MASTER

Argonne National Laboratory

MEETING ON THE
DESIGN OF LARGE SUPERCONDUCTING
BUBBLE CHAMBER MAGNETS

Edited by

C. Laverick

RELEASED FOR ANNOUNCEMENT
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MEETING ON THE DESIGN OF LARGE SUPERCONDUCTING BUBBLE CHAMBER MAGNETS

PREFACE

Representatives from AEC Laboratories considering the problems of large-magnet design with particular emphasis on large bubble-chamber magnets met at Argonne National Laboratory on November 18, 1965, to discuss problems of mutual interest. The meeting was called on the initiative of E. G. Pewitt of ANL, and The University of Chicago acted as host. The names of the participants in the meeting are included as Appendix C of this report.

Ideas on the design of very large supermagnets with stored energies of the order of 10^7 joules and above are not fixed since no such magnets have yet been made. The contributors to these informal discussions will probably change their points of view as the design studies continue. Their comments have been edited from taped transcripts, and I have attempted to report the sense of the remarks as faithfully as possible. The order of presentation here differs from that of the meeting itself, so as to provide somewhat better continuity. Argonne and Brookhaven General Programs were circulated before the meeting and include a list of the major problem areas for large supermagnet design. They are placed first since they may serve as an introduction and guide to the problems under discussion. The Livermore contribution is placed last since it deals with a large-magnet problem that is not specifically concerned with large bubble chambers.

This report is issued to stimulate discussion among those concerned with the problems of large-magnet design as well as to provide a record of a stimulating and enjoyable meeting.

I. ANL GENERAL PROGRAM

The outline presented here is intended to focus attention on the aspects of superconducting magnet design we consider most important for the design of the 12-ft, hydrogen-bubble-chamber superconducting magnet.

A. Magnet Design Problems

1. Conductor
 - a. Superconductor type and manufacture
 - b. Stabilizing material, type, quantity, and configuration
 - c. Strengthening material (if any)
 - d. Composite conductor--type and dimensions (i.e., cable or strip, etc.)

- e. Current in conductor
- f. Packing factor, interlayer insulation, and cooling system
- g. Anticipated forces
 - (1) Cool-down stresses
 - (2) Magnetic loading (radial and axial)
- 2. Coil Form
 - a. Material and compatibility with conductor
 - b. Arrangement of windings
 - c. Form dimensions
 - d. Loads and distortions due to:
 - (1) Cooling
 - (2) Winding
 - (3) Magnetic loads
 - e. Inductance calculations
- 3. Cryogenics
 - a. Refrigerator
 - b. Cool-down circulation system
 - c. Operating circulation system
 - d. Container insulation
 - e. Power-lead considerations
 - f. Heat load on magnet and on container support system
 - g. Safety precautions
 - h. Hydrogen temperature radiation shield
- 4. Instrumentation
 - a. Cryogenic instrumentation
 - b. Mechanical loads
 - c. Measurements of magnetic field, rate of change of field, current through the coil, voltage across the coil, and monitoring of joint resistances
- 5. Power Supply
 - a. Current range, regulation, overload protection, safety devices, voltage range, and current sweep control (if any)
 - b. Conventional, rotating machinery such as homopolar generators and flux pump
- 6. Safety
 - a. Stability criteria
 - b. Liquid dump and gas venting
 - c. External shunting arrangements
 - d. Pressure ratings on vessels
 - e. Has every type of accident been considered?

B. Outline of Current Program

We are considering both cable and strip. The strip may be a multiple sandwich.

Present preference is as follows:

- a. Supercon NbZr
- b. RCA Nb₃Sn.

We are also considering with lower confidence level:

- a. Atomics International and Supercon NbTi
- b. General Electric Nb₃Sn.

The final choice depends upon manufacturers' record and quality control, on our experience with the material, and with price. We have a suitable NbZr conductor and hope soon to have a stabilized RCA conductor. We have no experience as yet with operating superconducting magnets for long periods with closed cycle systems.

We prefer high currents, say 10^4 A. This gives fewer turns, lower inductance, a high-strength conductor, good cooling, and a reduced number of superconducting joints. Heavy-current conductor may have worse cooling than light-current conductor if no attention is paid to improving the heat-exchange efficiency between the inside of the conductor and the helium bath.

At present we work at 1000 A; we will go to 2500 A for operating experience as soon as possible.

A 10-in.-thick, 8-ft-long, magnet-winding aperture has been provided (this includes the magnet can). Allowing a reasonable design overload factor (5×10^6 ampere-turns correspond to 20 kG), we propose to calculate on the basis of 6×10^6 ampere-turns. Thus the acceptable current density is 1000 A/cm². We have operated a number of safe magnets in the range of 2000 to 6000 A/cm² and would suggest 3000 A/cm² as a safe figure, easily attainable with present commercial-grade copper wrap around the superconductor.

Our magnet design studies for the 12-ft hydrogen-bubble-chamber magnet are integrated for convenience and efficiency with our program of general superconducting magnet development.

Some relevant work at present (November 1965) includes the following items:

1. We are studying the properties of composite conductors.
2. We are conducting experiments on short samples of various cables and strips.
3. We are experimentally measuring the effects of stress and magnetic field in these conductors at 4.2°K.

4. We are comparing theoretical predictions of coil performance using various techniques with experimental data derived from the operation of more than 70 cable magnets.
5. We are considering various designs of multiple strip.
6. We have improved our cable making, dipping, and cleaning facilities.
7. We have almost completed the design and construction of a machine for making multiple strip with or without copper layers in the sandwich.
8. We are attempting to make a machine for applying any type of metal coatings, of any thickness, to single or multiple strands of superconductor.

II. BNL GENERAL PROGRAM¹

The Research and Development program for the 14-ft, cryogenic-chamber, superconducting magnet has as its aim the development of a stabilized superconducting cable, which can be produced economically and which, when wound and powered in the proposed coil configuration, will generate a central magnetic field at 30 kG or higher, reliably and safely.

In the design of a stabilized superconducting cable, consideration must be given to the selection of the type and form of superconducting materials; to the thermal, electrical, and mechanical properties of the normal material; and to the method and material used in bonding the superconductor to the normal conductor. Additional aspects of the design must deal with coil and temperature control, electrical connections, and mechanical support.

Various superconducting cable configurations are currently being investigated, particular attention being given to the type of material and bond necessary to achieve good thermal and electrical contact between normal conductor and superconductor. A magnet wound with this superconductor will be operated continuously for at least three months to verify that no long-term degradation effects are associated with the superconductor.

An effort is being made to find a suitable substitute for indium as bonding material for the cable. After such a substitute is found, stabilized superconducting cables will be stranded and used to wind a split pair of coils, which, when placed together, will generate a central field of 40 kG in an 8-in.-diam bore. These coils are intended as a test facility for developing instrumentation for the 14-ft cryogenic bubble chamber at liquid-helium temperatures and at ambient temperature. The two sections may

¹A final Pre-Title I Report dated Dec. 1, 1965, entitled 14-ft Cryogenic Bubble Chamber Project (BNL-9695) has since been issued by the Physics Dept., Brookhaven National Laboratory.

also be moved apart to permit insertion between them of coil pancakes wound with optimum cable configurations to be examined for use in the 14-ft bubble-chamber magnet. This facility will permit the coil pancakes and the stabilized superconducting cables to be tested in a magnetic field environment. Problems relating to power supplies and magnetic field measurements, to cryogenic design cooling, and to some mechanical aspects of the superconducting coil design will also be investigated in this facility.

The selection of an appropriate normal conductor for the stabilized superconducting cable is an important design consideration. Ideally, the normal conductor should have excellent thermal and electrical conductivities and a high heat capacity and should be mechanically strong. If this combination cannot be found in one material, it may be necessary to select one material for its electrical and thermal properties, and a second to provide mechanical strength and stability for the cable.

An effort is being made to determine parameters of the normal conductor to be used in the cable configurations. Some of the design criteria to be investigated are required purity and variation of electrical resistance ratios with strain and work hardening and with magnetic field intensity. Information is also being sought concerning the dependence on temperature of thermal and mechanical properties such as heat capacity, specific heats, and heat-transfer coefficients. The behavior of the superconductors and the superconducting cables when subjected to various strains will also be studied.

At Brookhaven, several small coils have been made which have operated in the persistent mode. Development of current leads, low-resistance joints, and superconducting joints will continue, as will the effort in the coil instrumentation which is being directed toward insuring that reliable and accurate devices and techniques for measuring temperatures and liquid levels are available. Various techniques for conductor and coil electrical insulation are being considered, the present emphasis being on the possibility of using materials that can be anodized.

