vacuum and pressure relief, and a flexible bellows. The joint is made by means of an Aeroquip type flange with an O-ring seal. This provides the rotational freedom necessary for magnet alignment.

Movement of conductors in a field causing friction heating at any contact points is a significant problem in superconducting magnets. This is especially so for all leads which tend not to be part of a well constrained bundle. The intercoil lead splices in this design are all brought to the end of the bore tube where they are mounted in slots in a low field region. They are then easily held down rigidly by banding. Similarly the conductors leading to the splice are easily held in slotted blocks properly banded. The beam tube is connected via a small flange and bellows directly to the next beam tube. This connection is entirely within single-phase helium. The single-phase vessel is connected concentric to the beam tube. A flexible bellows is used to gain access to the internal vacuum flange and lead splices. The lead splices form a simple omega strain relief in this space, bridging between solid support points on each coil bundle. The two-phase outer jacket is bulkheaded and the flow bridges across the top via a smaller tube. A small tube through the single-phase vessel into the bore tube provides vacuum access to the bore. The low thermal conductivity tube then connects it to the outside vacuum bulkhead. Pressure relief of the two-phase vessel to the exterior is through a low heat conductivity stack through the junction box bulkhead.

QUADRUPOLE MAGNET DESIGN

A cross-section of a quadrupole magnet is shown in Figure 11. A circular bore is used, since it can be easily accommodated within the design envelope (determined by the dipole magnets) as a result of the smaller coil area and lower forces in the quadrupoles. Only two shells of conductor are needed, both using the higher current density throughout. The upper and lower coils are split to provide percolation slots; to maintain symmetry, similar slots appear between coil turns at the mid-plane.

MAGNET FABRICATION

The fabrication techniques used for the energy doubler magnets must assure:

- Extreme accuracy

- Extreme rigidity at operating temperature

- Repeatability

Since about 1000 magnets are required, without sacrifice of any of the above items, the fabrication techniques must also lend themselves to low-cost mass production.

The coils must be accurate to within one or two thousandths of an inch, with individual conductors accurate to about twice this tolerance. Equally important, the coils must be supported in such a way that they will not move when subjected to the high magnetic forces induced at cryogenic temperatures. Finally, the errors which do exist must be predictable and repeatable throughout the entire production so that proper correction can be applied. Certain aspects of the fabrication procedures discussed below are illustrated by the photographs at the end of this chapter.

CONDUCTOR

The over-all accuracy is dependent upon that of the individual conductors. Using the shell concept, the proper shape of the conductor is trapezoidal or keystoned in cross-section. The conductor is typically 0.0750-in $\pm$ 0.0003-in on the wide edge and 0.0636-in $\pm$ 0.0003-in on the narrow edge by 0.156-in $\pm$ 0.002-in high (radial direction). This is accomplished by running the 0.075- x 0.150-in conductor through a set of rolls. The conductor is preinsulated with a heavy coating of Formvar. There have been no signs of damage by this rolling operation. We are also investigating the feasibility of having the wire manufacturer, Magnetic Corporation of America, keystone the wire before coating; but in any case, we would follow this with a final rolling since MCA cannot guarantee that the close tolerance required will be maintained during application of insulation.

The keystoning was originally an "in line" procedure as part of the coil winding operation. This presented some problems in winding double layers. It has now been made a pre-operation which has the benefit of going on in parallel, permitting the coil winding to proceed at a faster rate.

Since the filaments of the superconductor are twisted along its length, the keystoning operation tends to twist the conductor. The keystoning device has a reverse twist feature built into it so that the conductor comes out straight.

The wire is constantly monitored for uniformity of cross-section, straightness, malleability, and quality of insulating coating.

COIL WINDING

Coil winding is considered to be the most critical operation, both technically and schedule-wise, and therefore it should receive the greatest attention during production. While it should receive the largest slice of production time, it should be perfected to minimize the time for this operation and all other operations kept to a proportionately lesser slice of time.

Normally coils are wound on a rotating mandrel, but since these coils are 20-ft long, the floor space requirement for the winding table and conductor approach to the winding table would be excessive, especially considering that this operation will have to be paralleled many times. The design of our table is such that the coil mandrel only oscillates about its long axis but does not rotate. Instead, the conductor reel is mounted on a carriage which revolves around the coil mandrel mounted on a stationary table (see Figure 12).

This device permits a programmed speed and motion so that the reel can move rapidly along the long straight 20-ft run and slow up around the critical bends at the ends. The mandrel rocks as the carriage moves around the ends to form the shell shape (see Figure 13). The reel is mounted on a take-up device to compensate for the different radii about which the carriage and reel travel. The tension can be programmed so as to be increased as the ends are formed and reduced for the long straight portions. The latter was found necessary to prevent further twisting of the conductor which then introduces an over-all twist in the completed coil.

Upon completion of winding, the coil is clamped accurately into its proper envelope and painted with a room-cure epoxy resin which seeps between the conductors by capillary action. A completed coil is shown in Figure 14.

BORE TUBE

The bore tube forms both the vacuum chamber and the surface for mounting the coils. It is accurately made so that the coils are properly located radially and circumferentially by means of a key on top and bottom. A completed epoxy-fiberglass bore tube is shown in Figure 15. Ideally, the bore tube would be infinitely rigid with a zero coefficient of thermal expansion. Then the coils could be clamped tightly to it and remain rigid. A ceramic bore tube approaches this ideal condition but to make it 20-ft long to precise tolerances is beyond the state-of-the-art. Another approach is therefore an adequately rigid bore tube to permit accurate assembly and a rigid outer clamping or banding to maintain these positions of the coils as the magnetic forces tend to cause them to move outward toward the sides.

Both approaches are being considered. Epoxy fiberglass on a thin stainless steel tube is a reasonably good choice for either, but for the rigid bore tube approach it may have to be heavier in wall thickness than the present 1/8-in. Other fibers such as "S"-glass, boron, and Kevlar are also being considered. A design of rigid bore tube also being considered is a molded assembly consisting of a thin stainless steel tube with ceramic rings around it for rigidity and "potted" in a mold with a filled epoxy to accomplish the accuracy required. Insulated metal rings are also being examined.

COIL ASSEMBLY AND BANDING

The inner coils are accurately positioned on the bore tube and banded with a thin film of high-strength mylar (T film). The mylar has the dual purpose of supporting the coils during subsequent assembly and forming the cooling passages for the helium flow. The outer coils are then assembled over the inner banding; they, too, are banded with high-strength mylar film. The banding is applied with a pretension load which is about 80% of its breaking strength. Banding in progress is shown in Figure 16.

The mylar banding is consistent with the rigid bore tube approach since the mylar has a high coefficient of thermal expansion and a low Young's modulus, and thus tightly supports the coils against the bore tube throughout the temperature range. Since this high-strength mylar is available in a thickness of only 0.00075-in it takes 210 layers to produce the required strength. Obviously this layered structure has no flexural strength to withstand the outward sideways magnetic forces. Therefore, this type of banding is not satisfactory for the rigid outer-support approach. For this concept, epoxy fiberglass (or Kevlar fibers) is being considered. This would be a filament winding process using a wet, room cure, epoxy. The pretensioning would not be as great, since its strength would result from the curing of the epoxy matrix, which would also provide flexural strength to the banding.

Still other methods being investigated are metal bands and metal clamps, the former having only tensile strength and the latter having flexural strength.

Any of these techniques will work when properly sized. The total time needed to apply the thin mylar banding has been found to be excessive - it requires a disproportionate amount of time in comparison with that for coil winding. The other approaches being considered are all expected to improve the cost/time aspect.

CRYOSTAT

The cryostat consists of a series of thin-wall tubes which are very flexible so as to not interfere with the rigid suspension system members that transmit the magnetic and gravity forces from the coil "bundle" out to the iron core. The two inner tubes are merely pieces of sheet metal wrapped tightly around the assembly and seam-welded along the length. For our first full-scale prototype, the outermost vacuum tube consists of a series of 15-in long segments of tubing which allows the suspension to be supported directly on the iron core. The segments are butt-welded to flanges of the suspension to form the continuous tube. The assembly of the cryostat system is shown in Figure 17.

STEEL SHIELD

The laminated half-core is stacked in one of the original main ring bending magnet stacking fixtures. The stacking is done along a curved guide equivalent to the deflection due to the weight of the completed magnet. The laminations are roller-coated with a room-cure epoxy applied over the central region of each lamination. The stacking pressure of 50 to 100 psi is applied from time to time. A rubber tube is inflated inside of the stack to minimize epoxy run-out, and thus later clean-up. The entire 20-ft half-core is stacked and clamped within the 3-hr pot life of the epoxy. After cure, some of the clamps are removed and steel bars are welded to the sides (which will be the top and bottom) of the stack.

When the two half-cores are brought together, they are welded with steel straps to form a symmetrical beam. The deflection of this assembly measured out to be about 0.200-in for our first complete assembly in comparison with the expected deflection of 0.250-in. The curved guide for the stacking fixture can be adjusted when more data substantiate these figures. Two half-cores welded together are shown in Figure 18.

It is also being considered that the sagitta of the beam path be built into the magnet. Tests with the completed half-cores have substantiated the fact that this curvature can readily be achieved in the completed half-cores before welding them together. The cryostat and coil assembly can also be readily curved to this degree.

SUSPENSION SYSTEM

The suspension system must be constructed in a manner which minimizes the heat transfer from the warm iron to the coil assembly yet be rigid enough to support the coil assembly so that it will not move more than a few thousandths of an inch. Instead of supporting the coil continuously along its length, the supports are concentrated at 15-in centers. The suspension system consists of rigid G-10 epoxy in the coil bundle itself transmitting its force into the inner cryostat tube. It in turn provides stainless steel buttons which transmit the load to the intermediate cryostat tube. Suspension rings are tightly mounted onto the intermediate tube at the same 15-in centers. These rings provide the low heat-transfer link to the magnet core. The rings consist of inner and outer rings held together by toroidally wound epoxy fiberglass filaments. The filaments presently used are a high-strength fiber produced by DuPont called Kevlar.

The suspension rings are flanged so that tubes can be welded to the rings to form the outer cryostat tube.

Other designs of suspensions, such as a diaphragm slotted to minimize heat transfer, are also being tested in an effort to reduce costs.

SPLICES AND LEADS

Extreme care and accuracy in preparation of splices is required. Generally all are lap-joints and a minimum of 2-in overlap is required. Additional mechanical support -- copper heatsinks in channel form -- are added. Solder is 60 - 40. The support of all ends, banding, and configuration of leads are of special importance. No more than approximately 3/4-in length of conductor can be left unsupported.

STATUS

Having completed various small model magnets, we are now nearing completion of two 20-ft long dipole magnets.

In making the transition to the fabrication of full-scale prototypes, we feel that we have made meaningful progress in the development of tooling and techniques for their production. However, it is clear that many aspects of our design and assembly procedures demand further study and modification in order to minimize costs and construction time. It is our goal that as we incorporate these modifications into successive magnets, the final two to four of the eight dipole magnets to be constructed in this program will represent true production prototypes.

