SUPERCONDUCTING MAGNET
FOR THE 15 FOOT NAL BUBBLE CHAMBER^{*}

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NOTICE

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PREFACE

The document evolved during the design, construction, and testing of the NAL 15 ft bubble chamber magnet. It has been modified to keep pace with the changes in the magnet, and sometimes the grammar and the tense could not keep up with the magnet changes. The description is that of the finished magnet with no attempt to follow all the design perturbations.

Installation of Magnet in
Bubble Chamber Building

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BASIC PARAMETERS

Following the agreement between National Accelerator Laboratory and Argonne National Laboratory on the design, fabrication, and delivery by ANL of the superconducting magnet for the 30,000 liter bubble chamber, and after subsequent discussion between NAL and ANL, the main features of the magnet were decided upon as follows:

- The magnet clear bore, including cryostat, is 13 ft (396 cm).
- The clear opening for chamber snout and beam entry is 30 in. (76.2 cm)

vertically and 48 in. (122 cm) horizontally. The opening is unobstructed by the magnet system. The downstream beam opening presents a 90° horizontal aperture, but is obstructed by two vertical struts.

- The magnet is equipped with a separate vacuum jacket, which is adequate for independent testing of the magnet out of the chamber and for operation inside the vacuum vessel of the chamber.

- The overall size of the magnet, including its cryostat and vacuum tank, is designed to fit inside the 22 ft (670 cm) spherical vacuum jacket of the chamber.

- The magnet and its cryostat are supported on three legs at the bottom. The transfer lines and power leads are fed from the top.

- The central field is aimed at 30 kG to the extent that this can be achieved on the given budget.

- No iron return path or shield is provided.

- The total cost, including complete tests at Argonne and helium refrigerator is to be fixed at \$2,000,000.

- The delivery of the magnet to NAL, after complete tests at Argonne is planned for June 1972. (This plan was later modified in order to carry out the first tests at NAL.)

BASIC TECHNICAL CHOICES

From the previous specifications and after a preliminary investigation of the whole system, the following parameters were fixed; inner diameter of the winding 14 ft (427 cm), separation between coil halves 39 in., amount of superconducting material for 27 kG; 620,000 kA ft. The final cost is mainly determined by the cost of the conductor and of the cryostat. The design should devote the greatest care to minimizing fabrication cost of these two components.

Prior to the more detailed design of the magnet, a certain number of technical decisions were made. These were based on the experience gained from the ANL 12 ft bubble chamber and on more recent developments in superconducting magnet technology, and were expected to yield the most economical design and construction together with maximum reliability in performance and safety of the magnet.

- The winding is made of single pancakes, each pancake being mechanically self-supported against radial and hoop stresses. This favors simplicity in the construction, handling, and assembly of the winding. It also simplifies the design of the spacers between pancakes and eliminates the need for radial clamps and for clamped crossovers between pancakes.

- An overall current density of 2000 A/cm^2 is a good compromise between the available space and magnet efficiency on one hand and the

stability performances on the other, together with the need for limited peak field and stresses inside the winding.

- A cooling strip between turns is not necessary, as the cooling capacity for stabilization is provided both by edge cooling and by partial face cooling through narrow transverse grooves built in the conductor itself. Apart from the obvious economic gain in eliminating the cooling strip and the simplification in winding operations, the main advantage of this solution is to allow the maximum cross section area for the conductor itself, at a given average current density, thus reducing the power dissipation in the conductor in the normal state and the necessary cooling capacity for stabilization. It also minimizes the total resistance of the magnet in the extreme case of a complete transition to normal state and favors the removal of the stored energy through external resistors at a minimum discharge voltage.

- The conductor has twisted fine superconducting filaments, in order to reduce to a negligible level the eddy current time constants in the conductor and to improve the intrinsic stability.

- Splicing of the superconductor was avoided inside the pancakes, in view of the high current density and of the limited cooling capacity available.

CONDUCTOR CHARACTERISTICS

A current of 5,000 A was chosen. This value is high enough to keep the number of turns and the self-inductance reasonably small, and low enough to give a low heat loss from the power leads and present reasonably economical

power supply and bus bar distribution. The resulting length per pancake also represents a practical limit for the production of a continuous length of conductor.

Taking into account the space necessary for stainless steel reinforcing strips, turn-to-turn insulation, and inter-pancake spacers, the current density in the conductor itself is about 3500 A/cm^2 .

After estimating the available cooling capacity, an aspect ratio of 10:1 was chosen for the conductor dimensions. A higher ratio would reduce both the fraction of edge cooling and the face cooling grooves in the conductor. A smaller ratio would increase the number of pancakes and spacers, thus affecting the efficiency and cost.

The conductor dimensions were taken as 1.5 in.(3.8 cm) x 0.15 in.(0.38 cm), with an approximate length of 3100 ft (945 m) in each pancake.

The structure of the conductor was determined after a technical and economical optimization based on present technology and industrial capabilities. One of the major requirements was the need for twisted superconducting filaments. Twisting of filaments uniformly distributed through the whole area of the conductor was found impractical and very expensive, due to the large size and the high aspect ratio. Furthermore, such a conductor would be highly anisotropic because of filament flattening. It was then decided to split the conductor into components: a copper backing strip; two copper side strips with cooling grooves; and a smaller strip containing the superconducting filaments. This composite conductor is then soldered together with 50-50 lead-tin solder.

The superconducting inner strip is 0.5 in. (1.27 cm) x 0.1 in. (0.254 cm), an aspect ratio of 5:1. Preliminary tests on samples of the same outer dimensions but with a different superconductor content showed an anisotropic effect of about 15%. This is quite acceptable, and smaller than the difference between the maximum radial and axial fields which will be observed in the magnet.

