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A LARGE SUPERCONDUCTING MAGNETIC
SHIELD

R. H. Lundsten, et al

Naval Ordnance Laboratory
White Oak, Maryland

1 February 1973

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BY
R.H. Lundsten
J.F. Scarzeilo

1 FEBRUARY 1973

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NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

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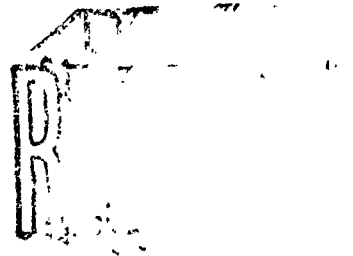
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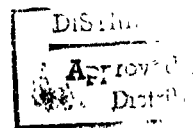
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ABSTRACT: A large superconducting magnetic shield was designed and constructed to provide a low intensity field in a temperature controllable volume approximately 30 cm (12 in) long by 10.2 cm (4 in) in diameter. Design, construction and operating techniques are discussed and illustrated. This shield was built by the Naval Ordnance Laboratory (NOL) for the NASA Ames Research Center in support of its magnetic sensor research and lunar magnetic field modeling programs.



Naval Ordnance Laboratory
Silver Spring, Maryland

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A LARGE SUPERCONDUCTING MAGNETIC SHIELD

This report discusses the design and construction of a large superconducting magnetic shield to obtain a stable low intensity magnetic field volume at and around room temperature. Detailed operating procedures and techniques are also presented. This information is of particular interest to persons conducting research on magnetic field sensors and related devices. The authors acknowledge the contributions to this work of Dr. Robert E. Brown and Mr. Daniel I. Gordon of the Naval Ordnance Laboratory and Dr. Palmer Dyal of the NASA Ames Research Center.

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ROBERT WILLIAMSON II
Captain, USN
Commander



W. W. SCANLON
By direction

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INTRODUCTION

A large superconducting magnetic shield was designed and constructed to provide a low intensity field in a temperature controllable volume approximately 30 cm (12 in) long by 10.2 cm (4 in) in diameter. Shield design and construction techniques are discussed and illustrated for this shield, which was built by the Naval Ordnance Laboratory (NOL) for the NASA Ames Research Center (ARC) in support of its magnetic sensor research and lunar magnetic field modeling programs.

The superconducting magnetic shield described in this report is a scaled-up version of a smaller unit originally designed and built by R. E. Brown (Ref. a and b). Design features, construction and operating procedures for this large shield are given.

Superconducting magnetic shields have been used extensively for fluxgate magnetometer sensor research since 1966. For example, at NOL a magnetic shield as described in reference (a) has been operated reliably for more than 2000 hours.

Other applications utilizing superconducting shields include lunar rock sample magnetic moment determination, paleomagnetic dating, screening for magnetic contamination, shielding for superconducting Josephson effect magnetometers and a stable magnetic field environment for numerous physical experiments.

The superconducting magnetic shield assembly (in operation) consists of basically three components:

- (1) the outer dewar containing the liquid helium,
- (2) the superconducting (2-mil thick lead foil) bag assembly,
- (3) the inner dewar positioned inside of the superconducting lead foil bag. This inner dewar provides access to the temperature controllable low-field working volume, the so-called "hot hole."

The sequence of operations involves putting a tightly folded lead bag into liquid helium in the outer dewar and allowing it to become superconducting. As the tightly folded lead bag becomes superconducting, it traps a small amount of magnetic flux contained within its original volume. The lead foil bag is then expanded. This expansion increases its cross-sectional area, thereby reducing the value of the trapped magnetic field, in inverse proportion to the area increase.

Successive cascaded stages of this operation, somewhat analogous to a "magnetic flux pump," reduce the trapped flux and lower the resulting field. Each added stage, however, requires that the added lead foil bag be kept above its superconducting transition temperature until fully in place in the reduced field region inside of the previous bag. At that time the lead bag is allowed to become superconducting, after which the outer bag is removed.