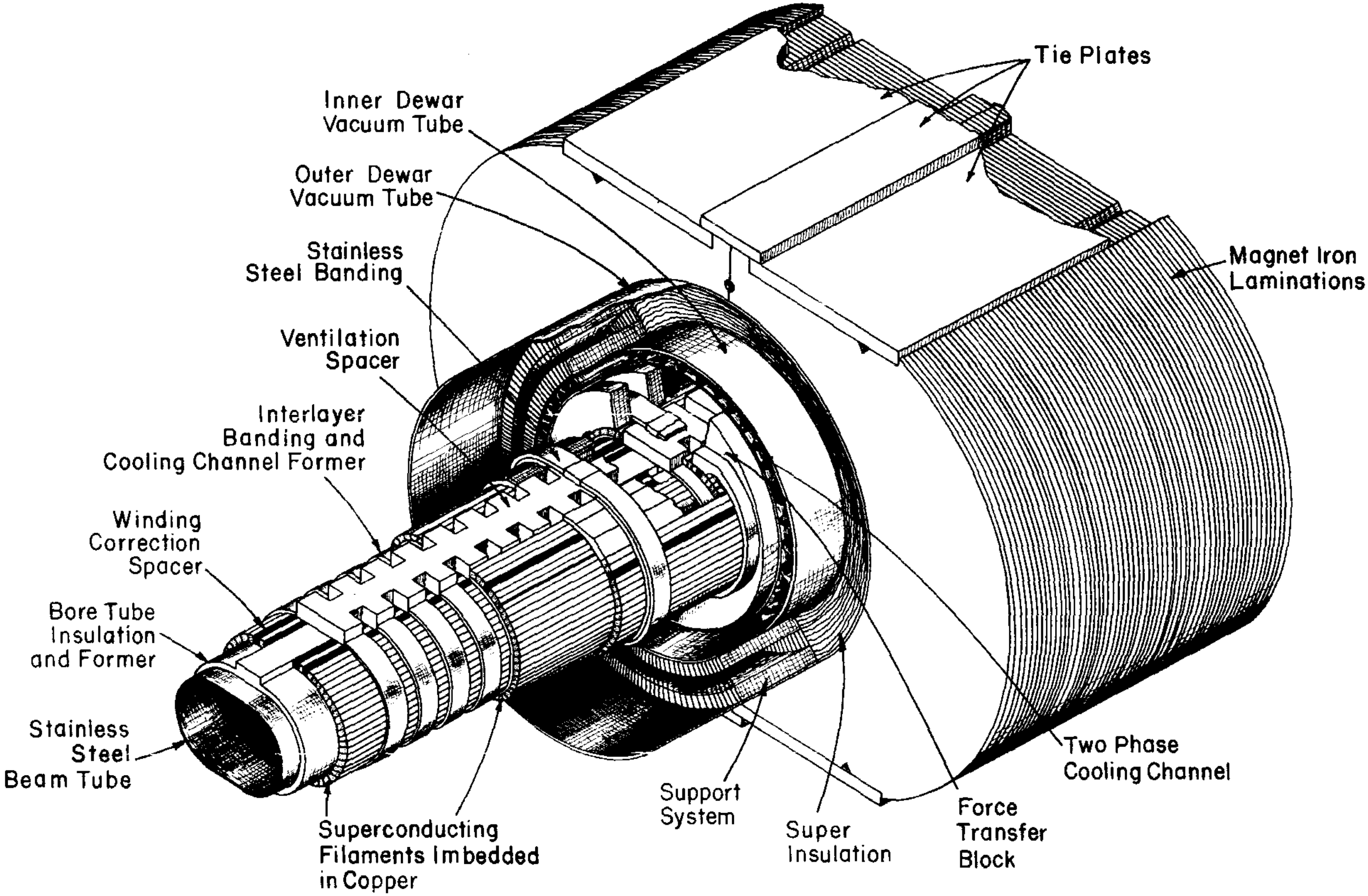

Figure 10a. Cutaway view of a superconducting dipole magnet, dewar and enhancement iron.

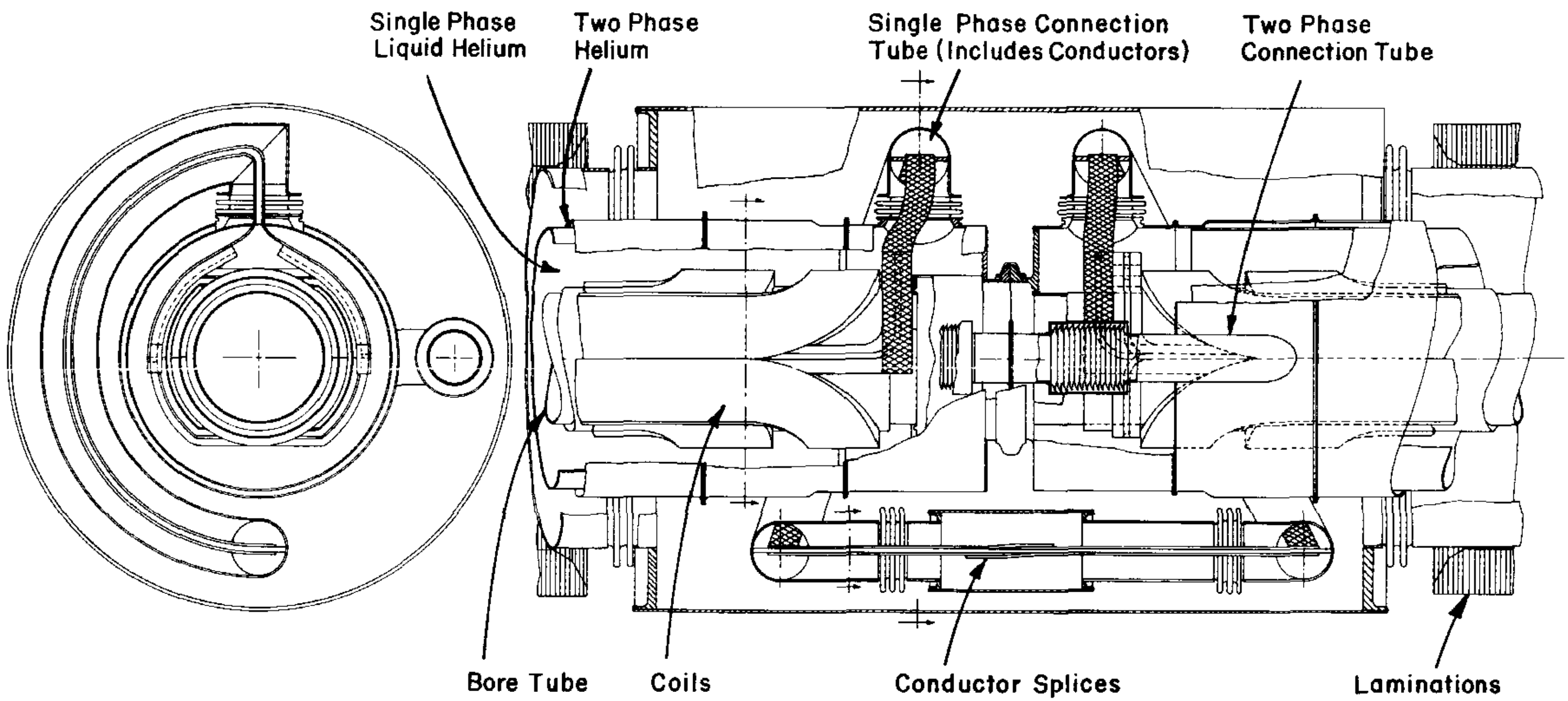

Figure 10b. Cutaway view of the inner-connection between two dipoles.

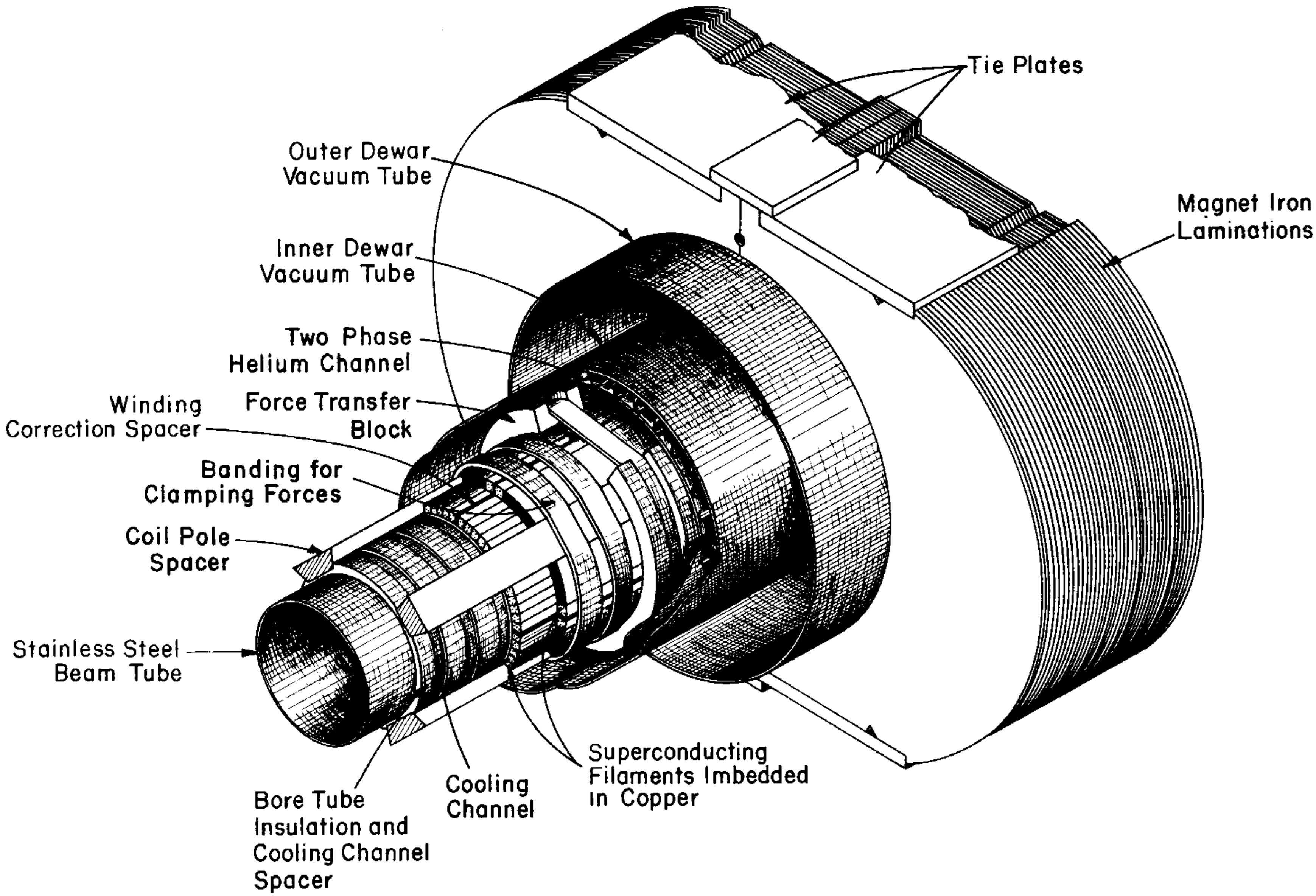

Figure 11. Cutaway view of a superconducting quadrupole magnet, dewar and enhancement iron.