The number of filaments is 60, and the copper to superconductor ratio in this strip is 4:1. This last ratio corresponds to a current density in the superconductor filaments of $70,000 \text{ A/cm}^2$; a common value at 60 kG. The size of the filaments is about 15 mils (0.38 mm) diameter which ensures adequate current sharing properties together with reliable manufacturing processings. The filaments are twisted at the rate of 1 twist per ft (30 cm). This twist pitch rate must be kept as large as practical to enable easy and reliable manufacturing. The preceeding parameters will be discussed in a later section with regard to stabilization criteria.

The stabilizing copper strip was initially devised in a single component of over all cross section 1.5 in. (3.8 cm) x 0.15 in. (0.38) cm with a longitudinal groove for the superconductor and transverse grooves for cooling passages. Bids from the copper manufacturers showed that such a strip would be too expensive. Most of the manufacturers declined to quote. The reasons may be found in the unusual strip profile compared to standard fabrication, the high tolerances requested for the strip and groove dimensions and the limitation of long continuous lengths.

It was then decided to split the copper strip into three components, which could be welded or soldered together in order to achieve the required

profile. For the assembly of the whole composite, soft soldering was found to be the most practical. It is reliable and economical. Another advantage is that the soldering of the superconducting strip and the three copper strips is done in one operation. The subdivision of the copper strip is shown in Fig. 1. The backing strip sets the overall width of the conductor at 1.48 in. (3.76 cm). The smaller copper strips are 0.48 in. (1.22 cm) wide, allowing a small recess from the backing strip at the edge after assembly. They have transverse grooves 0.020 in. (0.5 mm) deep and 0.125 in. (3.17 mm) wide at the back giving a 50% surface for cooling. The superconductor inner strip, being only 0.1 in. (0.254 cm) thick, is laid well below the copper surface level, so that no force can be directly transmitted to this strip from turn-to-turn pressure.

The main specifications of the soldering process are the following: The bond thickness must be kept below 0.002 in. (0.05 mm). The flatness tolerance of the assembled conductor is 0.005 in. (0.127 mm) and the parallelism 0.002 in. (0.05 mm) maximum. The solder should be a 50-50 lead-tin content or a higher lead content material, but the tin content should not exceed 50% due to the brittle effect of tin at low temperature. Special care was to be taken with regard to flux corrosion, and the bond quality and homogeneity must be checked and voids greater than 0.5 in. (1.27 cm) are not permissible. A continuous ultrasonic testing technique, checked by X-ray inspection was used.

The mechanical problems raised by the use of soft solder concern the shear stresses due to hoop stresses, to differential thermal contraction,

for which the chosen solder exhibits adequate properties, and the transmission of the radial forces applied to the conductor. For 70% of the turns, these forces result in a compressive stress on the solder, while for the outer turns, where the field is reversed, the conductor tends to be pulled out from the copper strip. But in this case, the maximum stress is only 120 psi (8.46 kg/cm^2) which is well below the strength of the solder bond.

COIL CHARACTERISTICS

From the preceeding sections, most of the coil parameters are determined and the remaining factors for optimization were the number of pancakes and the number of turns per pancake. In fact, the choice of these parameters was mainly dependent on the maximum length which could be manufactured for the conductor and which is about 3100 ft (945 m), giving about 65 turns per pancake. For 30 kG central field, we then need 22 pancakes per coil or 44 pancakes total. Variations of these parameters does not significantly affect the design performance of the magnet, as can be seen in Table 1.

In practice the length of conductor and the number of turns may vary from one pancake to another. The pancakes will be stacked with the shorter lengths at the extremities. The number of turns will be between 63 and 67 with an average of 65.

The complete characteristics of the coils are given in Table II. The field distribution is shown in Figs. 2, 3, and 4, which correspond respectively to the bubble chamber volume, the winding cross section, and the volume outside the magnet. A flux line plot is given in Fig. 5.

As already indicated, the magnet was to be made of 44 identical single pancakes, but due to conductor fabrication problems only 43 pancakes were installed. The conductor was wound with a stainless steel strip, type 304, 0.075 (1.9 mm) thick in parallel, in order to provide mechanical support for hoop stresses. Mylar insulation 10 mils (0.25 mm) thick was placed on each face of the conductor. This double insulation allowed a continuous short-circuit testing during winding. The last turn of the stainless steel strip is edge-welded to the preceeding turn to make each pancake self-supporting for the hoop load and to eliminate the need for radial clamps. The stainless steel strip is 1.5 in.(3.8 cm) wide, exceeding the conductor width by 20 mils (0.5 mm). The compressive force between pancakes is supported only by the stainless steel. This has the advantage of releasing some of the tolerances on the width of the conductor and of eliminating any possible compressive load concentration on the edge of the conductor with the risk of buckling of the wide copper strip in case of local bond deficiency of the solder.

The coils have been wound at ANL using winding line components which were built for the 12 ft bubble chamber magnet. Only one winding table was needed, as no epoxy is used in the present magnet. New tension devices were constructed for the conductor and the stainless steel strips.

Spacers between pancakes are 0.25 in.(6.35 mm) thick micarta (linen reinforced phenolic). These are 1 in.(2.54 cm) wide and give 50% coverage of the surface of the coil. Each coil stack is clamped directly

to the bottom plate of the cryostat as described in a following section.

STRESS ANALYSIS

The distribution of compressive or axial pressures across the whole section of the winding is shown in Fig. 6. The maximum average pressure, which occurs on the eighth pancake starting from the gap and on the middle turns of this pancake, is 2690 psi (1.89 kg/mm^2). Assuming a 50% coverage of the spacers, the stainless steel strip will be subjected to a maximum axial pressure of 17,200 psi (12.12 kg/mm^2).