The room temperature access dewar, i.e., the inner dewar, when inserted inside the last lead foil bag provides a working volume 10.2 cm (4 in) in diameter by 30.5 cm (12 in) long of stable low magnetic field at the bottom of the dewar. Residual fields of the order of 0.1 nT (0.1 γ) with a gradient of 0.39 nT/cm (0.1 γ /in) are typical after cascading three lead foil bags, starting with a 6×10^{-6} T (600 millioersted) background field. External magnetic fields are reduced by shielding factors of the order of 100 dB.

SHIELD DESIGN AND CONSTRUCTION

The superconducting magnetic shield is composed of three main assemblies, the outer dewar containing the liquid helium, the lead foil bag and the inner dewar which provides the room temperature access working volume, i.e., the temperature controllable region. Several other small dewars and many peripheral small parts and equipment are required to put the superconducting magnetic shield into operation.

Dewars

Cryogenics Associates designed and built the outer and inner dewars to meet the following NOL specified size and performance requirements: (1) 10.2 cm (4 in) diameter access hole, (2) the length/diameter ratio of 7 for the lead foil bag, (3) 50-liter liquid helium reserve and (4) boil-off rate of less than one liter per hour. The outer dewar has a nominal 30.5 cm (12 in) ID, a 43.2 cm (17 in) OD and is 1.93 m (76 in) high excluding projecting valves and fittings (see Fig. 1). The inner dewar's dimensions are nominally 10.2 cm (4 in) ID, 15.2 cm (6 in) OD and 1.80 m (71 in) in height (see Fig. 2). Both dewars are superinsulated and do not use liquid nitrogen jacketing.

Nonmagnetic construction materials and low magnetic contamination assembly techniques are the most important requirement for the construction of these two dewars. Design requirements for the outer dewar limited the magnetic field produced by the construction materials to 10^{-7} T (1 mG) in the lower 1.22 m (48 in) of the inside of the dewar. The inner dewar had tighter specifications. Material-produced magnetic field was limited to less than 0.1 nT (0.1 γ) in the lower 50.8 cm (20 in) of the inside of the dewar, since it would be used inside of the superconducting magnetic shield and any residual field would appear in the room temperature access working volume. The materials were basically aluminum, plastic and epoxy-fiberglass.

Both dewars have evacuation valves, to allow for pumping of the vacuum space, and vacuum case pressure release devices (burst discs). The dewars are capable of operating continuously for several months, with liquid helium periodically replenished in the annular space between them. The average liquid helium loss rate was specified to be less than 1 liter/hour when the inside of the inner dewar was maintained at 20°C. Actually the loss rate was approximately 15 liters per day.

Baffle Assembly

A top closure plate with baffle assembly (Fig. 3) was designed to fit the top of the large dewar. The top closure plate (Fig. 4) supports the baffle assembly and seals off the top of the large dewar. Provision is made for a fill hole with two pressure vent valves, one each at $6.9 \times 10^3 \text{ N/m}^2$ (1 lb/in²) and one at $13.8 \times 10^3 \text{ N/m}^2$ (2 lb/in²) pressure, and a liquid helium level measurement hole. The four slots spaced 90° apart are used in the lead foil bag opening procedure to allow the bag to be fully opened.

The baffle assembly consists of a series of six separated copper baffles (Fig. 3) used primarily as a temperature gradient stabilizing device between the liquid helium cooled volume and the room temperature top closure plate. The baffle assembly also provides a means of supporting the lead foil bag with its support rods and acts as a centering guide for inserting the inner dewar.

A square cover plate (Fig. 4) seals the four slots in the top closure plate and supports the inner dewar with its spacer ring (Figs. 1 and 3). The spacer ring is used to adjust the distance between the inside bottom of the outer dewar and the outside bottom end of the inner dewar. This is necessary so that the end of the inner dewar when fully seated will not damage the lead foil bag and destroy the low magnetic field region.

Bags

Lead foil bags 38.4 cm (15.125 in) wide and 1.07 m (42 in) long are fabricated from 51 μm (0.002 in) by 50.8 cm (20 in) wide foil. The lead foil is available in 11 kg (5 lb) rolls. The bags are formed by folding a 2.29 m (90 in) sheet in half, forming a bottom, trimming to size with a sharp blade, and soldering the sides together. (See Appendix A for bag making details.)