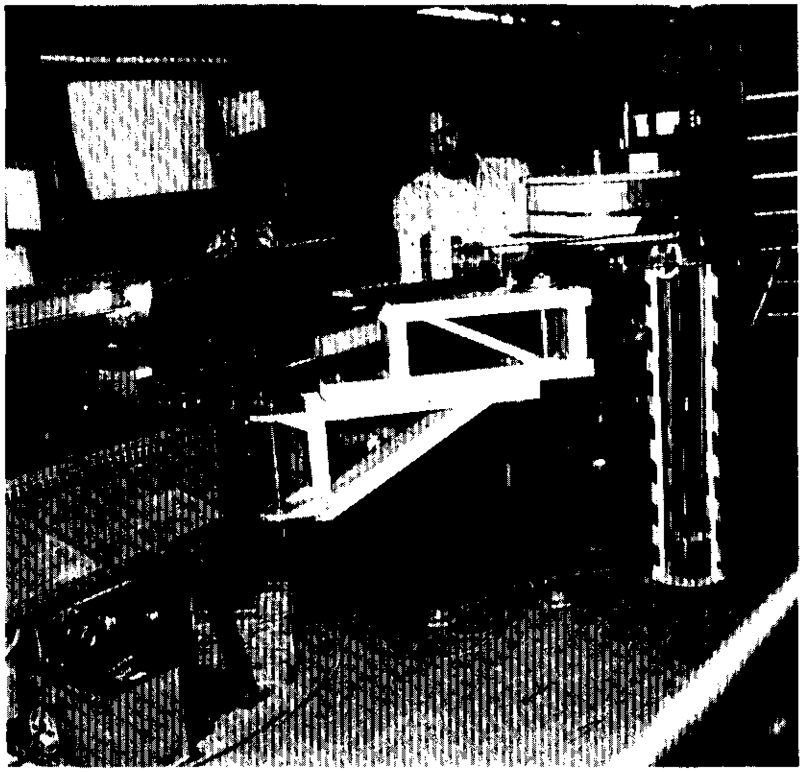

Figure 12. Coil mandrel, entering the picture from the left, rocks about longitudinal axis, while conductor reel on motor driven carriage "walks" around winding table.

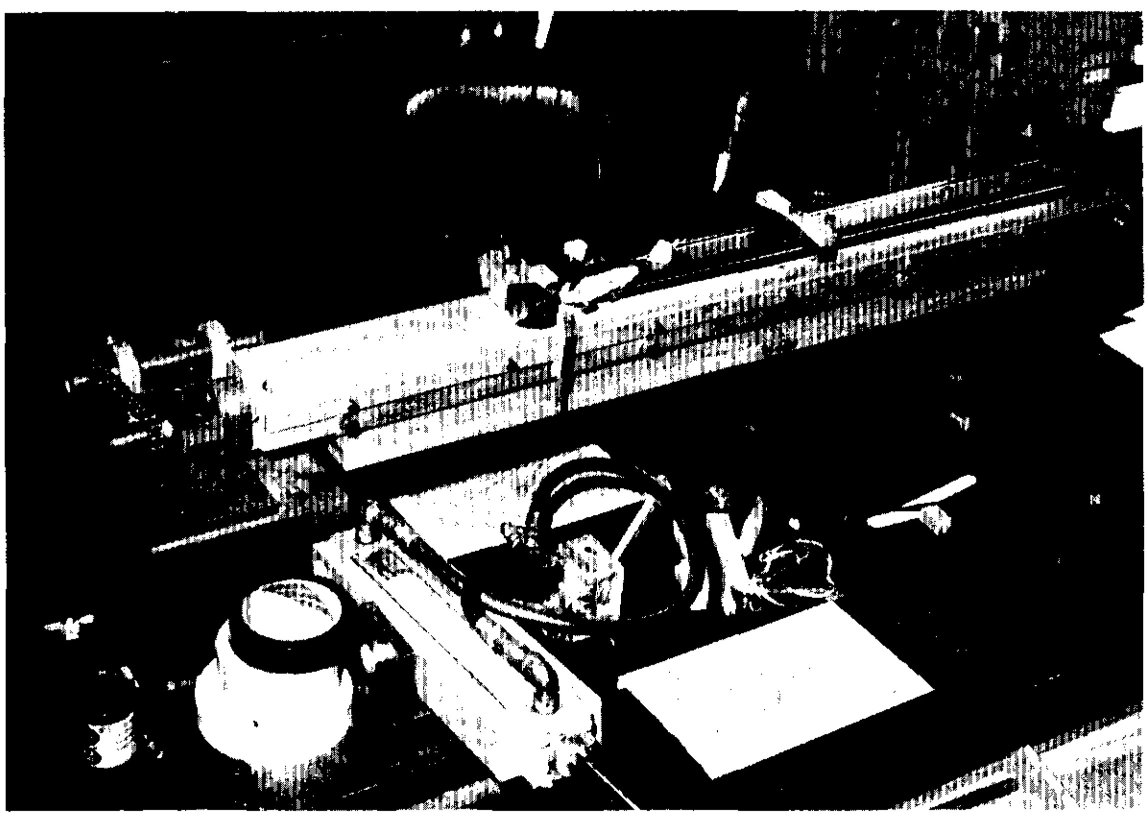

Figure 13. Coil shell taking shape on winding machine.

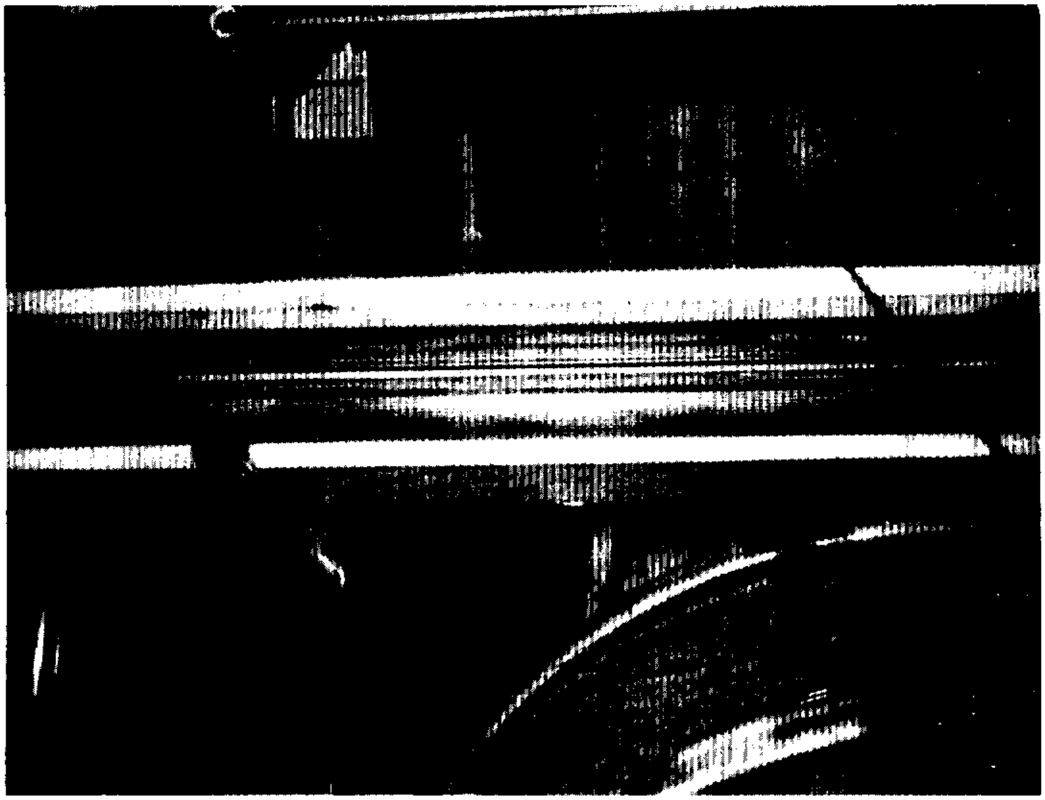

Figure 14. Completed coil shell resting in crate awaiting assembly on bore tube.

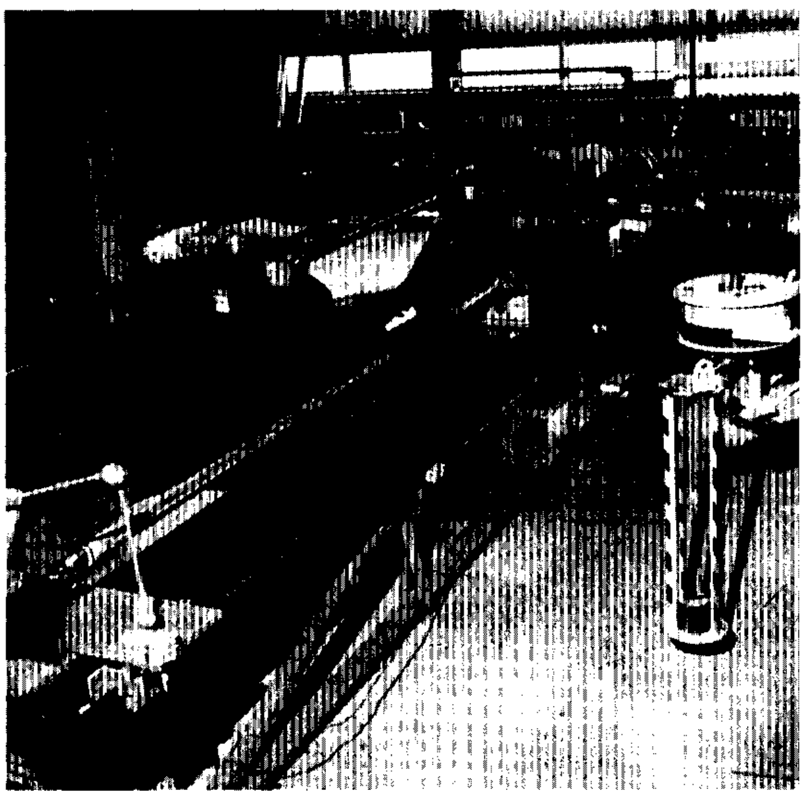

Figure 15. Twenty-foot long bore tube ready for mounting of coils. Light line visible on surface running length of tube is coil positioning key.

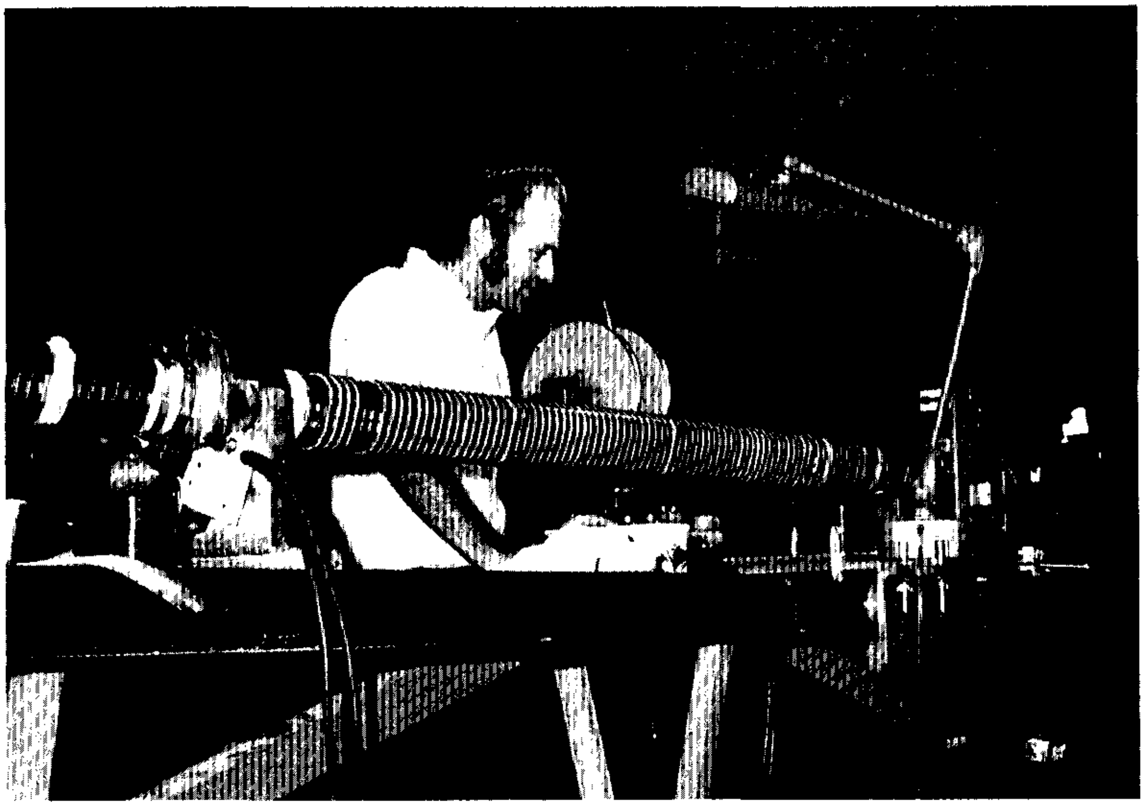

Figure 16. Coil banding in progress. Spools to right of technician supply tensioned mylar film as coil rotates about longitudinal axis.