The hoop stresses in the pancakes have been determined by using the simplified assumption of a homogeneous solid disc supporting the actual field distribution, and then redistributing these stresses in the materials according to their respective cross sections and moduli of elasticity. The maximum hoop stress occurs on the inner diameter of the pancake with a maximum hoop load of 4,080 lbs (1855 kg) per turn. Using moduli of elasticity of 30×10^6 psi ($2.1 \times 10^4 \text{ kg/mm}^2$) for stainless steel and 17×10^6 psi ($1.2 \times 10^4 \text{ kg/mm}^2$) for copper (average modulus up to 10,000 psi (7 kg/mm^2) hoop stress) the maximum hoop stresses are then 10,300 psi (7.26 kg/mm^2) for the copper and 17,000 psi (12 kg/mm^2) for the stainless steel. These hoop stresses decrease nearly linearly with the radius and on the outside diameter the stresses are 8,200 psi (5.78 kg/mm^2) for the copper and 13,500 psi (9.5 kg/mm^2) for the stainless steel.

Actually the hoop stress distribution must differ slightly from that indicated above due to the non-homogeneous structure of the winding and to the presence of mylar between turns. However, the difference was

found very small when using a more elaborate computer program,¹ provided that no gap exists between turns during windings. In any case, integration of the hoop stresses along the radial thickness of the coil must result in the total hoop load, which can be directly obtained from the average axial field in the pancake. In the present case, the field varies nearly linearly from the inside to the outside radius from 51 kG to -22 kG, giving an average field of 14.5 kG. With a total of 325,000 A turns in the pancake, the total hoop load in the latter is then 247,000 lbs (112,000 kg), or an average of 3,820 lbs (1736 kg) per turn, which corresponds to the result of the above analysis.

Another change in the hoop stress distribution arises from the fact that, in the present magnet, the extremity of the inside turn is not clamped. This is to avoid stress concentration on this portion of the conductor and on the electrical inner joint which might result from such a clamp. Consequently, the coil will have a tendency to unwind itself, starting from the inner turn. This tendency is overcome by the friction between turns due to radial forces. The radial pressure on the first turn is 97 psi (6.8 kg/cm^2), which gives a total radial force of 76,500 lbs (34,770 kg) on this turn. In order to balance the hoop load of 4,080 lbs (1855 kg) found before, a friction coefficient of 0.053 would be sufficient, which is very low even between copper or stainless steel to mylar interface. Supposing that the friction coefficient is smaller, the preceding radial force acting for friction is about 2 times higher on the second turn reducing the necessary friction coefficient to 0.027. It can be

concluded that only a small length of the conductor will tend to slip outwards. The amplitude of the displacement of the inner end of the conductor can be found from the expansion of the coil itself under the magnetic hoop load. This expansion is of the order of 0.054% on the inside diameter. If one turn is effectively allowed to slip, the end will move only 0.28 in. (7 mm).

A last remark can be added to the present discussion. As shown above, if we follow the conductor starting from the inner end, we must reach one point where the accumulated friction force is sufficient to balance the hoop force. From this point the tendency of slipping between turns disappears completely as the hoop stress itself is balanced at each point of the conductor in the two opposite directions.

The stress analysis described above only applies to the electromagnetic forces. The stresses given here should be combined with the thermal stresses due to differential contraction between copper and stainless steel during cooldown and with the pre-stresses induced by tension during winding. The first stresses have been estimated as 2,830 psi (1.99 kg/mm²) in the copper and -3770 psi (2.66 kg/mm²) in the stainless steel strip, using a differential contraction of 30×10^{-5} . On the other hand, the winding tensions are 4,500 psi (3.17 kg/mm²) for the copper and 9,000 psi (6.34 kg/mm²) for the stainless.

COIL STABILITY

We first examine the "external" stability of the conductor based on the classical "full stabilization" criterion, which is independent of

the nature of internal instabilities.

As previously indicated, two regions of cooling are provided for the conductor; edge cooling and face cooling. The power dissipated in the conductor when 100% normal is per cm of length:

$$W = \frac{3 \times 10^{-8}}{1.28} (5000^2) = 0.585 \text{ w/cm}$$

This is the power at the highest field point where the resistivity of the copper is $3 \times 10^{-8} \Omega\text{-cm}$.

Three-fourths of the conductor edge is exposed to liquid helium (only one edge of the conductor can contact the spacers), i. e. 0.572 cm^2 per cm of length. The heat exchange coefficient can be safely taken as 0.4 w/cm^2 , which enables the removal of 0.288 w/cm . For face cooling the exposed surface is $2.5 \text{ cm}^2/\text{cm}$. From Wilson's data² the heat transfer coefficient for the channels in the conductor should be higher than 0.15 w/cm^2 , which gives a heat exchange of 0.375 w/cm . Then the total heat exchange capacity for the conductor is at least 0.6 w/cm , and the stability factor is at most 0.97, which indicates that full stabilization is achieved with the provided cooling.

"Internal" stability refers to the behavior of the superconducting filaments inside the copper matrix. Two effects are responsible for internal instabilities: magnetization of the superconducting material with associated "flux jumps" and eddy currents due to flux variations during charging or discharging of the magnet.

With regard to the first effect, no attempt has been made to achieve

complete intrinsic stability for the present magnet, as the size of the filament would have been too small and their number too large for a practical, reliable, and economical conductor fabrication. Furthermore, such a requirement is not necessary in view of the external stabilization indicated above.