The feasibility of using a flux pump to power the bubble-chamber superconducting magnet is being investigated. Various types of flux pumps are being considered, and tests will be carried out to study the efficiencies and practicabilities of such devices.

As a continuation of these research and development programs, a test facility large enough to accept superconducting-magnet coils with a 3-ft inner diameter and a 5-ft outer diameter is being designed with a closed-loop helium refrigerator.

A single pancake of this size requires 1000 ft of conductor similar to that designed for the large bubble chamber magnet. This length may be compared to the length of 3600 ft required for the large magnet pancake. These 3-ft-diam pancakes will serve not only to model and test the superconducting cable configurations and to examine other associated design considerations, but also to test production capabilities and quality control. Eight of these pancakes arranged in split-pair coil configuration will also generate a field of 40 kG over an existing 30-in. bubble chamber.

It is expected that this test facility will be completed in 15 to 18 months.

III. ANL SUPERCONDUCTING BUBBLE CHAMBER MAGNET DESIGN PROGRAM

A. ANL Magnet Studies (J. R. Purcell)

Treating a large superconducting magnet as if it were a cryogenic magnet with a superconducting short results in a very safe design with the design parameters clearly defined. The major deviations from a good cryogenic magnet design is in the choice of optimum packing factor and the lack of forced convection cooling (large pumps). The problem of vapor-locking the coolant passages in such a magnet may be quite severe depending upon the actual I^2R loss in the magnet.

The refrigerator will be a simple J-T (Joule-Thompson) system with both liquid-nitrogen and liquid-helium precooling. This is a simple and reliable system with sufficient efficiency for our anticipated load of 100 W.

Internal shunts to protect sections of the magnet have not been considered. The only reason for shunts is to protect the coil if conductor breakage should occur. For shunts to be effective, even for this type of failure, a large number of shunts must be used to divide the total energy of 100 MJ into "safe" increments. Internal shunts increase the heat load during charge and may not be necessary.

Using the refrigerator compressor as a circulation pump and circulating the helium gas through a liquid-nitrogen bath, and later a liquid-hydrogen bath, enables 50,000 lb of material to be cooled in about 24 hr. About 2,000 gal of liquid helium will be contained in the magnet design.

In the event of a quench or some other condition of high heat load, the liquid should be dumped quickly. This ensures that the complete magnet is normal and that the stored energy is uniformly dissipated throughout the coil. The total stored energy will warm the coil to somewhat below room temperature. A liquid dump not only conserves the liquid but relieves the severe venting problem that would occur in attempting to absorb 1 MW by evaporating liquid. Time to dump the liquid, without a large vent rate, can be provided by allowing the pressure to rise (say to 1 atm gauge) and allowing the heat load to be absorbed in specific heat of the liquid. With 1 MW and 2,000 gal, this gives about 1 sec before gas evolution is necessary. The magnet container is being designed for 3 atm pressure, with a normal operating pressure of 1 atm.

Basing the idea of capability on the amount of heat that can be dissipated from the conductor to liquid-helium interface without getting runaway conditions, we choose 100 mW/cm^2 as a known safe and tolerable figure. Knowing the surface area of the conductor and its resistivity, we

obtain the stability level by equating the power dissipated in a given length of cable to the safe heat-transfer rate. Thus, with the conductor in liquid, the critical current is given by $I = \sqrt{0.1s/R}$, where s is the surface area and R is the resistance per centimeter of length. Using this technique to examine the critical current for a new magnet with lightweight aluminum conductor, we calculated the critical current to be 754 A. The experimental value was 800 A. The transient condition will never be as severe as the steady-state condition.

Two ways of performing short sample tests are as follows:

1. The heater is wound around the short sample, and the sample is then operated at various currents and pulses of heat are applied. The stable current (maximum) is that at which a normal region appears and remains when heat is injected.
2. The conductor is removed from one part of the specimen. In this case, the heat-transfer conditions are not changed from ordinary operation. The technique of breaking the superconductor at some point eliminates end effects if the break is long enough and, at the same time, checks the quality of the bond. Using potential taps closely spaced, one can examine the manner in which the current returns to the superconductor in the region of the break. This checks the bond, which is a critical parameter in a stabilized conductor.

Stability of a conductor need not be limited to a definition that includes the superconductor. A plot of voltage versus current for any pieces of copper wire will be a straight line at first and then rise to a runaway condition at some power level that exceeds the nucleate boiling heat-transfer rate. This copper wire then is stable up to this runaway current independent of any superconducting short if the superconductor is inherently unstable.

The heat-transfer coefficient in gases is a smooth curve, as the temperature differential between the wire and the environment increases, and is about a factor of ten smaller than that in the liquid.

Variations of resistivity with stress for ETP copper and 99.999% pure aluminum at 4.2°K have been measured. The results are shown in Figs. 1 and 2.

138-2636

Fig. 1. Resistivity versus Stress for ETP Copper at 4.2°K

B. Computer Calculations for Magnet Systems (J. G. Loken)

A computer program has been developed at ANL to calculate the magnetic field arising from a

138-2640

Fig. 2. Resistivity versus Stress for 99.9999% Pure Aluminum at 4.2°K

cylindrically symmetric configuration of coils and iron. This program has been used in the design of the iron and coils for a conventional 20-kG magnet with the following results:

1. The field uniformity is better than about 5%.
2. The radial field in the region of the expander is less than 100 G, keeping the eddy current heating well below 1 W.
3. The forces on the coils are known and acceptable.

The system was designed with a 12-in. space between the coils and 3 in. at either end between the coils and the iron. Using the detailed field plot and the known current in the coils, we calculated the bulk force on each coil to be 230 tons toward the poles (the magnet designers requested the force be definitely toward the poles). Using the method of images in the iron, we calculated the force to be 235 tons. Thus, the two methods seem to be in agreement. Variations of magnetic field with radial distance from the coil center are shown in Fig. 3.

Fig. 3

Field Strength versus Radius at Center and 60 in. above Center of Magnet for 20-kG Winding

138-2638

We intend to analyze the forces on individual conductors and pancakes for the 20-kG superconducting coil in detail.

Another computer program has been developed to assist in the design of the power leads for high-current systems. This program has been checked with some test apparatus, and both the heat input and temperature

profile are in reasonable agreement (1.2-W input for 600 A). In addition, the program indicates that with a better (but simple) design, the power could be cut to about 0.3 W. This program will now be used to design leads for test arrangements and later for the 12-ft magnet (if leads are used). It appears that a heat input of a few watts can be achieved with currents up to 10,000 A. The main difficulty in using this program is in estimating the heat-transfer coefficient at every point, but this problem is being investigated.

C. Stabilized Operation of a Composite Superconducting Winding (L. Lontai)

1. Discussion

Stability is properly defined in terms of the steady-state propagation velocity of the transition front. The transition front separates the normal and superconducting regions in the superconductor; here, a positive velocity of the front implies the growth of the normal region.

The suggested definition of a stabilized conductor is as follows: If at a fixed current and a fixed magnetic-field level, the steady-state propagation velocity of the normal transition front is negative, the conductor is stable at that current and field level.

The upper limit of stability is at current i_m , at which the velocity of the transition front is zero.

The lower limit of stability is at current i_a , at which the velocity of the transition front is $-\infty$.

For currents less than i_a , a normal region cannot exist in the steady state and the conductor is absolutely stable.

Velocity of propagation of a quench front in a superconducting wire with a normally conducting metal jacket in intimate contact (electrical and thermal) with it (see Fig. 4) is given by

$$v_q = a \frac{bi^2 - 2}{(bi - 1)^{1/2}} \quad (1)$$

where

$$a = \frac{(t_r S k_1)^{1/2}}{(C_1 \delta_1 \Lambda_1)^{1/2}} \frac{(1 + A_r k_r)^{1/2}}{1 + A_r C_r \delta_r},$$

$$b = \rho_1 \{t_r S A_1 [T_c(i_1 B) - T_b] (1 + a_r \sigma_r)\}^{-1},$$

i = Conductor current,

S = Effective cooled perimeter,

t_r = Equivalent heat-transfer coefficient [either film coefficient or $\Sigma (AX/k)$],

A_1 = Cross-sectional area of superconductor,

ρ_1 = Resistivity of superconductor in normal state,

k_1 = Thermal conductivity of superconductor,

C_1 = Specific heat of superconductor,

and

δ_1 = Density of superconductor.