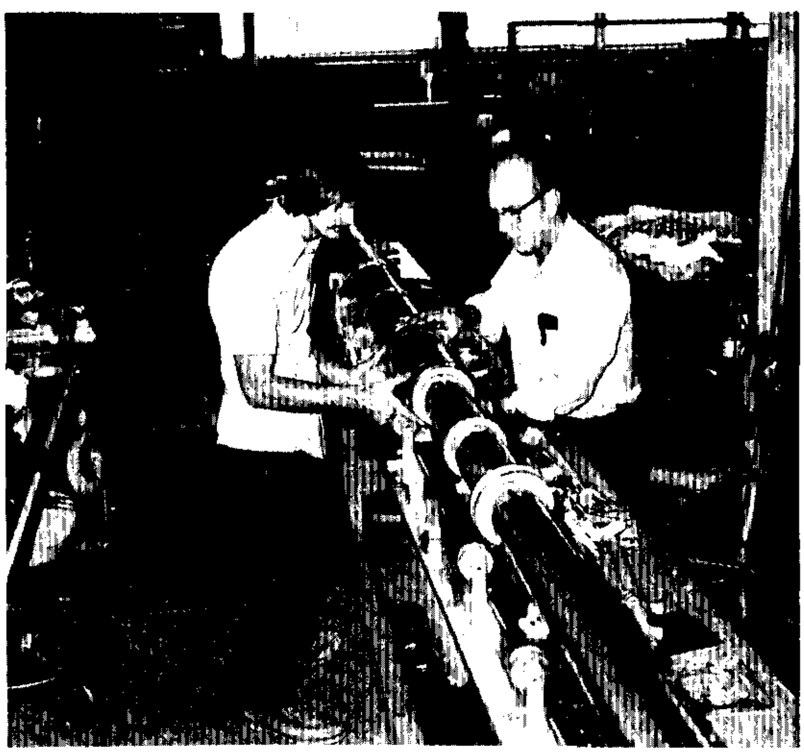

Figure 17. Cryostat undergoing assembly on dipole magnet. Near portion of magnet shows outer shell of two-phase flow vessel with suspension rings around it. Technicians are fitting outer vacuum chamber to suspensions.

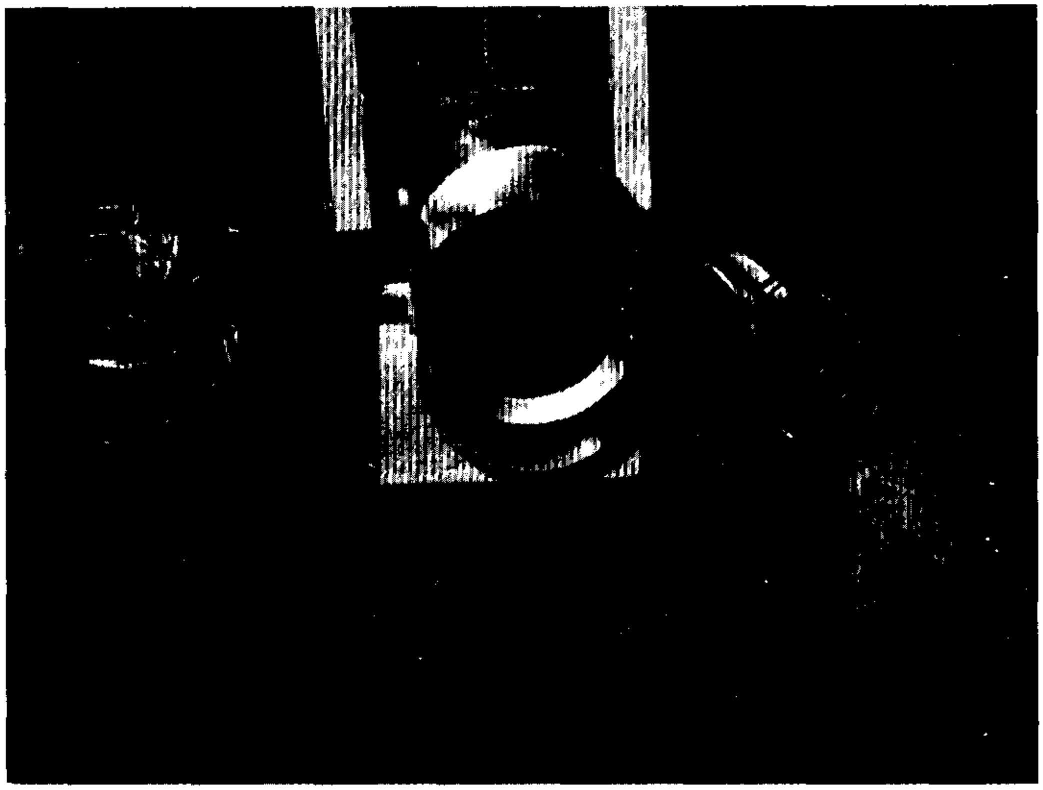

Figure 18. Steel shield in grasp of handling fixture. Thin portions at right and left of shield as shown will actually be at top and bottom of completed magnet.

CHAPTER 7

TEST OF MAGNET PROTOTYPES

INTRODUCTION

The object of the testing program has been to carry out that operational and performance evaluation of developing superconducting magnet technology at NAL necessary to provide timely input to the engineering evolution of energy-doubler magnets. Thus we have been concerned with the performance of the progressively more advanced superconducting wire used in successive magnets, mechanical integrity of magnet structures that must withstand the forces generated by high magnetic fields, thermal design of dewars and support structures which contain and constrain the magnets in the 4.2°K environment, and material properties at very low temperatures and over large temperature gradients.

As of January 31, 1974, seven magnets had been completed and successfully operated. A summary of properties of these magnets can be found in Table IV. Early testing of shell and pancake structures (see Figure 19), air-core dipoles representing two different ways of approximating cos θ current distributions were made for the purpose of comparing, under dc and ac electrical excitation, a geometry considered easy to fabricate; the pancake, with one promising more effective cooling; the shell. As testing progressed and instrumentation was improved, measurements began to include transfer functions (magnetic field as a function of current), longitudinal magnetic field shape, transverse field shape, harmonic content of transverse field both in the central bore and over the ends, and finally ac tracking tests between matched "dual dipole magnets." On February 13, 1974, an initial test of a full-scale, 20-ft long, dipole magnet was conducted; it is reported separately on Page 61. All tests have been carried out in pool-boiling liquid helium at atmospheric pressure, and most of the magnet operation has been with externally programmable SCR type solid-state power supplies.

In the next section of this chapter, we describe the test program as it evolved through the first five magnet models. We then turn our attention to the testing of the dual dipole magnets. Lastly, we give a brief account of the final test of a full-scale prototype dipole.

TEST ON FIRST FIVE MODELS

First test of Mark I pancake and shell prototypes, P8A and S4A, were made in January 1973, using a vertical dewar and a surplus, unregulated electroplating power supply. While both magnets ultimately reached a current of 1500 A, corresponding to a central field of 28 kG in the P8A and 30 kG in the S4A, the pancake exhibited significant "training"-- the phenomenon of reaching higher and higher current at which the magnet ceases to be superconducting, or "quenches," on successive runs. While this was originally thought to be due solely to motion of lead connections from the coil to the outer world, it was later shown to be endemic to the magnet. By the end of January both magnets were being tested under ac excitation using a Hewlett Packard HP6464A, 1000-A SCR power supply which could be externally programmed to vary magnet current as a function of time in a pattern similar to the main-accelerator waveform. Cyclic periods ranging from 10^4 sec down to 1 sec were possible. Now the ramp-rate sensitivity of P8A became most apparent; the magnet could not tolerate a rate of change of current which produced an inductive voltage drop across the magnet in excess of 50 mV. The best cycle time attained was ~ 10^3 sec. The shell magnet, on the other hand, could not be driven normal by any ramp rate producing an inductive voltage $\leq$ 10 V across the magnet terminals. As a life test, S4A was run for over an hour at a cycle time of 7 sec to a field of 16 kG. Transfer functions and field versus distance along the bore tube were measured using Hall probes and rotating coils, verifying calculations for these values. Agreement between predicted and measured inductances was less satisfactory.

These first tests, made with mostly borrowed equipment, successfully demonstrated operation of the superconducting wire close to its short sample limit in geometries suitable for the Energy Doubler. Equally important, valuable operating experience was gained by our personnel, most of whom had had little previous experience with cryogenics and superconductivity.

By March of 1973, the Mark I pancake and shell magnets were ready for testing in their horizontal dewars, and a second, 1-meter long pancake magnet, Mark II/P6C, had been prepared for testing in the vertical dewar. A large, 0.5 MW Transrex 500 B power supply was ready for use, wired with an NAL-designed electronic safety circuit for protection of magnets during a quench. The test with the Mark I (P8A) pancake magnet was disappointing, because gas entrapped in one end of the dewar limited operation to 60% of the current achieved in the vertical dewar. A vent stack added to the shell magnet (S4A) dewar prevented similar gas entrapment and the magnet reached a performance level similar to that achieved in the vertical dewar. The magnet was tested with and without iron, and showed an enhancement factor of 1.18 with iron as predicted by computations. Pulse testing of S4A with a main-ring type of current waveform having 300-A (7.2 kG) injection and 1400-A (35.5 kG) flat-top again permitted very fast cycling--to periods as short as 16.6 sec. Ramp rates of dB/dt = 800 G/sec were reached, and the magnet operated to its full critical current, achieving peak stored energy higher than in the previous best dc tests. Tests of the 1-meter pancake, P6C, operating in the vertical dewar, achieved a 1900-A current corresponding to a central field of 35 kG. Testing continued into April with pulse tests of P6C. These confirmed previous results with epoxy-impregnated pancake magnets by exhibiting a high ramp-rate sensitivity -- only at the slowest rates of increasing current could a 19-kG maximum field be reached.

These tests, which could be considered Phase Two of the program, demonstrated that both magnet geometries could support ac operation in horizontal dewars. The banding method of holding the magnets together against the strong, mutually repulsive hoop forces generated by magnet currents had given no evidence of failing at these fields. The concern that bicycle-spoke suspensions, used for the first time in the horizontal dewars, would not be rigid enough and that the resultant motion would quench the magnet was allayed. Any such motion would, of course, only have manifested itself when the steel shield, also used for the first time, was in place around the dewars. Automatic level control of the liquid helium in the dewars had been improved to the point where it became routine to walk away from an operating magnet for several hours in full confidence that the system would remain in operation.