The characteristic which in this case is most important for internal stability is the current-sharing characteristic of the superconducting filaments. This can be explained in a simple way: when a filament is heated, its current capacity is reduced accordingly and can become smaller than the transported current, in which case part of this current is transferred to the copper, with resistive heat dissipation taking place both in the copper and in the superconductor. The current-sharing transition must be smooth and reversible in order to avoid large jumps, but most importantly, the heat transfer capacity from superconductor to copper must be sufficient to allow the filaments to return to their initial temperature and full current capacity after the occurrence of the perturbation. This condition will be analyzed for the present magnet in the most critical case of maximum current and maximum field.

The current-sharing characteristics of the conductor are shown in Fig. 7 where the current and the dissipated power are plotted both for the copper and the superconductor as a function of the voltage along the conductor. The copper resistance is $2.35 \times 10^{-8} \Omega\text{-cm}$. The maximum voltage with all the current in copper is then $117 \mu \text{ v/cm}$. The maximum power dissipated in the superconductor occurs when the

current is equally shared between copper and superconductor and is equal to 147 mw/cm.

The heat transfer characteristic between superconductor and copper can be expressed by the following relation, first derived by Fairbanks³

$$W = 8\pi k (\bar{T} - T_0)$$

where k is the thermal conductivity of the superconductor, T_0 the copper temperature assumed uniform, $\bar{T}$ the average temperature in the superconductor, and W the heat flux per cm of length for one filament. If N is the number of filaments, $W_{\max} = 147 \times 10^{-3}/N$. Maximum $\bar{T}$ also represents the critical temperature at the current of 2,500 A and field of 60 kG, and is equal to 5.7°K .⁴ Supposing the copper temperature to be 4.7°K and taking a very conservative value of $K = 0.5 \text{ mw/cm}$ for Nb-Ti, the above formula gives $N = 12$.

The number of 60 filaments adopted for the conductor then ensures a very safe current-sharing characteristic for this conductor.

In the preceeding analysis, the thermal resistance of the bond between superconductor and copper has been neglected, as it is expected to be very small with the method of fabrication anticipated for the conductor.

The second effect mentioned above concerns the eddy currents in the conductor. By twisting the filaments, the amplitude of these currents can be reduced to a level well below the critical current. A characteristic length is universally used for determining the useful twist rate:

$$l_c^2 = J_c \rho / \frac{dB}{dt} \times 10^8$$

In the present case $J_c = 70,000 \text{ A/cm}^2$, $\rho = 3 \times 10^{-8} \Omega\text{-cm}$, $d = 0.038 \text{ cm}$, and $dB/dt = 2 \text{ G/sec}$ with a charge voltage of 10 volts. This gives $\ell_c = 63 \text{ cm}$, which indicates that the pitch of the twist should be well below 126 cm. The actual pitch has been specified as 35 cm maximum.

In fact, the main reason for twisting the filaments is to reduce the time constant of the eddy currents in order to eliminate any perturbation of the field shape in the useful volume. An expression for the time constant has been given by Morgan,⁵ which applied to the pitch of 35 cm, gives $T = 54 \text{ sec}$. Though this value may be far from exact, as it does not take into account the actual number and configuration of filaments, it indicates that troublesome long time-constant field perturbation should not occur in the present magnet.

CRYOSTAT

The cryostat is designed to operate with a source of liquid helium and to utilize the sensible heat of the boil-off gas to intercept incoming heat. The expected boil-off rate is 50 liters per hour. This mode of operation, as compared to use of a refrigerator, has the advantage of reduced boil-off in the event the magnet has to be run from a liquid source for a short period of time. By keeping a reserve of 3,000 to 4,000 liters of liquid in the storage dewar, the magnet can be operated for 60 to 80 hours without requiring the operation of the liquefier. This allows shutdown for maintenance without interrupting the magnet operation.

Pressure ratings of the cryostat were chosen to minimize the cost and weight without impairing the safety and operational characteristics.

The vacuum vessel is rated for normal operating conditions and is vented to the chamber vacuum for large internal or external pressures. This approach has the advantage of separate vacuum systems for the chamber and magnet, i.e. the cold surface is not exposed to possible H_2 leakage and the magnet will not be affected by poor chamber vacuum. Suitably venting the magnet vacuum to the chamber vacuum increases the maximum allowable pressure in the chamber vacuum to the buckling strength of the helium vessel rather than that of the lightweight magnet vacuum vessel. Pressure rating of the helium vessel is based on possible pressure rise during emergency conditions. The rating of 45 psi (3.2 kg/cm^2), results in a 0.75 in. (1.9 cm) wall thickness.

The magnet cryostat (Fig. 8 and 9) is a vessel 128 in. (32.5 cm) high by 213.5 in. (542 cm) o.d. by 156 in. (396 cm) i.d. (stiffeners on the outer vessel increase the o.d. to 222 in. (564 cm)). The components which make up the cryostat are a stainless steel vacuum vessel, two stainless steel helium vessels separated by a stainless steel bridge assembly to form the beam windows and an aluminum radiation shield covered with several layers of aluminized mylar.

DESIGN CRITERIA

The helium vessel and vacuum vessel are designed to meet the following conditions:

- 1) To withstand 45 psia (3.2 kg/cm^2) pressure both internal and external on the helium vessel.

- 2) To minimize the weight and cost of the cryostat fabrication and assembly.
- 3) To use 16,000 psi (11.3 kg/mm^2) for a safe stress level for the vessels at room temperature conditions.
- 4) To use a 30,000 psi (21 kg/mm^2) stress level for the design of the helium vessel bridge structure in tension and bending.