} Assumed same
for normal and
superconducting
states

Fig. 4

Longitudinal and Transverse Sections
through Composite Conductor

138-2630

(a)

(b)

Transverse Section
through Composite
Conductor

Longitudinal Section through
Composite Conductor Show-
ing Boundary Region

The subscript r refers to the ratio of the above quantities of the normal metal to those of the superconductor. The limits of stability occur at conductor currents defined below (see Fig. 5) where

σ_r = Ratio of electrical conductivities with superconductor in normal state,

T_b = "Bath" temperature,

and

$T_c(i_1 B)$ = Critical temperature at current density i/A_1 and external field B .

Fig. 5

Variation of Velocity of Propagation
of the Normal Region with Current

138-2631

The conductor is stabilized for all currents $i < i_m$, where i_m is defined as follows:

$$i_m = \left(\frac{2t_r S A_1 [T_c(i_{m1} B) - T_b] (1 + A_r \sigma_r)}{\rho_2 \sigma_r} \right)^{1/2}, \quad (2)$$

The conductor is absolutely stabilized for all currents $i < i_a$, where i_a is defined as follows:

$$i_a = \left(\frac{t_r S A_1 [T_c(i_{a1} B) - T_b] (1 + A_r \sigma_r)}{\rho_2 \sigma_r} \right)^{1/2} \quad (3)$$

2. Comparison and Comments on Stability Criteria

A method of predicting the performance of fully stabilized conductors (proposed by Z. J. Stekly) is based on the maximum current density in the normal conductor that will not result in a temperature rise in excess of $T_c(i_1 B) - T_b$.

The maximum current in the stabilizing metal for

$$\Delta T = T_c(i_1 B) - T_b$$

is

$$i_a^* = \left(\frac{t_r S A_2 [T_c(i_{a1}^* B) - T_b]}{\rho_2} \right)^{1/2} \quad (4)$$

Consequently, if the current in the superconductor is limited to i_a^* , then in the event of an induced quench, the normal stabilizing metal can carry all the current without the total conductor temperature exceeding $T_c(i_1 B)$. This then guarantees absolute stabilization.

When A_2 (i.e., $A_1 A_r$) is finite and $\sigma_r A_r \gg 1$, the above condition and the one obtained from the actual quench propagation velocity (Eq. 1) converge.

Equations 2 and 3 can be expressed in terms of the current density in the superconductor as follows:

$$j_m = \left[\frac{2t_r S T_c(j_{m1} B) - T_b (1 + A_r \sigma_r)}{A_1 \rho_2 \sigma_r} \right]^{1/2}; \quad (2')$$

$$j_a = \left[\frac{t_r S T_c(j_{a1} B) - T_b (1 + A_r \sigma_r)}{A_1 \rho_2 \sigma_r} \right]^{1/2} \quad (3')$$

Given the current density in the superconductor below which stabilization is desired (i.e., either absolute stability or partial stability) at a fixed value of B , the ratio of

$$\frac{t_r S(1 + A_r \sigma_r)}{A_1 \rho_2 \sigma_r}$$

is immediately specified in terms of

$$\frac{j_m^2}{T_c(j_m, B) - T_b}$$

The superconducting state of the superconductor is bonded by the T - B - j surface as indicated in Fig. 6.

This imposes the condition that $j_m \leq j_s(T_b, B)$.

Four parameters (T_r , S/A_1 , A_r , and ρ_2) may be varied to achieve the required stabilization. Of these parameters, the choice of A_r is the most flexible; ρ_2 should be minimized; S/A_1 is a function of design and may be coupled with A_r ; t_r is also design-dependent and may be varied over a considerable range (i.e., conduction cooling to forced-liquid-helium heat-transfer system).

138-2633

Fig. 6. Boundary T - B - j Surface for the Superconducting State

3. Choice of Parameters for Stabilization at Minimum Superconductor Volume

For practical magnet design, an important requirement is the average current density $\bar{j}$ in the total conductor,

$$\bar{j} = \frac{j}{1 + A_r}, \quad (5)$$

where j is the current density in the superconductor alone.

It is desirable to achieve the required $\bar{j}$ with a minimum volume of superconductor (for cost savings). This consideration favors stabilization at a high value of j . The choice of A_r on the basis of minimum superconducting volume and the required $\bar{j}$ is complicated by a strong dependence on the magnet size.

The central field and the total conductor volume for a coil are given by

$$B_0 = \lambda \bar{j} \Gamma_1 F(\alpha_1 \beta) \quad (6)$$

and

$$V_a = \lambda \Gamma_1^3 \nu(\alpha, \beta), \quad (7)$$

where

$$F = \mu_0 \beta \ell n \frac{\alpha + (\alpha^2 + \beta^2)^{1/2}}{1 + (1 + \beta^2)^{1/2}},$$

$$\nu = 2\bar{N}(\alpha^2 - 1)\beta,$$

$$\alpha = \frac{OD}{ID}, \text{ and } \beta = \frac{L}{ID},$$

$$\Gamma_1 = \text{inside radius},$$

and

$$\lambda = \text{winding space factor}.$$

Consequently, the superconductor volume is

$$V_s = \frac{V_w}{1 + A_r}. \quad (8)$$

The maximum field at the inside diameter (ID) of the coil (the field level at which the conductor must be stabilized) is a coil-geometry-dependent function,

$$B_{ID} = B_0 K(\alpha, \beta); \quad K(\alpha, \beta) \geq 1.$$

Therefore, the coil ID, length, and central field (and λ) determine the relationship between $\bar{j}$ and α (i.e., Eq. 6).

The optimization for minimum superconductor volume now reduces to an iterative procedure for achieving stabilized operation at field $B_{ID} = B_0 K(\alpha, \beta)$ such that

$$j_m \geq \bar{j}(1 + A_r),$$

$$j_m = \left\{ \frac{2t_r S [T_c(j_m B_{ID}) - T_b] (1 + A_r \sigma_r)}{A_l \rho_z \sigma_r} \right\}^{1/2},$$

and

$$V_s = \frac{V_w}{1 + A_r} = \text{minimum}.$$

There is no general analytic solution to this optimization. However, the following observations can be made:

- a. For small-ID coils, the optimization will tend towards low A_r and high t_r .
- b. For large-ID coils, the reverse of (a) is true.
- c. Pushing j_m to the limit of $j_s(T_b, BID)$ (i.e., short sample B-j curve) may not necessarily result in optimum conditions, since $T_c(j, B)$ will approach T_b , and, as is seen from Eq. 2', either high A_r or high t_r (or both) is required to achieve stabilization.

IV. BNL SUPERCONDUCTING MAGNET DESIGN STUDIES

A. BNL Superconductor Development (A. G. Prodell)

Working with Atomics International, we have built a stranding machine and stranded cable. Six 0.020-in. copper strands, braided around an 0.015-in.-diam NbTi strand, were used with copper plating of 0.001 in. thickness around the superconductor. Four and five superconducting strands, each with the six copper strands around them and two or three lengths of additional seven strand cables made solely of copper, were used in two separate cable lengths in the manufactured cable. The whole was then bonded in indium. This cable carried 1400 A at 25 kG and was limited to this current by the amount of copper. It carried 1050 A at 35 kG. We produced 1200 ft of this by connecting the separate lengths containing four and five superconducting wires in series and winding in various solenoid configurations to get different fields. This permits the choice of an optimum current with a reduction in the amount of superconductor used. The current at 35 kG was on the short sample characteristic. The resistance ratio for the copper used was 160:1 before it was wound. After the copper and superconductor were stranded together, the resistance ratio for the copper dropped to about 100:1.

TABLE I. BNL Estimate of Cable Cost

	Per foot
Copper	\$0.25
Superconductor	0.50
Indium	0.90
Labor	0.60 (assuming \$12/hr)
Total	\$2.25

We would seriously consider Atomics International's NbTi if BNL had to choose a material now (Nov. 1965).

The current-carrying capacity of this material has been improved even more. Small quantities of wire are being produced, but they are not

ready for production on any great scale. The most expensive item in the cable is the indium, and we are looking for a cheaper material. We investigated tin. The cost of the material of the cable at the moment is summarized in Table I.

Labor costs would be reduced for large-quantity production. The resistance ratio for tin is about 150:1 at 20 kG. We have not investigated the powdering of tin at low temperatures. The copper has not been dissolved by passing the cable through a tin bath. The resistance ratio of 150 is for tin that can be obtained in the BNL stockroom.

The time scale at BNL is somewhat easier than that at ANL. Other types of conductor configuration are being investigated, and stabilized conductor configurations which involved ribbon are preferred.

General Electric used a series of pancakes of the new material to wind a 60-kG coil. The bore of the magnet was 2 in. (Ref. 2).