In May 1973 the last efforts were made to resolve problems with the pancake geometry cooling. P6C was tested in a horizontal dewar with warm iron field-enhancement. The magnet proved less sensitive to ramp rate than it had been in the vertical dewar. The same maximum dc stored energy achieved in the vertical dewar was reached in the horizontal, and after significant training, the magnet was operated ac to 1600 A at a 60-sec cycle and to 1300 A at a 30-sec cycle, a factor of three more rapid than the 100-sec period projected at that time for Energy Doubler operation. Since there had been much speculation about the deleterious effects of epoxy impregnation on pancake performance and much engineering design effort expended in trying to find better ways to cast cooling channels in these magnets, an "open" pancake, the Mark III, was built without any impregnating compound, relying on mylar banding and self-bonding Formvar wire insulation to preserve structural integrity. This magnet was also ramp-rate sensitive; however, after considerable slow pulsing with the automatic ramp generator, a 100-sec ramp cycle from 300 to 1600 A could be sustained. At lower peak currents shorter cycle times could be sustained, but sensitivity to what should have been innocuous environmental perturbations -- such as a blast of gas from the liquid helium filling line -- would quench the magnet every time.

Thus far all testing had been to support dipole development. At the end of May a 2.5-in bore diameter "super-ferric," or cold iron, quadrupole was tested. Because of its open construction and low peak magnetic field at the windings, this magnet could be cycled very fast, and a 4-sec period to a peak field of 3600 A was achieved. This was the maximum stable performance possible with the Transrex power supply; at any faster rate the supply could not track the ramp generator. Peak dI/dt values of 3 to 5 kA per sec achieved during this testing clearly established the quality of the intermediate grade intrinsically stable superconducting wire usd in the Mark II, Mark III, and quadrupole magnets.

By the end of these tests, we felt that a case had been established in support of the shell geometry; the less efficient cooling of the superconducting wire endemic to the pancake geometry caused unacceptable ramp-rate sensitivity. The difficulty in restraining the pancake windings, as compared with the shell, while not preventing full operation, did result in extensive training. On the other hand, the shell magnets were not as difficult to build as originally believed. The magnet testing had reached a stage where it would be necessary to begin more detailed and time consuming investigation of magnetic field characteristics. Thus, faced with the accumulated test experience and in the interest of expediency a decision was made to cease development of pancake magnets and to construct a matching pair of shell magnets.

Tests on Dual Dipole Magnets

Testing of the dual dipole magnets, initiated in August 1973, was aimed at answering one of the most important questions raised concerning the use of superconducting magnets in accelerators: could two magnets be made identical enough in vital characteristics, ac and dc, to permit their use in an accelerator.[3]

Design and construction of the dual dipoles is very similar to that of energy-doubler magnets described in Chapter 6. Consisting of three layers of concentric shell windings placed to best approximate a cos θ current distribution with respect to the horizontal plane, the dipoles differ chiefly in being constructed on a circular cross-section bore tube rather than the doubler's oval. A more detailed summary of physical characteristics is given in Table IV under test magnets 6 and 7, but briefly each magnet is 29-in long, has a bore diameter of 2.16-in, and uses two different grades of superconductor. These are the first dipole magnets at NAL to distribute different types of superconducting wire throughout a dipole magnet coil according to design concepts outlined in Chapter 6. In doubler magnets the inner wall of the helium container, to which the windings are banded, also forms the wall of the evacuated beam tube, but since testing is facilitated by having ready access to the bore, a smaller, insulated warm-bore tube was installed inside the regular tube.

Initially, maximum currents were reached in both magnets only after much training; however, the training effects tended to be remembered by the magnets even after repeated warming to room temperature and so this problem faded with continued operation. Each magnet was first operated separately; then both were run together. As a unit the pair have reached maximum dc currents of 1620 A, corresponding to 24 kG and 90% of short sample in the smaller, limiting, conductor. Measured transfer coefficients of 14.785 and 14.809 G/A agree to 0.16% and are current independent as they should be; that is, the magnetic fields increase linearly with current. Operation in the ac mode was very successful. The magnets could be ramped continuously at a 15-sec cycle to 85% of the dc critical current, exceeding the design goal of 80% of short sample. The 24-kG maximum magnetic field cited for the dual dipoles is much less than the 45 kG required for Doubler operation. In order to expedite testing, the dipoles were built with an available wire which had lower critical currents.

The small bore of these magnets and relatively large size of most precision magnetic measurement probes preclude adequate direct field mapping. Consequently, one measures harmonic content of the magnetic fields with appropriate search coils which directly determine coefficients needed to mathematically reconstruct field shaped by use of Fourier expansions. Two methods were used. In the first a coil was rotated at constant angular velocity and the output fed into an electronic wave analyzer, a tuneable amplifier, which measured voltage amplitude at harmonic frequencies corresponding to the higher order magnetic multipoles.[4] The second method employed a long coil wound with turns placed in such a way (a cos $n\theta$ distribution) as to be sensitive only to the harmonic of interest.[5,6] Measurement of a harmonic consisted of rotating the coil through fixed angular steps and stopping after each step to record the output of an electronic integrator connected to the harmonic coil of interest. The tabulated function so generated represents the particular incremental flux intercepted by the coil from 0 to the final angle. As can be seen by comparing Figures 20 and 21, the measurements show a maximum deviation from a pure dipole on the midplane of 6 parts in 10^4. Not shown in these figures is a quadrupole component somewhat larger than the other harmonics. Its presence indicates that somehow necessary symmetry was lost in construction. Although measurements have shown that about 20% of the quadrupole is due to a magnetized seam weld in the warm bore tube, the source of the test of the quadrupole component is unknown and the subject of continuing investigation. A transverse, horizontal sweep of the bore in one of the magnets with a Hall sensor confirmed the quadrupole data, but the device is not sensitive enough to do more than reach the upper limits of component magnitudes measured with the search coils.

In order for accelerator magnets to be dynamically useful, the ratio of fields in any pair of magnets must remain constant at any current and any current ramp. To measure tracking of the coils under ac excitation, long pickup coils, matched mechanically, were placed in each magnet and connected so that the outputs of the two coils bucked. They were further matched electronically, and then the magnets were pulsed at various cycle lengths from 100 to 33 sec. The results showed an upper limit of difference due to ac causes to be 5 parts in 10^4 of total flux intercepted by the pickup coils. The limits are set by the apparatus; we are improving our apparatus to lower the limits of sensitivity.

The dual dipole tests mark the completion of an important stage of our prototype magnet program. It has been shown that two magnets can be constructed with dc and ac excitation characteristics sufficiently alike to be considered for use in an accelerator. At this point, a similar conclusion regarding field quality would be premature. Ramp-rate sensitivity -- a function of cooling geometry, mechanical stability, and superconducting wire characteristics -- infers no cause for concern about the type of wire to be used in the 45-kG, 20-ft long doubler magnets. Thus, apart from the anomalous quadrupole component, these magnets meet the design goal established for them. The dual dipoles are shown in Figure 22 and their associated control and data acquisition equipment in Figure 23.

Test of Full-Scale Magnet

By mid-February 1974, the first of the 20-ft long prototype dipole magnets was ready for testing in the laboratory. Service boxes had been fabricated for each end of the magnet that would permit operation of the magnet in either the counter-flow refrigeration mode outlined in Chapter 3, or in the "pool-boiling" fashion of the preceding tests. The goals of the initial test were, first of all, to verify that the magnet maintained mechanical integrity during cooldown, to identify sources of excessive heat leakage, and, once the superconducting state was achieved, to gain a preliminary impression of the magnet's training characteristics. The steel shield was not installed so that the entire surface of the outer vacuum chamber would be open for examination.

Cooldown was carried out gradually by flowing refrigerated gaseous helium through the inner cryostat chambers. No evidence of excessive mechanical stresses was found. As the interior of the magnet neared liquid helium temperatures, it became apparent that heat leakage through the suspension members was significant, since the outer suspension surface was several degress Celsius cooler than points on the vacuum jacket midway between suspensions. After approximately 24 hr of slow and careful cooldown, the magnet became superconducting, though the magnet was not energized until some 4 hr later when it was determined that liquid helium levels above the magnet volume had been established at both ends.

The initial quench of the magnet occurred at a current of 850 A; following a succession of five more quenches at increasing currents, the magnet was operated at a 200-sec cycle to 1060 A. The test was terminated by a quench at 1100 A, coincident with exhaustion of the liquid helium dewar. One oscilloscope trace showing various voltage and current waveforms during the test is shown in Figure 24.

Table IV. Summary of Characteristics, Energy Doubler Prototype Magnets

Mgt. No.	Geometrical Description	Max. Length	Bore Dia.	Inductance	Turns	Transfer Constant	Peak dc B	Peak ac Period/B	Wire Description
1	Pancake, Mark I, P8A	40"	1.93"	32.6 mH*	208	18.7 G/A[1]	28 kG[1]	10^3 sec/16 kG*	361 Filaments NbTi, Cu:sc = 1.25:1, 112x56 mils
2	Shell, Mark I, S4A	12	1.50	4.7	176	29 G/A*	35*	17/35.5*	361 Filaments NbTi, Cu:sc = 1.25:1, 112x56 mils
3	Pancake, Mark II, P6C	40	1.5x2.0[3]	15.2*	156	18.4*	35*	59/29.4*	1345 Filaments NbTi, Cu:sc = 2:1, 150x75 and 150x50
4	Pancake, "open", P6C	40	1.5x2.0[3]	8.5	156	15.3†	25†	100/25†	1345 Filaments NbTi, Cu:sc , 2:1, 150x75 and 150x50
5	Quadrupole - Cold Iron	28	2.5	~ 14*	212	17*[2]	61*[2]	4/61*[2]	1345 Filaments NbTi Cu:sc = 2:1, 150x75
6&7	Dual Dipoles, (a)	29	1.75	6.25*	130	14.79*	24.3*	--	#1; 1345 Filaments NbTi Cu:sc = 2:1, 150x75
	Shell, S3C, (b)	29	1.75	6.25*	130	14.81*	25.8*	--	#2; 361 Filaments NbTi Cu:sc = 1.25:1, 112x56
	(a&b)	--	--	12.5*	--	14.78	23.9*	25/22*	

* Indicates Quantity measured with iron enhancement.