This stress level was allowable because:

- a) The bridge will be at 4.2°K when the magnetic forces are applied.
 - b) The forces are applied slowly due to the slow charging rate of the magnet.
 - c) The magnetic forces cannot accidentally exceed those calculated for a central field of 30 kG providing proper precautions are taken to prevent overcharging the magnet.
- 5) The vacuum vessel is designed for 5 psia (0.35 kg/cm^2) internal pressure and 20 psia external pressure. Rupture discs are provided to so limit the pressure under emergency conditions.
 - 6) The magnet support legs are designed to support 500,000 lbs (227,000 kg) vertical external load and 50,000 lbs (22,700 kg) horizontal load. These loads may occur if it is found necessary to place iron near the magnet during it's operation.

HELIUM VESSEL

The helium vessel modules are Type 304 stainless steel cylindrical shells with cover plates. These assemblies envelop the coils and are welded to the bridge structure to form a vessel rated at 45 psi (3.2 kg/cm^2) internal and external pressure.

Two 12 in. (30 cm) pipes are located in the top plate of the helium vessel. These pipes provide access openings for the power leads, instrumentation, cryogenic piping, and the emergency dump system.

The helium vessel is supported from the bottom by three equally spaced legs fabricated from 12 in. (30 cm) pipes with cooling passages attached for intercepting heat. Between the three support legs and the helium vessel are pivot type bearings to take up the thermal contraction of the helium vessel. These bearings are designed to move 0.3 in. (0.76 cm) horizontally during cooldown of the cryostat and to support a vertical load of 3 g's and a horizontal acceleration load of 0.2 g's.

The aluminum radiation shield with its cooling coils encloses the helium vessel. Suitable openings are provided in the shield to prevent collapse of the shield during vacuum pumpdown or due to an overpressure from a broken rupture disc in the vacuum jacket.

BRIDGE ASSEMBLY

The bridge assembly is the support base for the coils in each module. The coils are clamped to the bridge structure by means of 1 in. (2.54 cm) aluminum tie rods and a clamping ring. The tie rods are spaced in pairs on 18° centers. The tie rods are screwed into the bridge structure

and extend through a 5/8 in. (1.56 cm) stainless steel clamp ring. The spacers between the clamp ring and the coil vary in thickness. Positioned radially and directly in line with the tie rods are spacers 0.430 in. (1.09 cm) thick. When the nuts on the tie rods are tightened, they deflect the clamp ring approximately 0.070 in. (1.78 mm). This spring effect loads the coils midway between the tie rods to approximately 130,000 lbs (59,000 kg). The tie rods are then further tightened to a tension stress of 15,000 psi (10.6 kg/mm^2), which produces a force applied to the coils of 480,000 lbs (218,000 kg). When the tie rods are tightened, they will elongate about 0.060 in. (1.5 mm). The spring action produced by the deflected clamp ring and the elongated tie rods will maintain a clamping force on the coils during cooldown and also as the coils tend to "bed down" under the compressive load caused by the magnetic field.

The bridge assembly also incorporates openings (beam windows) at 0° and at 180° . The beam entry window at 0° is a clear opening 22 in. (55.9 cm) high by 48 in. (122 cm) wide. The beam exit window at 180° is also a clear opening of 90° included angle with two vertical support struts 5 in. (12.7 cm) thick, located radially 15° each side of the 180° centerline.

The bridge structure has six 6 in. (15.2 cm) vertical pipes spaced in suitable locations to provide communication between the upper and lower coil modules. They are used for passage of helium (gas and liquid), for intercoil connections, instrumentation wires, and cooldown piping.

VACUUM VESSEL

The vacuum vessel is fabricated out of stainless steel and is designed for an internal pressure of 5 psi (0.35 kg/cm^2) and an external pressure of 20 psi (1.4 kg/cm^2). Rupture discs with the above ratings will protect the system in the event of either a bubble chamber or helium vessel failure. The vacuum pump for the cryostat is attached to a pumpout port located in one of the vessel support legs. The cooling tubes for the radiation shield enters the system through a bayonet fitted flange connected to a fitting in the vacuum pumpout line.

RADIATION SHIELD

The radiation shield is constructed of aluminum and is cooled by circulating cold helium gas through piping on the shield. The gas is circulated by a small compressor and is cooled with liquid N_2 . Average temperature of the shield will be about 90°K , and its heat load is about 300 w. It is insulated from the warm wall with aluminized mylar. Aluminized mylar is also used between the shield and the vessel. Due to space limitations, a radiation shield will not be used in the region of the inlet beam window. Here only aluminized mylar insulation will be used. The shield is slotted at various places to reduce the forces due to eddy currents when the magnet is discharged.

LEADS

The magnet current leads will be brought out of the top of the cryostat as shown in Fig. 10. The leads will introduce about 12 w into the helium bath. They will have a loss almost this great at zero current. This

is because the leads are designed to operate with zero gas flow for 10 minutes without burning out. A flow alarm will be installed in the lead gas exhausts. If flow is interrupted for any reason, the magnet energy can be dumped in an external resistor without burning out the leads.

LIQUEFIER

Liquid helium will be supplied to the magnet system by a 100 liter per hour liquefier. This was furnished as a complete system by a commercial firm, Cryogenic Technology, Inc. Liquid is stored in a gas shielded, 10,000 liter dewar. Pressure in the dewar will be maintained at 4 psig and liquid will be transferred to the magnet as needed to maintain the liquid level. Dual purifiers will be utilized in the system so reactivation of one can take place while the other one is operating. The purifier system is designed for 500 ppm impurity level. The machine can operate as a refrigerator, for cooldown of the magnet, and can produce 2,000 w of refrigeration at 50°K dropping to 1,000 w at 20°K. A complete flow sheet is shown in Fig. 11.

COOLDOWN

The cooldown heat exchanger is located near the magnet. It consists of counter flow gas exchangers and a liquid-gas heat exchanger. Helium gas is passed through the cooldown heat exchanger and is cooled to near the temperature of the liquid (liquid nitrogen or liquid hydrogen) used for precooling. This cold gas is then passed through the magnet.