The BNL proposal now includes a 30-kG superconducting magnet with no iron. The magnet has an ID of 16 ft and a 2-ft radial thickness for the winding and may be modular in construction with a number of separate pancakes. There will be two 6-ft-long coils separated by 21 in. The total number of ampere-turns required for 30 kG is approximately 18×10^6 . The conductor considered is of the order of 2 in. wide and would be wound in a double-layer pancake so that all connections would be made on the outside. This gives about 28 pancakes of 32 turns each.

BNL has considered the possibility of a 10,000-A conductor, and G. Mulholland has looked into the power supply for such a conductor. We feel there is no problem of making a magnet to generate the field. The question is how should the conductors be supported, what are the forces involved, and how should this be contained? These are the most serious problems. The compression load between the coils is 10,000 tons. The structure that will hold the coils apart must fit inside the Dewar and be at 4.2°K. The only difficult point is in the area of the beam port. The maximum field at the winding is about 36 kG. The hoop stress due to the radial forces at the inside of the winding is of the order of 19,200 lb/in.², with half this value at the OD. The induced stresses in the conductor are due to cooldown and to the magnetic field.

One possible conductor configuration uses high-purity aluminum for the normal conductor, backed by aluminum alloy, if there is a question of economics. Although the aluminum alloy is stronger than the high-purity material, its modulus is the same; therefore it provides no greater support than the entire thickness of softer material.

Another possibility is to use copper as a normal conductor. If the normal conductor is also the stiffening material, the conductor is uniformly stressed in the field. Sandwiches, such as aluminum with stainless-steel backing, have been considered, but the stresses on cooldown between the aluminum and steel due to the differential contraction are greater than would be obtained in the aluminum itself due to the magnetic field. These stresses would not be so high with a composite of copper and stainless steel. The effect of stress on the conductivity of the normal material is important, and BNL hopes to measure the resistance of these materials when they are subjected to various stresses, as J. R. Purcell has done at ANL at helium temperatures in magnetic fields. There is little in the literature, and we prefer to make our own measurements.

²Since the meeting, G. E. has announced its new, flexible, 0.5-in.-wide, stabilized Nb₃Sn material and demonstrated a 100-kG coil made from pancakes of this material.

The first conductor to be considered for the large magnet is a thin, superconducting ribbon, graded in thickness from 0.008 to 0.001 in. with a width of 2 in. This would carry 10,000 A and use Atomics International's NbTi. Good conductor would be bonded to either side. This might be high-purity aluminum or copper. The degree of purity would depend on the effect of strains, and magnetoresistance in various grades of purity of these materials. High-purity materials may not be suitable. The total thickness of aluminum might be of the order of $1/10$ in. The rest of the conductor, which may be increased in thickness to $1/2$ in., would either be aluminum alloy or metal stiffener, such as stainless steel. Grooves would be rolled in these stiffeners. The axial grooves would be liquid-helium channels. The conductor would then be wound in a double-pancake configuration so that cooling occurred on the face. With aluminum, the insulation may be anodizing. The pancakes would be wound on a cylinder, which might have a thickness of 2 in. with spaces of the order of 1-8 in. between this and the next layer. The pancakes would be supported with 1-in.-thick plates, which may be necessary to lift the pancakes. The plates would occupy only part of the area cross section so as to give both good axial and radial flow. Electrical connections between pancakes would be made by exposing the superconducting surfaces of the conductors and clamping them firmly together. Two conductors and two superconducting joints will be used in parallel to connect the pancakes.

Atomics International has used aluminum to make a cable configuration somewhat similar to that of AVCO. The aluminum is bonded together and bonded to the superconductor by a diffusion-welding process with little silver on the superconductor. This gives an extremely strong bond. In attempting to pull it apart, they pulled the aluminum apart and not the joint. The material has not yet been tested electrically. They are also investigating the possibility of producing strip. They have made one short test sample involving a $1/2$ -in.-wide NbTi bonded to aluminum. The current-carrying capacity of the superconducting strip was 2,500 A. Thus, there are now three firms interested in the possibility of making stabilized superconductor: Atomics International, RCA, and Supercon.

The Atomics International principle involves subjecting the niobium ribbon to some sort of diffusion process. Atomics International felt that the strip they were making now was performing better than the wire. They expressed some doubt as to how the current density in the RCA strip would vary with thickness and did not think that if the strip thickness were doubled the current would increase in proportion.

BNL will consider some of the bonding problems and at the same time get other people to do the same. The bonding process in Atomics International has been under development for $3\frac{1}{2}$ years.

B. Calculations of the Magnetic Fields and Forces for the BNL Large Bubble Chamber (B. Culwick)

These calculations are of rather specialized interest since, to my knowledge, no one else currently envisages a similar configuration for a large bubble chamber, i.e., high magnetic-field intensity created by air-cooled coils.

The basic program written for this problem calculates the magnetic field of a set of rectangular-cross-section, coaxial solenoids. More complicated geometrical shapes can be approximated by division into equivalent rectangular sections. The current in each solenoid is first distributed over an array of circular filamentary conductors, each at the center of an approximately ($<3:2$ aspect ratio) square portion of the cross-sectional area of a coil. The magnetic field of each filament is then compared with that resulting from a fourfold subdivision of the filament. If agreement within a previously specified accuracy is achieved, the calculation is advanced to the next "master" filament; if not, the filaments are further subdivided until the required agreement is obtained. By this means, a high density of filaments is used in regions in which the resultant field intensity is sensitive to the distribution, such as at points within the conductors, with minimal densities elsewhere. Convergence and overflow problems within the conductors are eliminated by specifying a minimum distance between filaments and field points. The error due to this omission can be made small.

A typical distribution of filaments and some results for a proposed coil are shown in Figs. 7 and 8. The field intensity falls off by about 25%

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Fig. 7. Typical Distribution of Filamentary Conductors

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Fig. 8. Magnetic Field versus Radius for a Possible Cryogenic Chamber Coil Configuration

between the center and top of the chamber volume. The falloff can be reduced to about 10% by a triangular-shaped cross section instead of the rectangular one presently proposed. The maximum angle of the field direction to the axis is 20 to 25° in the visible region. For a 30-kG central field, the maximum field at the conductors is about 39 kG. On the midplane, the field reverses near the outer edge of the conductors with a maximum reverse field of 4.7 kG at 150 in. from the center. It is planned to place a nuclear resonance probe here for monitoring since the gradients of the field intensity are zero at this point. The stray field intensity falls to less than 1 G at 200 ft on the midplane of the chamber. Since the AGS will be about 1000 ft from the chamber, no interaction should result.

Forces on the magnetic objects around the chamber have been considered. No severe problems have been encountered. Shielding methods have not been examined in detail but are certainly feasible for devices such as TV cameras. The building will be of aluminum to avoid the effect of magnetic forces on it.

A version of the program has been modified to calculate the forces on the conductors over an array of points within the cross section. Various integrals of the forces useful in stress analysis are also calculated.

C. BNL 14-ft Magnet Considerations (G. T. Mulholland and A. G. Prodell)

Having decided that the vacuum space between a bubble chamber and its vacuum tank affords an ideal location for a superconducting magnet application, we must accept the 24-hour day, 7-day week reliability requirement standard for production bubble chambers. The proposed operation of a superconducting magnet for periods expected to be 6 months with energies of the order of 10^9 joules, as proposed for the BNL 14-ft bubble chamber, resulted in a few interesting (if unpopular) conclusions.

The two versions of the magnet considered, 30- and 40-kG central field air-core Helmholtz pair, differing only in current density, will have currents of 1 and 1.33×10^4 A and an inductance of 10 H. The most probable failure for the properly designed, fully stabilized conductor is thought to be in the helium refrigeration system necessary for operation. This eventuality or other source failures resulting in helium-refrigeration loss, necessitate an orderly means of magnet shutdown to limit the temperature rise of the magnet assembly (a warm magnet represents a heat load on the chamber). Every joule dissipated in the magnet assembly represents additional refrigeration to be supplied before operation can be resumed. Reasonable estimates of joint resistance, conductor resistance $F(T)$, and a realistic terminal voltage suggests that all but a small percentage of the total energy can be dissipated in an external (water-loaded) resistor when necessary.

A case having been established for the existence of external leads, the interesting flux pump has serious competition. Our assessment of

flux-pump technology suggests that current levels of 10^4 A are (or will be) realizable, but the power requirements due to realistic charging times (10^5 sec here) for large magnets are a long way off. The required power and efficiency of a flux pump to charge the proposed BNL magnet are 10 kW and 90%. The efficiency figure results from consideration of the proposed 1-kW helium-refrigeration capacity.

The flux-pump efficiency figures (about 1/1) available to us suggest that our requirement at 10^4 A cannot be met. Thus, the conventional power supply is indicated. Magnet charge rates (10^5 sec), power-supply location, and thus bus-resistance considerations lead to a 150-kW power supply (15 V at 10^4 A).