In order to support and manipulate the lead foil bags in liquid helium the bags are glued to flat paddles (Fig. 5) which in turn attach to support rods and support rod extensions. The paddles are made from nonmagnetic phenolic and the support rods and extensions are made from thin wall nonmagnetic stainless steel. After the glueing of the lead foil bag to the paddles, the bag is then folded in an accordion pleat style after which it is held tightly in place with retaining clips. (See Appendix B for bag glueing and folding details.)

There are numerous items of equipment required to put the superconducting magnetic shield into operation. They will become apparent in the following section.

OPERATING PROCEDURE

Start-Up Equipment

To facilitate the start-up procedure, several items of equipment are required:

1. A platform to work on so that the top of the outer dewar is readily accessible.
2. A large pot-type liquid nitrogen dewar, approximately 30.5 cm (12 in) diameter by 1.52 m (60 in) depth, is needed to pre-cool items to minimize liquid helium loss.
3. A vacuum pump to evacuate the dewars before use.
4. An insert dewar for inserting all lead foil bags except for the first one. This dewar is made of two concentric tubes of glass which are glass-welded together at the bottom and closed off at the top with a toroid-shaped rubber plug. The dewar is open at both ends of the center tube. Provision is also made so that this dewar can be evacuated.
5. Liquid helium transfer equipment, including supply dewars, transfer tube, tank of gaseous helium, gages and rubber or tygon-type tubing.
6. Liquid nitrogen for pre-cooling.
7. Several special small covers, stoppers, a heat gun and assorted equipment that will be described later.

Start Up

Both the outer and inner dewars are evacuated to less than 0.67 N/m^2 (5 $\mu\text{m Hg}$). After cleaning the interior of the outer dewar of foreign particles, the top closure plate and baffle assembly is installed. The square cover plate which covers the slots and a round cover plate with a vent are next attached to close off the dewar. The round cover plate with a vent is a 0.635 cm (1/4 in) thick x 21.9 cm (8-5/8 in) diameter brass disc with a 0.952 cm (3/8 in) OD right-angle vent pipe offset from the center. In the center there is a 1.27 cm (1/2 in) diameter clearance hole with a 1.27 cm (1/2 in) lip. This hole is plugged with a rubber stopper.

The bag to be used first is glued to its paddles (bag construction and assembly are described in Appendices A and B) after which the support rods are attached, with the longest set on

the two wide paddles (#1 and #3) and the shorter set on the inside narrow paddles (#2 and #4). The four numbered support rod extensions are attached to the support rods, observing the counterclockwise sequence, #1 (wide), #2 (narrow), #3 (wide), and #4 (narrow). Two clips with strings attached are placed on the bag paddles to hold them tightly closed. They are adjusted to pull off easily when in the liquid helium, by means of strings. These strings are run up the support rods, wrapped around the support rod extensions, and fastened in place with tape. The bag is now ready for use.

Bags that are to be inserted after the first bag (i.e., when one bag is already in place and superconducting) must first be installed in the insert dewar. This dewar has a stopper in the top open end which has provisions for holding a lead foil bag assembly with clips and strings inside of the dewar. It also has provision for helium gas input (Fig. 6).

With both inner and outer dewars evacuated and two lead foil bags ready for use the start-up procedure is as follows.

1. Fill the outer dewar with liquid nitrogen to a level 15.2 cm (6 in) to 30.4 cm (12 in) below the baffles, i.e., approx. 75 liters. Let stabilize for approximately 16 hours to allow for the timely development of a temperature gradient across the superinsulation.

2. Remove the liquid nitrogen from the dewar by attaching a helium gas line to the 0.95 cm (3/8 in) vent tube on the round cover plate and insert a 152 cm (60 in), 1.27 cm (1/2 in) diameter stainless steel tube into the 1.27 cm (1/2 in) clearance hole until it reaches the dewar bottom. Seal the 1.27 cm (1/2 in) stainless steel tube to the 1.27 cm (1/2 in) high lip of the cover plate with a short length of rubber tubing. Attach a length of rubber tubing to the top of the stainless steel tubing and vent into the pre-cool pot dewar. Approximately $13.78 \times 10^3 \text{ N/m}^2$ (2 psi) pressure of helium gas is required to transfer the liquid nitrogen from the outer dewar.