The magnet is cooled to operating condition in four stages. Thermal stresses limit the maximum cooldown rate to about 20 kw. In the

first stage helium gas is circulated through the cooldown heat exchanger by the liquefier compressor. Liquid nitrogen is used to cool the helium gas. After about 12 hours of cooling, the magnet is down to 115°K . About 29,000 liters of LN_2 is required.

At this point the liquid N_2 is replaced by liquid H_2 for the second stage of cooling. Fifty hours later the magnet has been cooled to 40°K , having consumed 11,000 liters of LH_2 .

At this point the liquefier is connected as a refrigerator for third stage cooling down to 20°K . The fourth stage is to transfer liquid helium from the storage dewar to the magnet to cool down to 4°K and fill with liquid. About 500 liters of liquid helium will be evaporated in cooling the magnet from 20°K to 4°K and another 5,150 liters required to fill it. The expected cooldown rate is shown in Fig. 12, and the magnet heat capacity in Fig. 13.

INSTRUMENTATION

Each pancake has a potential tap so that joint resistance can be checked. A thermocouple is placed on each pancake to monitor temperature and temperature gradients during cooldown. Continuous liquid level indication is provided by several superconducting indicators in series along the height of the coil. A continuous level indicator is placed in the top pipe that contains the leads and the level will be controlled in the top pipe that contains the fill line. Strain gauges are bonded to the stainless steel clamp rings to indicate any changes in the amount of bending to determine if the coils are loosening up.

POWER SUPPLY

The power supply will furnish 10 volts at 5,000 amp which will charge the magnet at a maximum rate of 0.33 amp per sec. Current sensing will be accomplished by an electronic transducer with a basic stability of 10^{-4} , which will be then the limiting factor in the precision of power supply control.

The power supply will be similar to that of the 12 ft HBC magnet, i.e. on-off. For more information on this type of power, see Ref. 6.

DUMP RESISTOR

To rapidly decrease the field, a 0.036 ohm dump resistor is provided. The resistor is constructed of stainless steel and immersed in a water bath. Enough water is used to absorb more than 200 Mj in bringing the water to the boiling point. The remaining 200 Mj will boil water, but the current will be down to 3,500 amp by this time. The resistor has been tested, with separate power supplies, to 6,000 amp or 144% power. Upon dumping at full field, the magnet terminal voltage will go to 180 volts. The design is intended for 1,000 volts to give adequate safety factor. The time constant of the discharge through the dump resistor is about 14 min.

TABLE I

Variation of Magnet Parameters With Number of Pancakes for 30 kG Central Field

Total Number of Pancakes	40	42	44	
Turns Per Pancake	70.2	67.4	64.9	
Length of Conductor, ft (km)	3,390 (1.03)	3,240 (0.987)	3,110 (0.948)	
Total Length of Conductor, ft (km)	135,600 (41.3)	136,080 (41.5)	136,840 (41.7)	
Stored Energy (Mj)	395.81	394.85	394.35	
Max. Field on Conductor (kG)	52.7	52.04	51.35	
Max. Radial Field (kG)	40.9	40.5	40.1	
Field Uniformity in Chamber $\Delta B/B_o$ (%)				
R_{cm}	Z_{cm}			
100	0	+3.1	+2.8	+2.4
150	0	+2.1	+1.3	+0.4
0	100	-9.3	-8.9	-8.4
0	150	-21.9	-21.1	-20.3
100	100	-2.	-1.5	-1.

TABLE II
MAGNET CHARACTERISTICS

Winding inside diameter	14 Ft	4.27 m
Winding outside diameter	16 Ft 8 In.	5.08 m
Spacing between coils	39 In.	99 cm
Length of bottom coil	38.25 In.	97.2 cm
Length of top coil	36.75 In	93.3 cm
Number of pancakes bottom coil	22	
Number of pancakes top coil	21	
Number of turns per pancake (average)	65	
Total number of turns	2860	
Length of conductor per pancake (average)	3100 Ft	945 m
Total length of conductor	134,000 Ft	40.84 km
Weight of conductor	55 Tons	5×10^4 kG
Weight of stainless steel strip	26 Tons	2.3×10^4 kG
Operating current	5000 A	
Ampere-turns	14.3×10^6	
Current density in conductor	3700 A/cm^2	
Average current density	1885 A/cm^2	
Central field	30.06 kG	
Maximum axial field	51.4 kG	
Maximum radial field	40.1 kG	
Maximum field on end pancake at R = 220 CM	45.3 kG total 26.6 kG axial 37.3 kG radial	
Self-inductance	31.7 Henrys	
Stored energy	396 MJ	
Compressive force between coils at bridge	5920 Tons	5.382×10^6 kG
Maximum compressive force between coils	11,250 Tons	10.23×10^6 kG

CRYOSTAT

Liquid helium consumption	50 L/hr
Shield heat load	300 Watts
Shield cooling method	He gas cooled by LN ₂
Helium vessel pressure rating	3 atm. (external and internal)
Cryostat weight	45 tons (4.1×10^4 kG)

REFERENCES

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- 3) D. F. Fairbanks, "The Transition to Current-Sharing in Composite Conductors," Norton Internal Report, 1967.
- 4) R. Hampshire, J. Sutton, and M. T. Taylor, Effect of Temperature on the Critical Current Density of Nb-44% Ti Alloy, Proc. of Conf. on Low Temperatures and Electric Power, London, Eng., March 24-26, 1969.
- 5) G. H. Morgan, "Theory of the Twisted Multicore Superconducting Wire in a Uniform Magnetic Field," BNL Internal Report No. 13792.
- 6) John Purcell, ANL/HEP 6813, "The Superconducting Magnet System for the 12-Foot Bubble Chamber," (June 1968).