† Indicates test limited to Vertical Dewar

1. Peak dc field in the Vertical Dewar

2. Transfer in Gauss/inch/amp and Peak gradients in kG/in, computed from peak I.

3. Ellipse: minor x major axes.

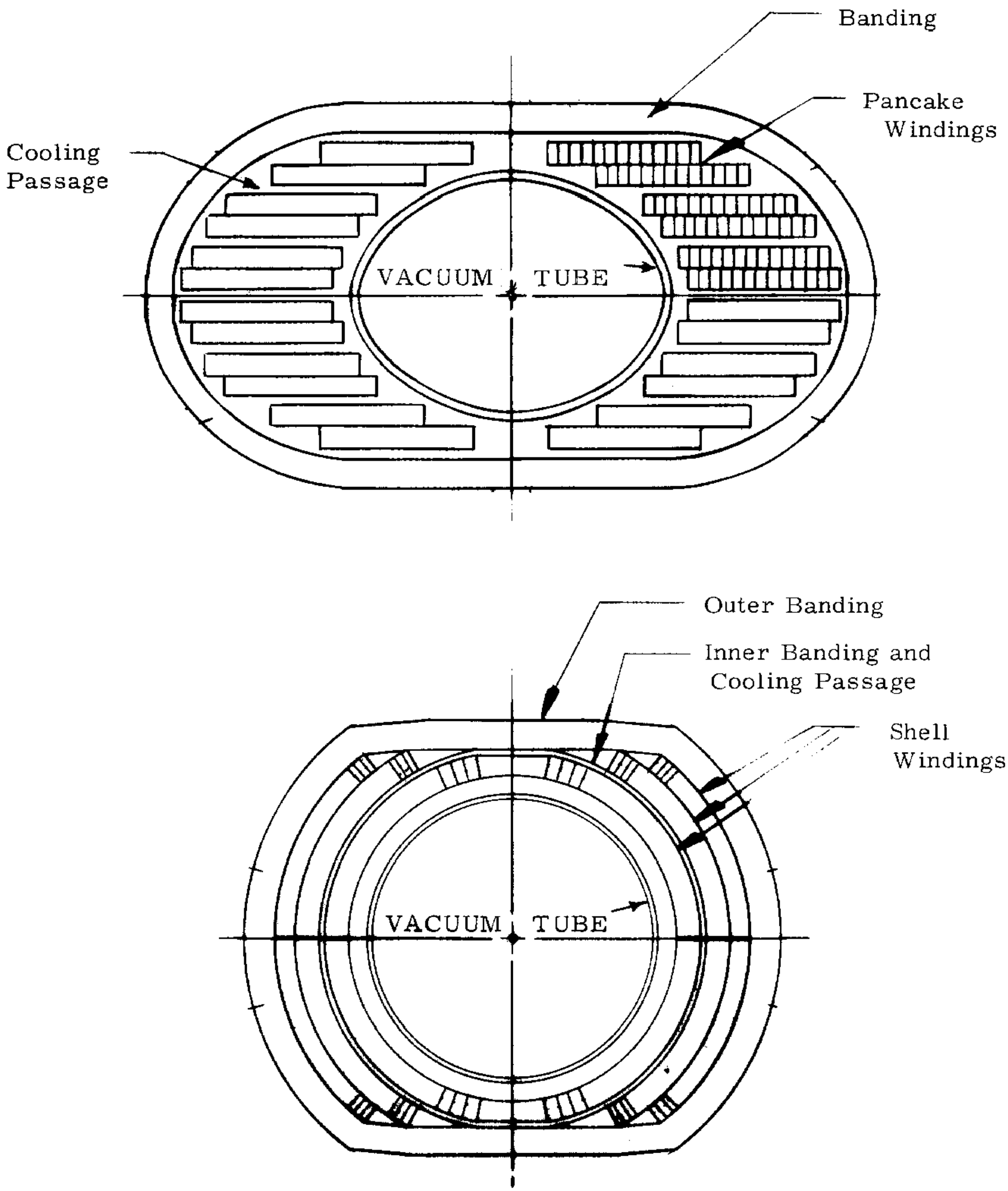

Figure 19. Typical Cross Sections of pancake (top) and shell (bottom) wound superconducting magnets evaluated in the prototype testing program.

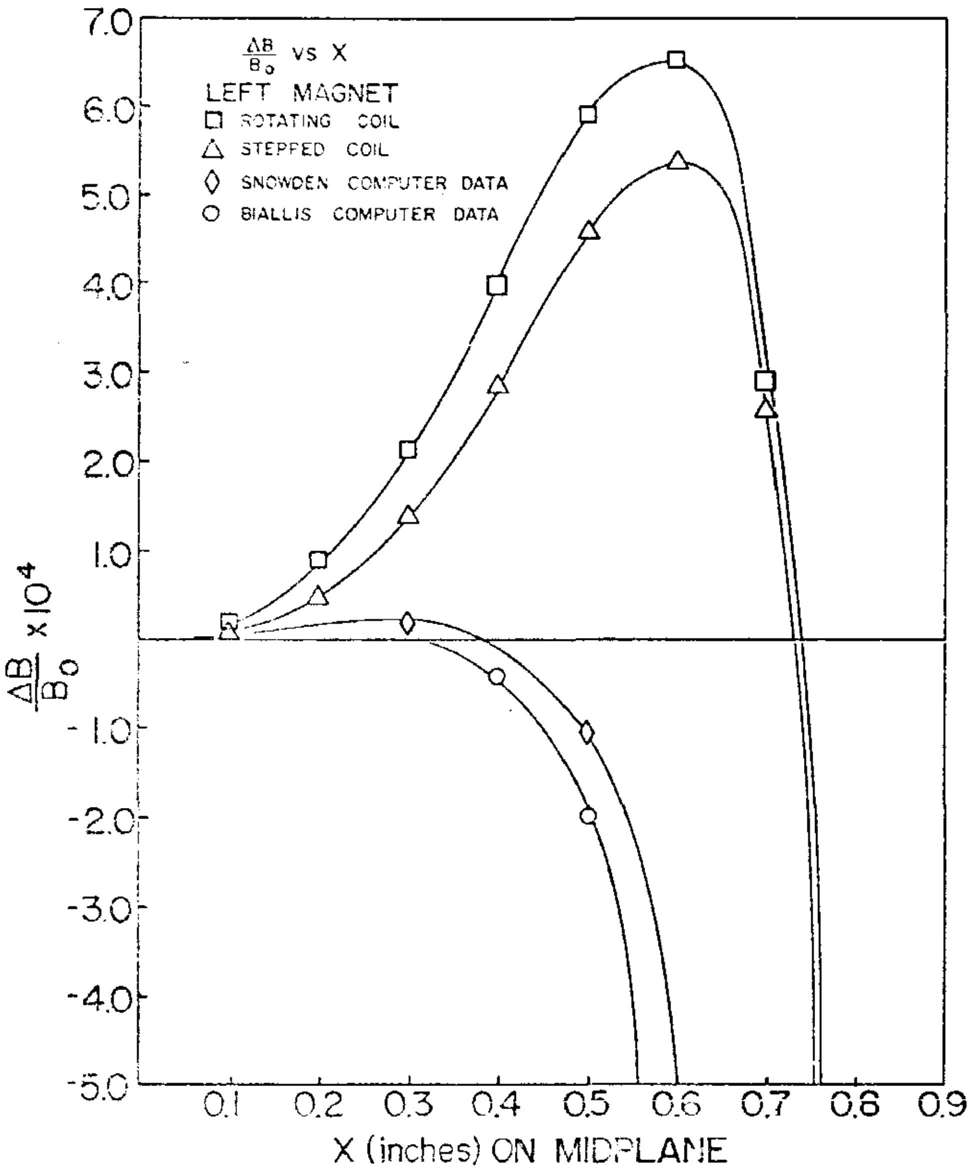

Figure 20. Midplane Field Deviation. Left Dipole.

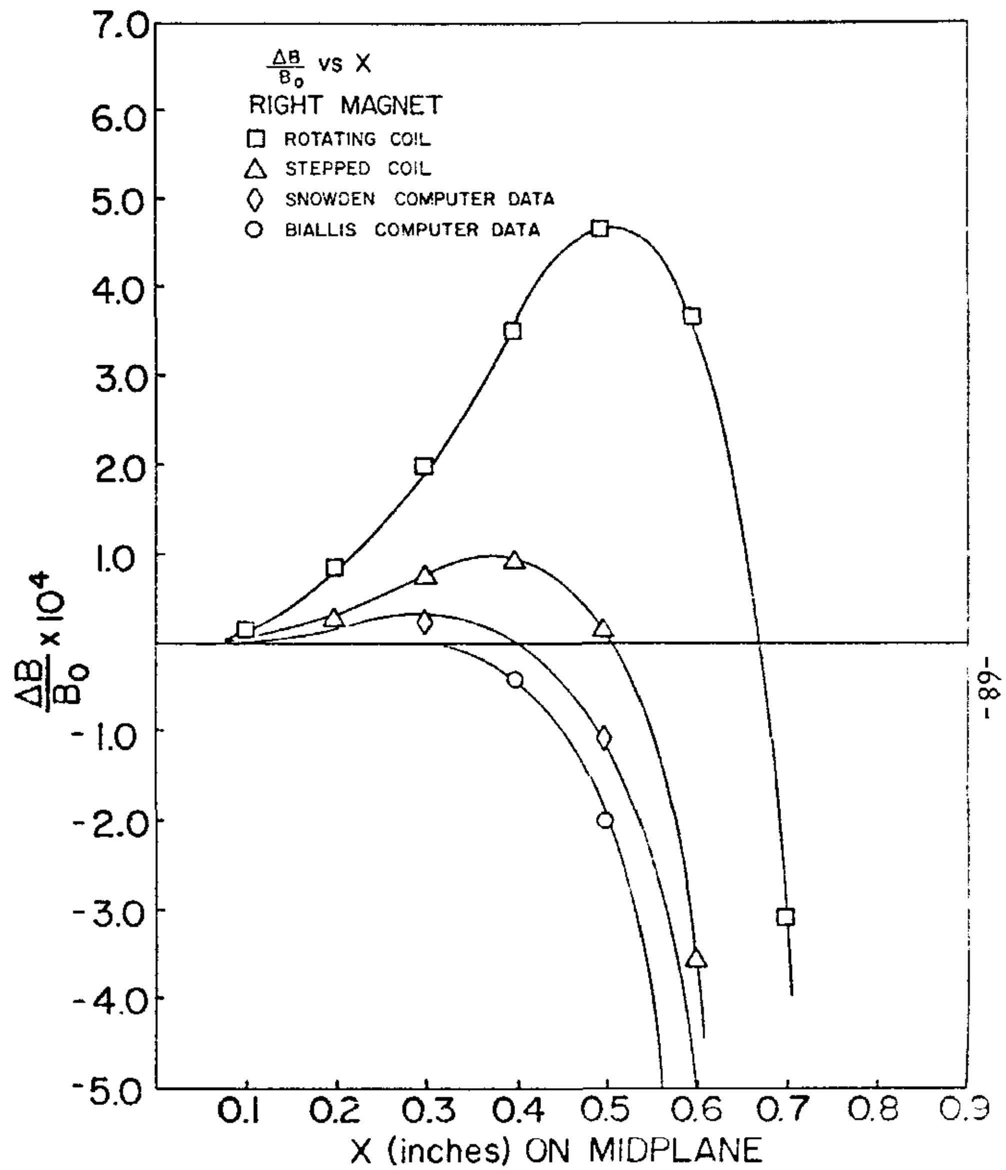

Figure 21. Midplane Field Deviation, Right Dipole.