The magnet construction is seen as the pancake type with 28 required, 14 for each half. The connections (56 joints in all) are to be made on the (accessible) outside. The closed-cycle refrigeration system proposed requires that the return gas be delivered at nearly 4.2°K, precluding effluent-gas cooling of the power leads. Consequently, plans call for bottom-of-the-Dewar entry and liquid nitrogen, liquid-helium precooling of the power leads. The expected heat load presented to the nitrogen and hydrogen precooling paths and the helium Dewar are 800, 160, and 62 W, respectively.³

The operating helium refrigeration load due to internal joule heating is estimated to be less than 100 W at 10^4 A with unit joint resistance of 10^{-3} ohm. This electrical loss is within the capability of near-future flux pumps.

The most catastrophic failure possibility we can imagine is conductor failure (a series connection is proposed). Individual 10-milliohm shunts for each pancake have been suggested to limit pancake damage in the event of failure, although it is recognized that a sufficiently large cross section of normal conductor will increase bath and conductor thermal conductivity to limit the tendency of the strongly temperature-dependent specific-heat capacity and resistance of the normal conductor to make hot spots hotter. Clearly, the ideal conductor design is one that allows a number of small lengths of superconductor to fail completely without dynamic normal-zone propagation.

D. Some Comments on the BNL 14-ft Magnet Refrigeration System (J. E. Jensen)

The BNL refrigeration system consists of a 30-kW hydrogen refrigerator and a 1-kW helium refrigerator. The hydrogen cycle is precooled with purchased liquid nitrogen and contains one expansion engine. The helium cycle is precooled with nitrogen, hydrogen (from the refrigerator), and

³R. McFee, Rev. Sci. Inst. 30, 2, 98 (Feb 1959).

one expander. Both refrigerators are supplied by two compressors each for full capacity, each compressor providing 50% of the required mass flow. The cost of these systems has been estimated by several industrial people and BNL. The prices quoted were of the order of \$1.5 million, which is in reasonable agreement with BNL estimates if profits are included. One area of big savings is in the compressors, where BNL can save as much as \$200,000 on one of the quotes.

I mentioned some of the problems due to the high stray field which make it necessary to move some portions of the equipment away from the chamber. Also mentioned was the capacity of the helium system in the gas and liquid, 12,000 liquid liters of helium and sufficient storage tanks to contain this amount of gas.

V. STANFORD LINEAR ACCELERATOR CENTER (SLAC) PROGRAM

(H. Brechna)

The Stanford Linear Accelerator Center is particularly interested in high-field superconducting magnets in the region of fields higher than 50 kG in the center. The choice is based on the thought that the present water-cooled SLAC bubble-chamber magnet with an inner diameter of 1.37 m generating a field of 30 kG should be replaced in due course by a high-field superconducting magnet, producing a field of 60 to 70 kG.

The present SLAC 1-m liquid-hydrogen bubble chamber, its vacuum chamber, the optical system, and related parts can be preserved. It is even planned to use the iron shell around the magnet after a few modifications (better reinforcements, etc.) are provided. With the assumption of energizing the superconducting magnet from a 10,000-A flux pump or power supply, we anticipate using for the superconductive coil the space used presently by the copper coil.

The magnet dimensions are listed in Table II.

TABLE II. SLAC 1-meter Bubble-chamber Magnet Parameters

	Water-cooled Magnet	Superconductive Magnet
Coil inner diameter ($2a_1$), m	1.37	1.37
$a = a_2/a_1$	1.89	1.89
Axial length, left side coil $2a_1\beta_1$, m	0.368	0.368
Axial length, right side coil $2a_1\beta_2$, m	0.645	0.645
Axial-gap width, m	0.36	0.36
Field at center, kG	20	70
Total ampere-turns	2.8×10^6	14.63×10^6
Coil current, A	10,000	10,000

We plan to use fully stabilized superconducting conductor. For steady-state condition, the product of heat transfer and temperature rise in the liquid is calculated from

$$h\Delta T = \frac{I^2 \cdot \rho}{Q \cdot A},$$

where Q is the cross section of the substrate and A is the cooling surface of the conductor in cm^2 .

The values of $h\Delta T$ for various cables are measured for Nb-22%Ti and given in Table III.

TABLE III. Values of $h\Delta T$ for Various Stabilized Coils

$h\Delta T$	Maximum Cable Current, A
0.16	1000
0.4	300
0.6	500

The values of $h\Delta T$ are slightly pessimistic and depend on the cable geometry and the resistivity of the substrate. After measuring the magnetoresistance in liquid helium at different field levels, we decided to use OFHC (oxygen-free, high-conductivity) copper instead of pure copper.

The resistivity ratio for high-purity copper is measured to be

$$\frac{\rho_{300}}{\rho_{4.2}} = 1.5 \times 10^{-3} \text{ at zero field,}$$

and

$$\frac{\rho_m}{\rho_0} = 40 \text{ at 80 kG (field at wire).}$$

Thus, $\rho_{m,80kG} = 80 \times 10^{-8} \text{ ohm-cm.}$

For OFHC copper substrate,

$$\rho_{4.2} = 1.2 \times 10^{-8} \text{ ohm-cm,}$$

and at 80 kG,

$$\frac{\rho_m}{\rho_0} = 3.8,$$

which gives

$$\rho_m = 4.6 \times 10^{-8} \text{ ohm-cm.}$$

In the above values, the effect of cold work, which is always present during the winding process, has not been included. For specific copper alloys, the effect of strain has to be incorporated.

SLAC has tested Supercon's Nb-25%Zr cables in combination with 3/8-in.-bore small coils producing up to 46 kG. It is investigating heat-treated six-strand cables in different coil structures.

Parallel to the Nb-25%Zr experiments, work is being carried on with Atomics International's Nb-22%Ti with different wire diameters, such as 0.010 and 0.015 in., and various cable geometries. Figure 9 shows some results of the latest efforts.

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Fig. 9. Experimental Variation of Magnetic Field with Current for Wires and Coils of Supercon Heat-treated Nb-25%Zr and Atomics International Heat-treated Nb-22%Ti Material

The design of an adequate liquid-helium pump, the additional heat losses through transfer lines, etc., due to the high-pressure level are under investigation.

The leads are cooled from a separate system, which uses the latent heat of helium. The average current density in the coil does not exceed 10^4 A/cm².

The amount of helium inside the coil is about 20 liters. Two reservoirs each for 100 liters of helium are provided to compensate for any kind of trouble.

An experimental setup, with two Nb-25%Zr wires and 0.010-in.-diam wire indium-soldered to the outer surface of a 0.3-in.-square hollow conductor with 0.2-in. hole, carried 625 A continuously. The helium was circulated during the test.

In large, high-field magnets, the problem of forces on the conductors is of prime importance. On the other hand, the acting forces on the Dewar between the iron shell and the superconducting coils lead to inner-cooled superconducting wires, where the liquid helium is pressurized through the hole of a copper or aluminum conductor, which bears the superconductors. With this method, it is possible to eliminate the helium jacket, wind superconducting double pancakes, and insulate them in the same way as conventional water-cooled coils are insulated and impregnated. Superinsulation is provided around the coils, and liquid hydrogen and nitrogen shields may also be required to reduce the static heat losses to the lowest possible level.

To be able to operate at higher temperatures than 4.2°K, the system is pressurized at about 1-10 atm and the pressure drop across each double pancake is foreseen to be about 2-3 atm.

A coil system with 12 double pancakes and an inner diameter of 6 in. is now being built using the above system.

To investigate the effect of indium tinning, several tests regarding current-carrying capacity of the cable, cooling phenomena, and magneto-resistance effects were conducted. The improvements of the indium-impregnated (compared to copper-wrapped) cable did not justify the use of pure indium. It was decided to eliminate pure indium and use soldering tin or leave any tinning out.

The joint problem is still one of the most crucial. Though SLAC is not planning to run coils in persistent mode, we try to make joints that may have a resistance of less than 10^{-7} ohm at higher fields.

We plan to build a fully or partially stabilized 70-kG split-coil magnet with the following specifications:

Working-bore diameter	11 in.
Coil diameter	12 in.
Axial split	3 in.
Maximum field in magnet center	70 kG+

This coil is to serve as a model for a large coil, which could replace the present conventional magnet of the 1-m chamber. The coil is designed for continuous operation using a current-regulated power supply. The liquid-helium level is controlled automatically. This magnet consists of four sections (see Fig. 10) with the following configurations:

Coil I (inner section)	Central Field	70-60 kG
Coil II		60-45 kG
Coil III		45-30 kG
Coil IV		30-0 kG
Maximum field at the superconductor		~80 kG

Coils I to III are Nb-Ti; Coil IV is Nb-Zr. The cables are chosen to operate in stable mode up to 400 A.