Fig. 1 Photo of magnet conductor.
The various components are soft
soldered together.

FIG. 2 - CONSTANT - FIELD LINES IN CHAMBER TOTAL FIELD
IN % OF CENTRAL FIELD

FIG. 3a

CONSTANT - FIELD LINES (k GAUSS) (V) COIL
 SOLID LINES: VERTICAL FIELD
 DOTTED LINES: HORIZONTAL FIELD

FIG. 3b — CONSTANT-FIELD LINE IN COIL TOTAL FIELD (k GAUSS)

FIG. 4 STRAY FIELD PLOT (TOTAL FIELD IN GAUSS)

FIG.6 - DISTRIBUTION OF VERTICAL FORCES IN THE WINDING

FIG. 7 — CURRENT — SHARING CHARACTERISTIC OF THE CONDUCTOR

Fig. 8 Overall cross section of
bubble chamber and magnet

Fig. 9 Top view and cross section of magnet

**Fig. 10 Vertical penetration
used for leads**

Fig. 11 Magnet system flow sheet

FIG. 12
MAGNET COOLDOWN

FIG. 13
HEAT CAPACITY OF NAL MAGNET
BASED ON 5×10^7 g COPPER (110,000#)
 5.27×10^7 g STAINLESS (115,500#)

Fig. 14 NAL BC Magnet
Assembly

Fig. 15 Two Ft Model used
in Conductor Tests

Fig. 16 Single Pancake used
in NAL Magnet

Fig. 17 Interior of Coil
Showing Joints
and Spaces

Fig. 18 Detail Showing Joint,
Potential Tap and Bolt

Fig. 19 Coil Assembly

APPENDIX I

The NAL Two-Foot Magnet Test

First Test

In order to test the NAL magnet conductor for stability, a model magnet was constructed from the first production run of conductor. The model consisted of 8 pancakes with a bore of 24 in. and an outside diameter of 34 in. Height of the completed stack of 8 pancakes with 1/8 in. spacers is 12 7/8 in. In order to test stability rather than short sample characteristics, the model is designed to produce a peak field of about 30 kG at a current of 5,000 A.

Cooldown of the magnet went very well requiring only 300 liters of liquid helium to cool the 2,000-lb magnet to 4° K. Charging began when the magnet was covered with liquid helium. The magnet was noisy in that the loose turns could be plainly heard as they slid into place as the magnet was energized. It is difficult to model the mechanical motion that will occur in the large magnet, however, the 2-ft model demonstrated that large mechanical movements did not disturb the stability.

Electrical stability of the magnet was determined with a heater wound along a 3-ft length of conductor in the winding. The magnet was charged to some current level and then the heater power was increased until the 3-ft section of conductor was driven normal. Heater power was then increased to its maximum of 300 watts in an attempt to force the magnet to quench. This was done for magnet currents of 4,000,

4,500, 5,000, and 5,500 A. In every case, the length of conductor went normal with 100 W of heater power (33 W per ft), and the normal region would not propagate with a maximum heater power of 300 W (100 W per ft).

At 6,000 A, a thermal instability occurred in the power leads which led to a slow quench of the magnet. Several minutes are required for the normal region to propagate, and this agrees with the calculations that have been made.

During the quench, a sharp rise in current was recorded. This could not be explained until the magnet was removed from the cryostat and the connection to the bottom pancake was found to be broken. Apparently when the lead broke, it was shorted to the third coil from the bottom and continued to carry the main magnet current. The two bottom coils were disconnected and discharged between themselves with a small amount of arcing between pancakes.

The model demonstrated that the conductor stability is adequate for the large magnet. Since power dissipation in a normal region varies as the current squared, 6,000 A is $36/25$ or 144% of rated power at 5,000 A.

Second Test

During the first test of the NAL 2 ft magnet, a normal region developed at 6,000 A. At the time this was thought to be due to the leads but could not be verified. The leads were rebuilt to carry higher currents, and the magnet was retested November 19, 1971.

During the test one power lead became plugged so no intercept flow could be taken, and a bad leak developed in the top of the cryostat.

This leak prevented the cryostat pressure from building to a level sufficient to give proper heat intercept flows, resulting in a high heat leak.

The magnet was charged several times and each time the power supply primary circuit breaker tripped between 5,000 and 6,000 A. This circuit breaker was rewired, and the magnet was charged to 7,100 A before the circuit breaker tripped. During all of these charges, the magnet was carefully monitored for normal regions and none were observed. The magnet was also allowed to stay at different current levels for several minutes to see if any normal region would develop. The 7,100 A developed about 40 kG peak transverse field and about 25 kG peak radial field.

The magnet was then charged to 5,900 A and held while the lead intercept flow was completely valved off and the liquid level allowed to drop. After 15 to 20 minutes, the liquid level dropped about one inch below the bottom of the top pancake, and the magnet slowly began to quench. During the quench, the top pancake appeared to go partially normal with the remaining pancakes remaining superconducting.

The 2 ft magnet was disassembled and the conductor inspected with the same ultrasonic equipment that is being used for the final conductor. Inspection of the 2 ft magnet conductor indicated about ten voids, 3 to 4 in. long. One area about 4 in. long was completely unsoldered. The normal criteria for conductor to be used in the large magnet is: voids shall be no longer than 1 in. The performance of the conductor

in the 2 ft, with its larger voids, leaves little doubt as to the electrical stability of the conductor in the large magnet, operating at 5,000 A.

Appendix II

Testing the Magnet

Cooldown of the magnet started September 6, 1972. The cooldown proceeded as described in the design section of this report. Cooling was first accomplished with the cooldown heat exchanger containing liquid nitrogen, then with liquid hydrogen, and finally with the helium refrigerator to 20° K. At this point the magnet was filled with liquid helium. Minor equipment problems and other work on the bubble chamber interrupted the cooldown several times. This extended the time required for cooldown considerably, although the cooldown proceeded essentially as planned.