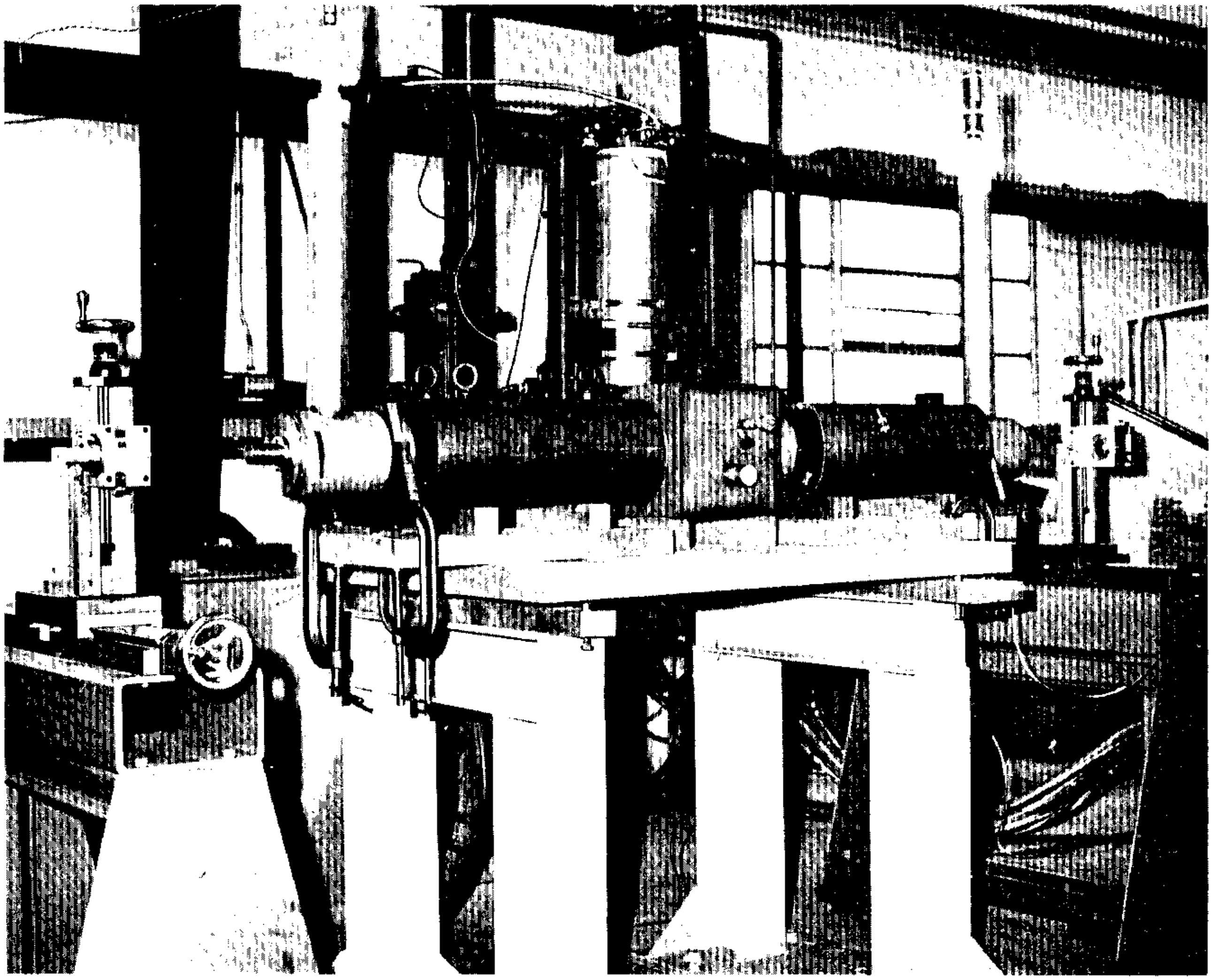

Figure 22. Dual dipole magnets in test area. Coils lie within the cryostat surrounded by the two steel shields visible on either side of the center service box.

Figure 23. View of data acquisition and control equipment used in superconducting magnet tests.

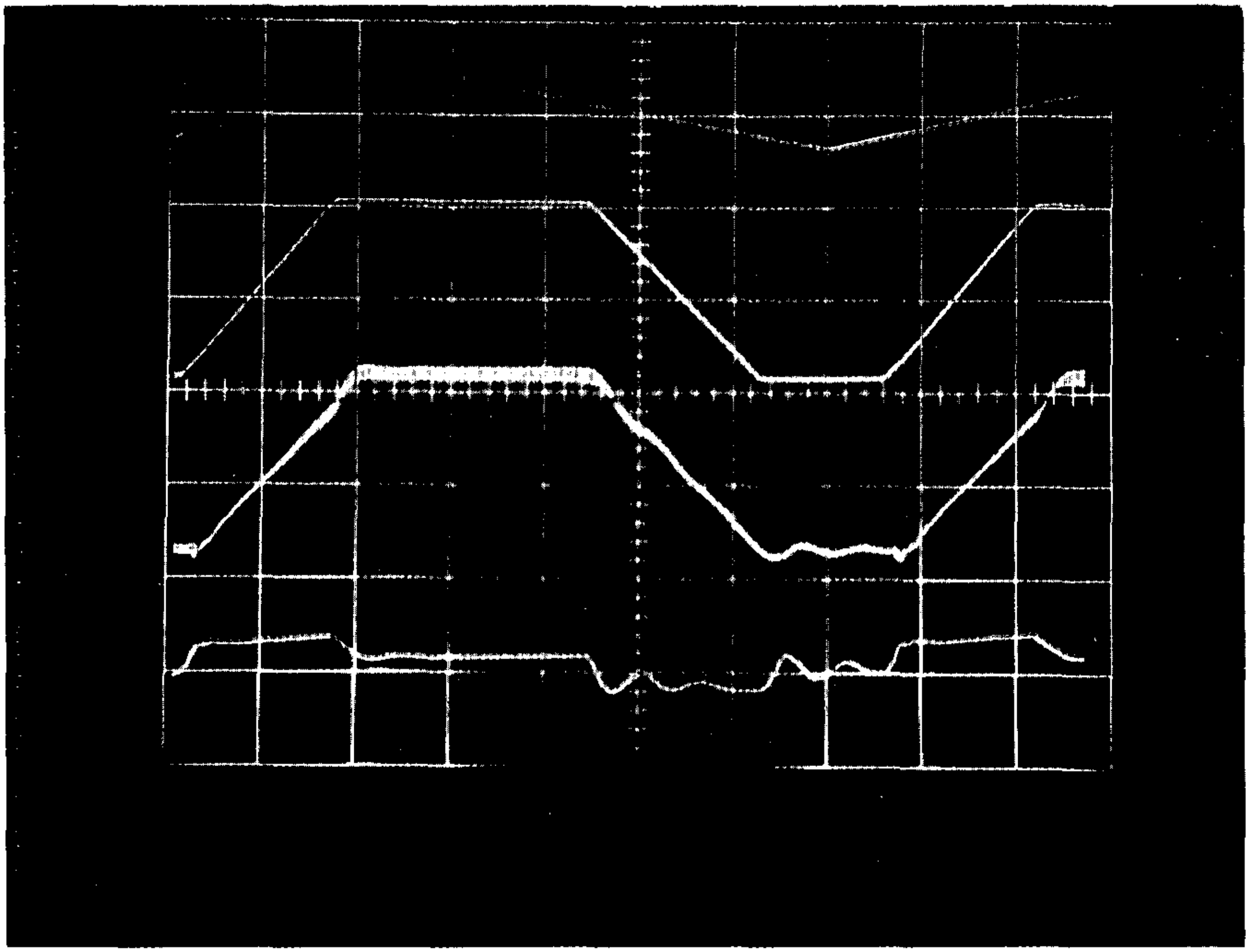

Figure 24. Oscilloscope trace showing various voltage and current waveforms during magnet test. Second trace from bottom is current through small shell model magnet versus time, programmed to simulate accelerator cycle for cycle time of 7.4 sec.

REFERENCES

1. Peter C. Vander Arend and W. B. Fowler, "Superconducting Accelerator Magnet Cooling Systems," Proceedings of the 1973 Particle Accelerator Conference, San Francisco, March 5-7, 1973.

2. T. von Hoffmann, U. Lienert, and H. Quack, "Experiments on Thermally Driven Gas Oscillations," Cryogenics, Vol. 13, No. 8, August 1973, pp. 490-492.

3. B. P. Strauss and D. F. Sutter, Evaluation of Matched Superconducting Dipoles; National Accelerator Laboratory Technical Memorandum TM-456, 0428; December 11, 1973.

4. R. Juhala and G. Michelassi, A Rotating Coil Device for Harmonic Analysis of Magnetic Fields; National Accelerator Laboratory Technical Memorandum TM-455, 0423.02; November 6, 1973.

5. B. P. Strauss and D. F. Sutter, Stepped Motion, Cos $n\theta$ Wound Pick up Coils for Harmonic Analysis of Magnetic Fields; National Accelerator Laboratory Technical Memorandum TM-457; February 1974 (to be published).

6. G. H. Morgan, "Stationary Coil for Measuring the Harmonics in Pulsed Transport Magnets," Proceedings of the 4th International Conference on Magnet Technology, 1972; USAEC, CONF-720908.

Appendix 1

ORGANIZATION OF THE DESIGN STUDY

In the spring of 1973, NAL Technical Memorandum TM-421 entitled "Some Preliminary Concepts about the Proposed Energy Doubler Device for the 200/500 GeV Proton Accelerator at the United States National Accelerator Laboratory," was published. This report formed the basis for the work which has been done on the proposed Energy Doubler in the last year.

The goals of the design effort were to produce a design for an energy doubler magnet and refrigeration system that would cost approximately $20 million, would fit in the present main-ring enclosure and service buildings, and would be capable of accelerating protons on a slow cyclic rate of once every 100 sec or less to energies well above our present capability.

In order to accomplish a feasibility study the URA and AEC authorized the expenditure of $1.5 million with the stipulation that a report would be prepared in early calendar 1974.

In order to accomplish this feasibility study effort four parallel activities were established.

First, an Energy Doubler Group was set up within the Accelerator Division; the primary responsibilities of this group were:

a. To maintain systems responsibility for all prototype Doubler efforts.

b. To establish specifications for and to procure the superconducting wires to be used to construct the prototype magnets.

c. To establish testing procedures and systems to measure the superconducting wires to insure that current density specifications were being achieved.

d. To establish magnetic field criteria (in conjunction with the Accelerator Theory Group of the Accelerator Division) and to measure the electrical and magnetic performance of the prototype magnets; this included the provision of a cryogenic testing set-up with appropriate electrical, electronic, magnetic measurement, and control system hardware and equipment.

e. To install a commercially procured used helium liquefier in the NAL Village and to make it function both as a refrigerator for the energy-doubler test loop and as a facility for producing liquid helium for other Laboratory programs on an emergency basis.

f. To magnetically measure the short prototype magnets that were built (6 dipole and 1 quadrupole magnets) to establish that the basic concepts for magnetic field shape, central field, reproducibility of production techniques, adequate tracking under pulsed conditions, achievable current and current density, adequate cooling and the like, were being achieved.

g. To install and perform experiments on a simulated energy doubler test-loop in the old Protomain enclosure in the Village, the test loop to operate and circulate liquid helium cryogenically at about 4°K with transfer lines, heat exchangers, circulating pump, etc., and with simulated pressure drops and temperature rises equivalent to those expected for an identical length (200 ft) of energy doubler magnets, eight 20-ft dipoles and two 7-ft quadrupoles.

h. To install and cryogenically test full-scale prototypes of the proposed energy-doubler magnets in the cryogenic test-loop and to measure pressure drops and thermal losses due to both radiation and pulsing of magnetic field in the magnets, thereby confirming the concepts for the refrigeration systems.

i. To perform similar functions relative to the design, measurement and procurement of large aperture (3- x 5-in good field) beam transport superconducting magnets. (This work is not discussed in this report.)

Secondly, the Technical Services Division through its Engineering Services Group and Magnet Facility Group, was asked to:

a. To accomplish the mechanical design of the energy-doubler prototype dipole and quadrupole magnets based on the criteria generally established in TM-421, the most important of which are:

1. An approximately elliptical bore 1.750-in vertical by 2.500-in horizontal to conserve on the total amount of superconducting wire that would be required. (A circular geometry is more favorable mechanically.)

2. A three-shell coil design with smaller cross-section superconducting wire in the outer two shells to conserve on the total amount of superconducting wire to

be used. (The so-called variable current density design.)

3. A mechanical clamping system in which approximately one-half of the linear surface of the solid wire in each coil is clamped to the rigid bore tube. (This is done in order to prevent movement of the superconducting filaments in the solid wire bundle.)