The three inner sections are energized from the same power supply, and the outer section is energized from a separate power supply with a maximum current of 500 A.

A further plan is that after initial testing, the coil will be enclosed in a low-carbon iron jacket, and therefore engineering problems regarding mechanical Dewar structure are under consideration.

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Fig. 10. Layout of 12-in. Superconductive Coil

With this arrangement, the reliability of the magnet, the force distribution, the economical aspects of operation, and the stability of the superconductor can be tested.

A model magnet with a working bore of 2.5 in., featuring partially stabilized superconducting cables, was built and produced 72 kG in the center. A small coil with a working bore of 0.75 in. was placed into this magnet, producing another 8 kG. The composite coil structure is used for short sample tests, magnetoresistance experiments, and $h\Delta T$ measurements at high fields.

SLAC is working on a new conductor configuration for superconducting coils, and is performing short sample experiments as well as experiments with different alloys such as heat-treated Nb-Zr wires and heat-treated Nb-Ti cables and ribbons.

Experiments to determine heat transfers, flow rate, and stability of two-phase flow in multichannel configurations are under investigation. The time schedule for the SLAC program was as follows:

12-in. coil, ready for tests: June 30, 1966

Heat-transfer work: January 30, 1966

Conductor configurations for
stable or semistable operation: December 30, 1966

VI. THE LIVERMORE MAGNET PROGRAM

(C. E. Taylor)

The magnet for the Alvarez cosmic-ray experiment at 75,000 ft has a diameter of 1 m and a length of 2 m (Fig. 11). The coils are arranged

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Fig. 11. Superconducting Magnet Assembly

in a saddle-shape configuration to produce a transverse magnetic field at about 12 kG in the aperture, which contains the emulsion plates in a controlled-temperature chamber. The field is not uniform, but uniformity is not required for momentum calculation since the computer allows for variations in magnetic field. The total radial thickness of the winding is about 1 in. If a decision on conductor type had to be made now, the conductor chosen would be a cabled niobium zirconium (heat-treated) wire because it is the only material with which we have had a reasonable amount of experience in larger systems and on which we have good experimental data.

Cornish of Culham Laboratory found that with ordinary copper and NbZr (heat-treated) a ratio of 6:1 in copper to NbZr produced a fully stabilized cable. When wound

into a magnet, the magnet performs as expected from the short sample data. Thus, Livermore would use 49-strand conductor with seven superconducting strands and the remaining strands of copper. The winding will be clamped to the surface of the shell in an aluminum "Z" section with dimensions $1 \times 1/2$ in. The structure can be unwound if required. This is probably necessary since damage to the system may occur on landing and the system has to be light to be carried in the balloon. Consequently, the conductor is not bonded in any way so it can be easily unwound. The forces on the magnet are mainly circumferential forces, on the frame of the conductor and the frame of the magnet, which try to flatten the magnet so as to turn the circular section into an ellipse.

The magnet Dewar, helium, and support structure weigh about 3000 lb. The Dewar without the magnet will be flown in June, and the magnet should be airborne in about 12 months. The magnet will be charged before takeoff and switched into the persistent mode. The main problem being considered now is the question of what happens to the stored energy when the magnet goes normal. The stored energy in the

system is 1.5×10^6 joules. The amount of helium to be sent up with the magnet will be twice that necessary for the 48-hr flight. There will be added flexibility by having a lightweight helium Dewar strapped to the outside of the system to maintain the low temperature for longer periods if necessary. The heat leak can be kept within 5 W, which would mean that about 250 liters would be sufficient for the flight. The vacuum system will be open to atmosphere for landing to prevent its collapse under the landing shocks, and the magnet will be discharged at high altitude.

There is always the danger of a catastrophic accident, which may cause the vacuum to disappear during flight. Turnoff will be initiated either by some sort of thermal switch (delay) or by a signal from the ground. The superconducting switches, which are being used in Livermore at the moment, are pieces of cable with copper removed and wrapped with a heater. These switches are extremely reliable. We hope to use lighter-weight conductor with higher-purity copper. Extrapolating from Cornish's data, this would mean that we could use a ratio of copper to superconductor of the order 2:1 for a fully stable system with high-purity copper, instead of the 6:1, and get 200 A from each single strand. This is a basic 19-conductor cable with six superconducting strands and a center copper strand for 1200 A in a conductor $1/16$ in. in diameter. The effect of eddy-current heating due to relative motion of the magnet and the Dewar with respect to the remainder of the structure should be small.

In conjunction with Cominco, the problem of obtaining high-purity, high-resistance-ratio, copper wire has been studied. Typically commercial copper wire has a resistance ratio of about 100:1. If the wire is carefully annealed, the resistance ratio can be 175:1. The high-purity ingot, which is the starting material at Cominco, has a resistance ratio of about 2500:1, and so far the resistance ratio for the 10-mil wire is of the order of 400:1 after annealing. The ratio of 400:1 would almost get the results described. The manufacturer is annealing in air at the moment, which may account for some of his trouble. Magnetoresistance and increase in resistivity due to strain is a greater problem in high-purity material. There would still be a significant gain in this magnet because the magnetic field is relatively low, and it is not planned to get the stress levels as high in the conductors of this magnet as might be expected in the large bubble-chamber magnets or very high-field magnets. Thus, we hope to improve the conductivity of copper at maximum field by a factor of three over that obtained using normal commercial material. This should give about the same performance with the 2:1 copper ratio by area of cross section as Cornish gets with the 6:1 ratio. With 2500:1 copper and a magnetoresistance ratio increase of 10, there would still be an advantage in using the high-purity material. In the high-purity sample, the resistance ratio increases by about 10:1 at 20 kG.

Aluminum is very attractive since the magnetoresistance of aluminum tends to saturate at higher fields, but aluminum-stabilized conductors are not available yet, although ANL has operated its aluminum cable and Atomics International and Supercon are working on it. The next-generation magnet may have an aluminum conductor. The conductor weight is a small portion of the total weight of this device, being about 600 lb out of 3000 lb.

VII. GENERAL COMMENTS

(C. Laverick)

At no time during the meeting did a participant question the wisdom of designing and constructing a large supermagnet. The unanimous conclusion was that large magnets of this type would be built and would work; only a few somewhat difficult engineering problems remain to be resolved for each project.

The Brookhaven and Argonne magnets are similar from the point of view of refrigeration; yet there was a considerable difference in the estimated power dissipation for an operating magnet. Brookhaven estimated 1-kW dissipation with a \$1,500,000 helium-refrigeration system; Argonne estimated 100-W dissipation with a \$150,000 refrigeration system. Subsequent discussions have revealed that the Brookhaven figure was based on an estimated 450 W with a high factor of safety, while Argonne was quoting the estimated steady-state dissipation and assuming that charging losses would be absorbed separately.

The Brookhaven and Argonne points of view differ in emphasis for two reasons:

1. Argonne is committed to the construction of a working chamber with procurement beginning in the near future; Brookhaven is not yet in this situation and therefore has more time to exploit later developments.
2. Argonne has not yet decided whether to use a conventional magnet or a superconducting magnet; Brookhaven is definitely committed to the use of a large superconducting magnet and further proposes to utilize its advantages even more fully by designing for 30 kG with an air-core system.

In a supplementary talk, R. Benaroya of ANL described his work on the fabrication of Nb_3Sn plates and on their use for magnetic shielding. Points of interest to magnet designers are that there was a limiting rate of magnetic-field increase below which flux jumps did not occur. The flux jumps degrade the shielding capacity of the plates and change the induced diamagnetic current pattern. The production of field-free regions between the plates results in distortions of the magnetic field beyond the plates. Thus, very unstable superconducting magnets may operate to higher currents if low charge rates are used. This feature was built into the first large ANL magnets by the use of stainless-steel interturn and interlayer shunts.

An interesting feature with this use of bulk Nb_3Sn to trap fields or to shield regions from magnetic fields is that high screening-current densities have been attained. Fields of up to 60 kG have been trapped in some laboratories in small Nb_3Sn cylinders. Thus, high current densities can be supported in bulk material, and it may become possible to operate large coils at current densities of $100,000 \text{ A/cm}^2$ or more.