To aid in filling the magnet with liquid helium, a reliquefier was added to the system. The reliquefier is a counter flow heat exchanger that takes cold vent gas from the magnet and uses this cold gas to cool a high pressure helium stream. The high pressure gas is expanded through a j-t valve and produces refrigeration in the magnet at a temperature somewhat lower than the vent gas. This process is advantageous when the magnet is full of 20° K or colder gas that must be displaced with liquid helium during filling.

The first magnet fill with liquid helium was attempted on Sept. 30, 1972. The helium storage dewar contained 7,500 liters of liquid when the magnet fill began. During this first fill, the temperature instrumentation was not working properly on the reliquefier and proper gas flow rates could not be established. This resulted in an inefficient transfer and the magnet lacked 8 inches of level when the storage dewar was empty. The difference in liquid between the 7,500 liters and the 5,500 liters in the magnet had been converted to gas and put into gas storage. It was later discovered that the

helium liquefier was not operating at its full capacity of 100 liters per hour.

This would help explain the poor efficiency of the first transfer.

During the following week the liquid helium in the magnet was allowed to boil away, and the liquefier was run to refill the liquid helium supply dewar.

The magnet was then successfully filled on October 8, 1972. Time required for filling was about 12 hours, and during this period the liquefier more than kept up with the losses in the system. Even during transfer, with the reliquefier operating, the liquefier was increasing the liquid inventory.

Energization of the magnet began October 8 around noon. The current was increased in steps of 100 amps each. After each current increase, strain gauges located on the magnet tie bolts were recorded, and the building deflections were noted. The dump switch was tripped every few hundred amps to monitor switch arcing, boiling around the dump resistor, etc., and then reset after the current had decreased by about 100 amps.

By six o'clock on the morning of October 9, the current had been increased to 2,500 amps. The magnet energy was dumped and testing terminated in order for construction work to continue on the bubble chamber. Testing was resumed about seven o'clock that evening and full current of 5,000 amps was reached by five o'clock the next morning.

During the test the stray field was of considerable concern. The area was continuously searched for loose pieces of iron or some failure of the building structure. At about 1,000 amps, a large X brace on the building was bent out several inches. The current was reduced to zero, and the X brace was clamped and later welded to the rest of the building frame. Forces on

iron in the stray field is not a great problem. Although the stray field is large, the field gradient is small. This results in a large force twisting the iron to line up with the field, but only a small force pulling the iron toward the magnet. Any small iron tool that is accidentally brought near the magnet will give warning by the twisting force before the force toward the magnet becomes large. Aluminum or other conducting material is difficult to move near the magnet due to eddy currents in the aluminum. The force occurs only during motion of the conductor in certain directions and should not present any particular problem.

Fig. 1

The relaxation of the tie bolts with the magnet fully energized is less than half the prestress on the tie bolts. The coil compression appears to be elastic as shown by the strain readings to near zero. The strain readings were quite reproducible on subsequent magnet current cycles.

During energization and dumping, the difference voltage between the upper half and lower half of the magnet were recorded. A complete charge cycle gave approximately 10 small voltage spikes of a few millivolts each.

Similar instrumentation on the ANL 12 ft. bubble chamber magnet¹ gave signals several orders of magnitude greater in both number and voltage excursion. The signals from the 12 ft. magnet were attributed mostly to nonelastic mechanical motion although the large untwisted conductor probably contributed some signal. The lack of signals from the NAL magnet during charge can be attributed to the twisted conductor with small filaments, and to a completely elastic mechanical structure.

Boil-off of liquid helium was not accurately measured during the run because the warm gas makeup flow meter was locked by the stray magnetic field. The liquid level in the magnet was operated somewhat above normal due to problems with the liquid level control system. The helium liquefier had been previously tested and can produce 100 liters per hour liquid helium in the storage dewar. During the test the liquid level in the storage dewar continually increased, sometimes apparently by as much as 30 liters per hour. This would give a magnet boil off rate of 70 liters per hour including all transfer lines. This is somewhat higher than the expected 50 liters per hour, but may be partially explained by the high liquid level in the magnet.

As expected the boil off rate of the magnet is independent of the current in the magnet. The leads are operated in a region that heat leak is almost independent of current. No increase in boil off is detectable at the full charge rate of 10 volts. During discharge, when the voltage is a maximum of 180 volts, the magnet pressure goes from its normal pressure of 2 psig to about 4 psig. This pressure rise is primarily due to eddy current heating of the copper in the composite magnet conductor.

The water in the dump resistor was at a temperature of 65°C , due to previous energy dump tests, when the magnet energy was dumped from full current of 5,000 amps. As the current began to decrease the water in the dump resistor became very hot and started boiling so rapidly the dump had to be stopped at 3,600 amps. Some of the hot water was removed and replaced with cold water and the energy dump resumed to zero current. It is planned to increase the water capacity of the dump resistor in the future.

Testing of the NAL bubble chamber magnet went very well. The liquid helium boil off seems to be somewhat higher than calculated but well within the capacity of the helium liquefier. The magnet vacuum system appears to be leak tight. During the actual magnet test, the vacuum pump was valved off from the magnet and the vacuum was always better than 10^{-6} torr. Mechanically the coils seem very good. The complete absence of electrical spikes during charge and discharge along with the strain gauge readings indicate that all motion is elastic and that the coils will not loosen with repeated thermal and magnetic cycling.

1. "The Superconducting Magnet System for the 12 Foot Bubble Chamber" ANL/HEP 6813.