4. To develop a rigid bore tube construction which can withstand, at liquid helium temperatures, compression forces sufficiently in excess of the peak radial forces of the opposite sign that will be caused by the magnetic field. Approximately 20 per cent of the inner coil area closest to the inner coil radius can be used to develop the rigidity of this bore tube as the magnetic field in this region is not of sufficient quality to be used for proton acceleration or extraction.

5. The requirements of (3) and (4) suggest a series of banding rings along the length of the magnet. These rings are to be separated longitudinally and radially in a manner so that approximately one-half of the linear surface of one side of the superconducting wire can be cooled by convection currents in a single-phase liquid helium bath. In other words, the coil volume is to contain sufficient ventilation for adequate cooling without compromising any of its structural integrity.

6. As an aid to accomplishing the above, each shell of the three-shell coil system will have its individual turns bonded together so that the shells will form a beam structure, again to prohibit motion of the wire or its filaments between clamping rings.

7. To develop techniques and procedures for placing this fully clamped and ventilated three coil-bore tube structure into first, the supply tube for the liquid helium dewar; next the return tube where two-phase helium is brought back to the helium refrigerator removing heat from the coil assembly as it flows back, thereby performing the function of a heat exchanger; next the 20°-K helium shield followed by superinsulation; and then the final room temperature vacuum tube. The insertion of the coil assembly into this four-layer dewar system must be done in such a way that the inner coil assembly is held firmly and the location of the magnetic center and median plane is known. This requires the development of a system of special clamping rings for the coil-bore tube assembly, rigid clamping studs or similar devices between the layers of the dewar, a special low loss support system between the cold inner layer of the dewar and the room temperature outermost layer, and a fiducial system to translate crucial geometric information.

8. To develop methods for stacking and fabricating the magnetic shield.

9. To develop procedures for assembling the magnetic dewar systems into the magnetic shield while preserving the correct alignment of the magnetic field center and median surface.

10. To develop the mechanical assemblies for the ends of the magnets that will provide for a variety of interconnections between magnets.

b. To perform calculations and model tests at both room temperature and reduced temperatures to verify:

1. The structural integrity of the bore tube and banding system for different configurations and materials.

2. The adequacy of the cooling channels.

3. The adequacy of the wire locating techniques to be used in fabrication of models.

4. The adequacy of the methods proposed for coil connections and electrical insulation.

5. The adequacy of the clamping systems proposed to center and hold the superconducting magnet in its iron shield.

6. The effect on all of the materials at cryogenic temperatures due to both the long magnet (20 ft) and the different coefficients of thermal contraction.

7. The determination of thermal losses due to various types of structural and clamping systems.

c. To build six short prototype dipole magnets and one short prototype quadrupole magnet to test out the concepts developed in (a) and (b) above.

d. To build a series of eight full-scale 20-ft dipole magnets and two full-scale 7-ft quadrupole magnets as follows:

1. The first two 20-ft long prototype dipoles to be built from full specification solid wire of the two sizes but without the helium shield to reduce construction problems.

2. The second two to be built essentially the same as the first two, except that wire locations are to be changed to improve field quality and the helium shield will be added.

3. The third two dipoles to be built essentially the same as the second two, but with three component superconducting cable that should have less thermal loss due to pulsing than the solid wire.

4. The fourth two dipoles to be built essentially the same as the third two, but with a new solid cable made from drawn-down solid wire that is fully insulated before being twisted into a fully potted cable, that should be similar to the solid wire now on hand as far as magnet fabrication is concerned.

5. The two quadrupole magnets are to be built using the same solid wire as the dipoles for (a) and (b). Parts for these quadrupoles, except for the coils, are to be the same as those for the dipoles.

e. As the above programs evolve, to develop a cost optimization effort so that appropriate adjustments can be made in the production run to strike an optimum cost balance among production tooling, production parts, production labor, and complexity of assembly. A major consideration in the achievement of a cost optimization is the trade-off between the complexity of adding a helium shield and the cost savings in refrigeration that it would allow.

f. To develop approaches, designs, and cost estimates for production tooling.

g. To prepare production specification and assembly drawings for the magnets and all their parts.

h. To prepare quality control and acceptance testing criteria for the electrical and mechanical aspects of the production dipoles and quadrupoles. (The Energy Doubler Group and Magnet Measuring Group of the Accelerator Division will prepare magnetic field acceptance criteria.)

Thirdly, Cryogenic Consultants, Inc., of Allentown, Pennsylvania, was contracted with to accomplish the basic refrigeration system design for the test loop and the Doubler as a whole. Their technical report, entitled "Refrigeration System for the NAL Energy Doubler," is included in the backup material associated with this report.

The major elements of the Cryogenic Consultants, Inc. scope of work are as follows:

a. To provide support to NAL in the procurement and installation of a 200-liter/hr helium liquefier. Included are:

1. Foundation drawings for compressor, nitrogen

vacuum pump, helium expansion engine, cold box, and liquid nitrogen tank.

2. Preliminary equipment layout and elevations with connecting piping.

3. Up-to-date preliminary flow sheet of the helium liquefier with valve and instrument numbers and line sizes.

4. Observation and participation in the acceptance test of the helium liquefier at Gardner Cryogenics' facility in Hightstown, New Jersey, which was purchased as used equipment by NAL.

b. To provide support services to NAL in the design and installation of a helium pump-loop installation. Support will consist of and include:

1. Preliminary design of 400 ft of liquid helium piping.

2. Preliminary investigation of a liquid pump installation.

3. Design and specification of piping required to connect the pump-loop components and permit complete testing of the loop.

4. Provide a final flow sheet of the pump-loop facility.

5. Specify instrumentation required for the loop.

6. Perform engineering calculations required to size lines, vessels, and heat exchangers, and specify instrumentation.

7. Provide technical support for review of prospective vendor's proposals and follow-up during procurement of the equipment.

8. Provide cost estimates of equipment to be procured, and installation and checkout of the equipment.

9. Participate in checkout and testing of the pump loop after installation.

c. To design cooling passages and cryogenic system for prototype model magnets.

d. To complete pre-Title I design of an energy-doubler cryogenic system and submit a cost estimate for the refrigeration system.

Fourthly, The Magnetic Corporation of America of Waltham, Massachusetts was contracted with to furnish design and support and independent analysis on various aspects of the proposed dipole magnet design. The scope of work which they were to accomplish is summarized as follows:

a. To perform calculations of quench currents and temperatures for magnet configurations supplied by NAL.

b. To analyze hysteresis and eddy current losses for a variety of superconducting wire types and for a variety of magnet operation cycles.

c. To conduct a preliminary study of problems associated with achieving reproducibility in magnet fabrication.

d. To perform estimates of the effects of bore tube and cryostat shell permeability on the central field.

e. To review and make recommendations concerning the support system including the problems of structural support of windings against electromagnetic forces in both a transverse section and in the magnet end region, gravitational loads, net electromagnetic loads toward the shield, and heat leaks.

f. To review and design multi-unit production procedures, including a production winding and assembly procedure.

Reports prepared by the Magnetic Corporation of America entitled "Superconducting Energy Doubler Dipole Design Study," three volumes, are available in the file of supplementary material listed in Appendix 2.

APPENDIX 2

BACKUP MATERIAL ON FILE AT NAL

Some Preliminary Concepts about the Proposed Energy Doubler Device for the 200/500 GeV Proton Accelerator at the United States National Accelerator Laboratory, Batavia, Illinois. Edited by P. J. Reardon and B. P. Strauss. Revised May 1973 and published as an NAL Technical Memorandum (TM-421-0428).

The work from October 1972 through March 1973 is summarized in this 200-page document. It also represents the first attempt at NAL to make a write-up of the Energy Doubler. This document was used to justify the design and model work carried out from February 1973 through February 1974.

Superconducting Accelerator Magnet Cooling Systems, P. C. Vander Arend, Cryogenic Consultants Inc., and W. B. Fowler, IEEE Transactions on Nuclear Science, Volume NS20, No. 3, June 1973, pp. 119-121.

Paper presented at the 1973 Particle Accelerator Conference,March 5-7, 1973 on refrigeration system work.

Preliminary Modeling and Testing of Ramped Superconducting Dipoles for the NAL Doubler, P. J. Reardon, B. P. Strauss, D. Sutter, R. McCracken, D. Richied, M. A. Otavka, IEEE Transactions on Nuclear Science, Volume NS20, No. 3, June 1973, pp. 744-746.

Paper presented at the 1973 Particle Accelerator Conference March 5-7, 1973. Reports on model testing up until the time of the conference. Early models were constructed extremely rapidly and were very successful in operating at design points. Models incorporated new concepts not explored by other laboratories.

Refrigeration System for the NAL Energy Doubler, Cryogenic Consultants Inc., April 26, 1973 (unpublished).

The main refrigeration system design work for the Energy Doubler was sub-contracted to Cryogenic Consultants Inc. of Allentown, Pennsylvania, beginning in November 1972. This is the same group that worked on the NAL 15-ft Bubble Chamber refrigeration system design from July 1970 through 1972. The above 57-page report was widely circulated with a request for critical comment. In addition to the exercise of carrying through a complete preliminary design they also performed a cost analysis of the system which was separately reported to NAL. Necessary research and development effort was identified and was at a later time implemented.

Cost Estimate of the Refrigeration System for the NAL Energy Doubler, Cryogenic Consultants, Inc., April 26, 1973 (unpublished).

Sixty-one page cost report referred to in the report description above.

Superconducting Energy Doubler Dipole Design Study, Magnetic Corporation of America, January 1974 (unpublished).

This substantial three volume report was prepared by Magnetic Corporation of America, Waltham, Massachusetts, under a sub-contract with NAL. The report described in detail the work performed from January 1973 to November 1973.

Engineering effort is reported in two volumes. Volume I contains analytical results and conclusions while Volume II contains engineering drawings of the components for a prototype dipole and certain items of tooling required for production. Volume III contains cost estimates.

Facets of the prototype design which were considered in detail include magnetic field calculations, determination of loads of electromagnetic origin, analysis and specification of support structure and design of dewar components. In addition, analyses were performed of ac losses and magnetization effects and an investigation was made into multi-unit production and economics.

Operating Experience - Helium Extraction and Liquefaction Expansion Devices, T. R. Strobridge and C. F. Sindt, January 1974 (unpublished).

In December 1973 NAL contracted with the Cryogenics Division of the National Bureau of Standards to develop and evaluate information from the large helium refrigerators used in the Kansas gas fields for helium extraction from natural gas. The above 31-page report, "Operating Experience - Helium Extraction and Liquefaction Expansion Devices" of January 1974 covers a total of 35 years of high capacity helium refrigerator operation. Thirteen illustrations are also included. Reliability information is summarized below.

Refrigeration Study for the NAL Energy Doubler, Cryogenic Technology, Inc., January 25, 1974 (unpublished).

The most active commercial helium refrigerator manufacturer is Cryogenic Technology, Inc., of Waltham, Massachusetts. Various design studies have been carried out by CTI including cycle design, compressor investigation, reliability studies and cost schedule estimates. This work is summarized in the above 21-page report. Seven illustrations are also included as well as a preliminary schedule.

Specification for 1400 W Helium Refrigerator, NAL Specification No. 0428.09-ES-53497, W. B. Fowler, January 28, 1974 (unpublished).

Based on current estimates of the Energy Doubler refrigerator requirements, a specification was prepared assuming that the refrigerators would need to be ordered as an advance procurement item.

Specification for Stabilized Superconducting Wire, NAL Specification No. 0428.090-TS-52500, Revision 1, B. P. Strauss, September 7, 1973 (unpublished).

This is the specification on which the procurement of superconducting wire for the Energy Doubler study has been based.