A problem that may arise with large magnets is the introduction of instabilities by the migration of flux through large volumes of superconductor. These effects are reduced or eliminated by the addition of copper as a shunting material. We have observed considerable flux movements in operating large magnets, although in this case, these were unstable coils with relatively small amounts of copper. In the ANL 67-kG system we observed a large, uncontrollable movement of flux into the center of the coil at 13 kG. This magnetic field is obviously a function of this particular coil system, its geometry, its close-coupled low-impedance power supplies, and the types of superconducting material in it. The movement took place over a period of 15 min because of the very long time constants built into the system. The magnitude of the change was not measured, but was large enough to make us think that the system was about to discharge when we first operated it. In very large magnets, particularly with iron, much larger volumes of superconductor will be at the same magnetic field at any given time during the charging or discharging cycle. There is a possibility that such an effect may occur and result in a lowered stability for some magnet designs. Conductors containing large amounts of copper are probably not affected at all.

Large superconducting magnets act as single molecules, thus demonstrating flux quantization on a macroscopic scale. There was some speculation that some types of flux jump may be connected with this phenomenon. Berlincourt⁴ has pointed out that in a persistent-mode supermagnet at absolute zero, energy levels exist in which the spacing between the zero-current normal and superconducting levels is approximately $(1/4) \gamma T_c^2 V$, where V is the volume of superconducting material, T_c is the critical temperature, and γ is the electronic specific heat, while the normal and supercurrent current-carrying "states" lie higher in energy by $(1/2) L I^2$, where L is the magnet inductance. Berlincourt reasoned that, for a given conductor size, the ratio of quench-triggering energy to the inductive energy decreases rapidly with increasing magnet size. This is true for unstabilized coils in which only a small fraction of the winding-material cross section over a small length need be transformed to the normal state and so lead to a discharge of the coil.

Future large magnets will operate in the high-current range of 2000 A to more than 10,000 A. Test and development facilities should be equipped to study conductors in this current range, the associated lead-cooling problems, the problems of making good, reliable, persistent switches, and the problems of making satisfactory low-resistance or zero-resistance contacts between different conductor lengths.

⁴T. G. Berlincourt, High Magnetic Fields by Means of Superconductors, Brit. J. Appl. Phys. 14 (1963).

The progress in supermagnet development has been impressive, but in the construction of a 14-ft-ID superconducting magnet, there will be a factor of approximately 100 increase in stored energy over the ANL 67-kG magnet, which operated in 1964, and a factor of 10 increase over the Avco-Everett 39-kG, 12-in.-bore, 5-MJ magnet, which operated in March 1966. Since this report was drafted, Avco-Everett Research Laboratories has reported the successful operation of a 7-MJ prototype MHD magnet. My opinion is that it would be wise to operate the first such large coil at 20 kG rather than to design for higher fields. Stable magnets of this kind have been operated at about 5000 A/cm². Unless radical changes in technology take place soon, the first large magnets should be operated below this level. Current densities of 2000 or 3000 A/cm², averaged over the cross-sectional area of the coil, represent conservative design. Even more space is available in the ANL magnet design since it is intended to leave room for a copper coil operating at a current density less than 1000 A/cm². This is being done because no decision has been made as to the type of magnet, and if a superconducting magnet is chosen, room will be available for copper coils if necessary. This approach is conservative but may not lead to the best supermagnet design because of the wasted space between coil and iron.

The ANL magnet was originally estimated to have 4,500,000 ampere-turns, and the latest design requires about 5,000,000 ampere-turns. My feeling is that an overcurrent capability of at least 20% should be built into the coil. Thus, the coil should be designed for normal regions to develop at about 6,000,000 ampere-turns, at which point the stable conductor can be chosen to permit a further percentage overcurrent without self-propagation of the normal region occurring. The power supply should be limited in maximum current to some value slightly greater than that actually required so that there is no possibility of approaching the current levels at which normal regions can be induced.

Current densities of the order of 400,000 A/cm² (approximately 200 A in a 0.010-in.-diam wire) are being considered for the superconductors in the composite conductors. This is typical for heat-treated NbZr in cables and strips. Heavy-current composite conductors can be operated at much lower current densities, and therefore at much lower stresses, without a great deal of change in price by using superconductors with at least a factor of two greater current-carrying capacity than that required.

Composite-strip-type conductors in which superconductors are embedded in copper or aluminum are being considered by BNL and ANL. These require some development unless the AVCO Supergen strip is accepted, since this is the only commercially available strip at present. Most contributors seem to favor the use of a strip containing greater amounts of copper than this. I favor heavy-current conductors (10,000 A or more) so that conductors of adequate size and strength can be used. I also feel that conductors incorporating even less copper than AVCO has used can be operated safely in large magnets.

Where large-magnet designs provide the absorption of substantial amounts of stored magnetic energy in the coil, if the system has to be discharged quickly, copper is considered to be superior to aluminum, and low-resistivity copper to high-resistivity copper. This is because a larger mass of low-purity copper has to be used because of its lower electrical conductivity, and this has the largest thermal capacity of the three types. The amount of copper chosen in this case is much greater than that required to provide stabilization of most conductors and is computed on the basis of allowable temperature rise in the coil. The MHD system considered by the British Electricity Authority has a stored energy of 10^{10} joules. If it is assumed that under emergency conditions 90% of this energy can be discharged into an external shunt, then 10% of the energy, or 10^9 joules, must be absorbed in the coil. It may be that copper induction rings separated from the magnet should absorb some of this energy.

Aluminum, with its low density and low thermal mass, is superior to copper for the electrical protection of superconductors required for air-borne, balloon-borne, or satellite-borne systems. Aluminum is also superior to copper at high magnetic fields because of its higher electrical conductivity.

The ANL and BNL designers emphasize the stable-conductor concept and consider the magnet as a cryogenic magnet with a superconducting short circuit bonded to the conductor. They then concentrate on the problems of vapor locking and refrigeration which may occur when the conductor is operated with normal regions in the conductor. Large quantities of liquid helium may be boiled off during operation under these conditions. Conductors, cooling channels, and refrigeration systems are then sized on this basis. The approach is sound, though expensive, but may not be as conservative as appears at first since the coil structure and its associated refrigerator have to be much larger than when lighter conductors are used.

Other points of view are possible and may result in equally effective and perhaps cheaper magnets. The magnet can be regarded as a superconducting magnet rather than a cryogenic magnet, and the amount of normal conductor can then be reduced to that required to produce a safe conductor as opposed to a stable conductor. Conditions that necessitate the development of normal regions in the conductor are to be regarded as unusual and unlikely to occur. Such conditions can be assessed, and protection systems can be devised. A conductor designed to operate up to 20,000 A without a normal region may be very safe if operated at 10,000 A when well protected.

Typical emergency conditions include conductor breakage and deterioration of contacts. Catastrophic discharge of the field energy in the unlikely event of conductor breakage must be avoided, but it should not be necessary to insist on continued operation of supermagnets with broken conductors. Contacts between successive lengths of conductor are being

planned as resistive and may be made by soldering strips together in a lap joint. This may preclude persistent operation and lead to contacts that deteriorate with time. The deterioration may place an increasing strain on the refrigeration capacity of the system. Some thought should be given to the possibility of developing truly superconducting contacts if many separate lengths of conductor are to be used in the magnet system.

Pancake-type constructions favor solenoids with horizontal longitudinal axes since good cooling is assured. Layer-type constructions give best cooling in solenoids whose longitudinal axes are vertical. Pancake-type constructions, which allow only edge cooling of the strip-type conductor, require much more normal material when operated in the dissipative mode than those that permit some reasonable percentage of face cooling.

Persistent switches should be positive in action, and considerable attention should be paid to the charging and discharging technique if the switches are used with a number of coils. We have accidentally damaged a small, multiple-coil system by energizing one coil with the persistent switch on an adjacent coil unknowingly in the zero-resistance mode. The system supports were not strong enough to prevent one coil from being forced away from the other.

The problem of dealing with the stored energy of the system when the magnet discharges accidentally or has to be discharged quickly has been given some thought, but other possibilities exist. The point was made during the meeting that external power supplies may as well be used since heavy-current leads have to be installed in any case. These are part of the protective system needed to discharge an appreciable amount of magnet energy under emergency conditions if required. These leads represent a considerable heat leak. There is the possibility that such a discharge resistor, if required, could be installed at or near helium temperatures so as to reduce this problem.

Flux pumps are being considered as possible power sources for large magnets. Present models are low-power devices, which demonstrate principles and practicability. The efficiencies of these devices are not yet adequate for large magnets, and more work has to be performed to measure and improve efficiency. Volger⁵ has expressed doubt about obtaining 90% efficiency in his superconducting dynamo; Wipf⁶ has said that the efficiencies of his devices may be made to approach 35 to 50%. Buchhold's⁷ devices are claimed to have higher efficiencies than 90%, but these claims have not been substantiated. These devices must be evaluated. Charging times are critical at these levels of efficiency, even if it is assumed that adequate power output can be attained.

⁵Philips Research Laboratories, Eindhoven.

⁶Westinghouse Research Laboratories, Pittsburgh, Pa.

⁷General Electric Advanced Technology Laboratories, Schenectady, N. Y.

A 10^8 -joule magnet requires a charging rate of 1 kW if it is to be charged in 10^5 sec, and 100 W if it is to be charged in 10^6 sec. At 90% efficiency, this represents a flux-pump power dissipation of 100 W for 10^5 sec, 10 W for 10^6 sec, or 1 kW for 10^4 sec. It is doubtful if this can be acceptable. The chief advantage claimed for flux pumps is that energy dissipation in the liquid helium is reduced because the devices operate at liquid-helium temperature. Thus, the heat input due to heavy-current leads passing into the liquid helium from room temperature is presumed to be eliminated. As can be seen from the above, this is only true for large magnets where long charge times are permissible at the present stage of flux-pump development. Volger attained a current of 12,800 A in a recent model, but the power output is low, of the order of 10 W. Flux-pump output voltages are often quoted for low currents, so that it becomes difficult to estimate their output power at full current.

A possible application for flux pumps may be to supply the steady-state power losses after the magnet has been charged. This is probably not practical if heavy-current leads are necessary for a room-temperature discharge resistor and if a large power supply has to be installed in any event for the initial charging of the coil.

We are now able to predict stable current-carrying capacities for many coils. The accuracy of prediction is high for magnets where the conductor is completely surrounded by liquid helium. For a recent magnet we constructed, Purcell (ANL) calculated the stable current using 0.1 W/cm^2 of conductor surface exposed to liquid helium as the heat-transfer coefficient and obtained a value that was close to the experimental value and somewhat lower. Bogner of Siemens, Lontai of MEA, and I used the Stekly calculation techniques when they visited ANL in August and September 1965 and found that we could not predict the current-carrying capacities of a large number of coil types in this way. The indeterminacy is due to the lack of good heat-transfer figures for insulated conductors in poorly cooled coils.

At the magnet meeting, I mentioned that we wished to obtain operating experience with a stable magnet operating for a long period of time so as to obtain experience in the reliability of stable-magnet systems. I also mentioned that the only conductor with which we had any experience was cable, so that it would be the conductor to use if a decision had to be made in November 1965. The thought at ANL at that time was that some sort of magnet should be built and tested, preferable with iron around the coil. It has since been decided that we should encourage the development of strip-type conductors in industry because their heat-transfer characteristics and internal stresses can be calculated. The hope is that adequate quality control can be developed in time to establish the point-to-point uniformity in characteristics of the strip lengths we require.

We issued a specification for a 20-kG magnet operating at an average current density of 5000 A/cm^2 for the model 2-ft-ID bubble chamber. The

object of the specification was to inform industry as to what we considered necessary in a practical superconducting magnet. Only two bids were received, of which one did not comply with the specifications. It was subsequently decided not to proceed with the purchase of the model coil since a 20-kG magnetic field was not considered large enough to make the model chamber a satisfactory working tool. Our technical specification is included here as Appendix A and may be of value to others in defining properties of an adequate low-current-density supermagnet.

Subsequent to the meeting, J. Purcell (ANL) and E. G. Pewitt (ANL) have decided on a conservatively designed 2000-A strip-type conductor. The conductor specification has been included as Appendix B and has been given wide circulation to assist others in a possible approach to the design of large, safe supermagnets.

APPENDIX A

Technical Specification For
20-kG Superconducting Magnet

October 19, 1965

I. INTRODUCTION

- 1.1 This specification is based on our confidence that superconducting-magnet technology has reached the requisite state of development for industry to be approached on a fixed-price basis with a simple set of magnet-performance requirements.
- 1.2 The specification should permit considerable freedom in design philosophy and construction techniques and has been formulated with this end in view. The requirements imposed are essential for safe and successful operation.

II. TECHNICAL REQUIREMENTS

2.1 Coil Container

The windings shall be contained in a Type 304 stainless-steel housing of welded construction, which will fit into the space whose dimensions will be supplied on request. The housing will be designed according to ASME to withstand a pressure of 40-psi differential pressure and will be checked for vacuum leaks. The container shall be fitted with liquid connections and current leads. The magnet will be operated in a liquid-helium bath at 4.2°K.

2.2 Field

The magnet must generate a field of 20 kG at the geometric center of the solenoid without the use of iron in the magnetic circuit.

2.3 Leads

Steady-state heat leak into the liquid-helium bath, due to the leads when the magnet is at full field, shall not exceed 5 W. All of the boil-off gas can be used to intercept the heat from the leads. Only one pair of current leads can be used; i.e., all individual magnet coils must be connected in series.

2.4 Charging

Charging time of the magnet must not exceed 60 min at its normal charging voltage.

2.5 Insulation

Internal electrical insulation of the coils shall be sufficient that under no circumstances can the structure be damaged by voltage. No internal shunts shall be used except the stainless-steel lead housing, which will prevent damage should the external current leads be opened.

2.6 Dissipation

2.6.1 The heat dissipation in the coil winding shall average less than 10 J/sec for a rate of change in magnetic field of 10 G/sec.

2.6.2 In any circumstance, limitations in refrigeration require that no more than 5 kJ shall be dissipated in the coil during any 5-sec interval.

2.6.3 The heat dissipation in the coil for operation at constant current shall not exceed 1 W at any field not exceeding 20 kG, as measured in actual use on the bubble chamber.

2.6.4 The coil shall be capable of operation at any current from zero to 25% overcurrent without self-propagation of a normal region under any condition except loss of liquid helium.

2.7 Current

The vendor is free to choose a magnet current consistent with his design and these specifications. The necessary power supply shall be supplied with the coil and be current-regulated to limit fluctuations to within 0.1% of rated field.

2.8 Instrumentation

The coil shall have at least two potential taps at the ends of the superconductor, and a dB/dt pickup will be provided with a sensitivity of 1 mV per G per sec.

2.9 General

2.9.1 The coil must operate at any current from zero to 25% overcurrent without any possibility of magnetic field decay due to any cause, except where the liquid helium is lost through some failure of the cryogenic system or where the circuit external to the magnet malfunctions. If helium is lost, the winding, the superconductor, and the container must not be damaged.

- 2.9.2 In the range of current between the rated current (for 20 kG) and 25% overcurrent, normal regions in the superconductor will be tolerated, provided that all other relevant parts of the specification are met for this type of operation, and the magnet power dissipation does not exceed 50 W.
- 2.9.3 It should not be possible to induce a normal region in the superconductor, except as specified, in the current range up to maximum current, by any means, while the coil is being operated as specified. The object of this condition is to ensure that normal regions are not induced by accidental conditions such as impact, vibration, or electrical transients in the system.

2.10 Proof of Competence

Companies desiring to bid on this magnet should be prepared to furnish proof of competence in the manufacture of medium-field, large-volume, superconducting magnets. Competence will be judged on the past performance of the companies on work in this field and on the technical standard of the composite conductor of the type proposed for this magnet.

2.11 Guarantee

The magnet will be guaranteed to perform according to this specification for at least one year with no limitation on the number of thermal cycles (4 to 300°K) during this period.

APPENDIX B

Specification for Conductor
for the 12-ft Bubble Chamber

1. Cross section	$2.000 \pm 0.010 \times 0.100 \pm 0.005$ in.
2. Conductor resistance at 20 kG, 4.2°K, 6000-psi tension, in normal state	4×10^{-7} ohm/ft max
3. Edge straightness, crown, etc.	To be determined
4. Current-carrying capacity of superconductor	2000 A minimum at 20 kG at 4.2°K
5. Allowable tensile stress	6000 psi
6. Quantity	125,000 to 150,000 ft
7. Magnet field	20,000 gauss

Please indicate interest in supplying superconductor only, complete composite conductor, and/or the completed magnet windings.

This specification indicates a possible configuration. Alternate proposals will be considered.

We recommend that vendors who are interested in bidding on this material should have their technical people contact the ANL project engineer as soon as possible.

The overall conductor cross section must be such that the heat-transfer rate to the liquid-helium bath in the as-wound configuration is approximately 0.1 W/cm^2 when the total current is flowing in the copper. The conductor is assumed to be cooled on both edges in the as-wound pancake.

A sketch of the proposed superconducting magnet, using the conductor described in this specification is shown in Fig. 12.

Fig. 12

Proposed Superconducting Magnet for
12-ft Bubble Chamber

APPENDIX C

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