3. The liquid helium should be ready to be transferred into the outer dewar as soon as the liquid nitrogen has been removed. Remove the stainless steel tube and rubber tubing from the round cover plate (may require heat gun) and stopper the 1.27 cm (1/2 in) diameter hole. Fill the dewar through the fill hole with liquid helium to within 2.5 cm (1 in) of the bottom copper baffle. When filling the dewar additional venting of the boiled off helium gas may be necessary to avoid back pressure which will prevent liquid helium transfer.

4. Remove the round cover plate and square cover plate covering the slots in the top closure plate and replace with a 21.9 cm (8-5/8 in) diameter lucite plate with a stoppered 6.67 cm (2-5/8 in) diameter hole in the center. Pre-cool the first lead foil bag assembly in the liquid nitrogen-filled pre-cool dewar to 0.635 cm (1/4 in) below the bag's top opening. Remove the bag from the liquid nitrogen and shake off any excess liquid. Quickly remove the rubber

stopper from the lucite disc and insert the bag into the liquid helium slowly while rotating it. Put a stopper having a 2.54 cm (1 in) diameter hole into the lucite disc so that only the extension handles are exposed when the bag is completely in the dewar.

5. The lead foil bag is now ready to be opened. First remove the bag clips by pulling each string separately and withdraw the clips at the dewar top. Attach a helium gas line to the helium level measurement hole to defog the inside volume when performing the bag opening operations. A small flow (~ 5 liter/min) of helium gas is all that is needed to provide a slight positive pressure at the outer dewar top. Remove the lucite disc and stopper, manipulate outer paddles (#1 and #3) to opposite slots in the top closure plate and then manipulate the inside paddles to occupy the two remaining positions so that the sequence of numbered extensions is 1, 2, 3 and 4. Replace the lucite disc and stopper the hole with a solid rubber stopper.

6. Pre-cool the telescoping opening device consisting of two sets of folding arms which can be spread open. Place it into the baffle area to spread open the bag by pushing on the support rods. Remove and replace the lucite disc and stoppers again as required. Capture the #1 and #3 outside paddle support rods with the bottom telescoping opener and spread them apart. Rotate the #1 and #3 support rods after they are spread apart so as to remove all bag folds. Use the top telescoping opener in a similar manner to position support rods #2 and #4. By visually inspecting the bag and manipulating the support rods, open the top of the bag as fully as possible. Withdraw the telescoping opening device and replace the lucite disc and stoppers.

7. The next operation is the inserting of a pre-cooled former, a 10 cm (4 in) to 15.4 cm (6 in) diameter plastic ball or bottle shaped unit mounted on a stainless steel thin-walled tube, (Fig. 1) into the lead foil bag. Place the former in the baffle section until the fog clears, after which slowly lower it into the bag and push until the bag bottom is reached. It may be moved from side to side to open the bag wider than the former's diameter. Remove and then replace the lucite disc and stoppers when the former is introduced and again when it is removed.

8. The first bag is now open and its effectiveness as a shield can be measured by inserting a measurement dewar, either a small diameter unit (Fig. 6) or the 10 cm (4 in) inner dewar (Fig. 2), and using a sensitive d-c magnetometer to measure the absolute field values along all three axes for the bottom 61 cm (2 ft) of the shield.

One bag has now been placed in operation, resulting in the attenuation of the magnetic field in the bag. In order to further lower the field a second bag has to be inserted. However, it cannot be allowed to become superconducting until it is fully inside of the first bag. If it were inserted using the same method as for the

first bag, it would attenuate the same external field to the same level as did the first bag. By not allowing the second bag to become superconducting until it is fully inside of the first bag, the attenuated field in the first bag will be the ambient field that is further attenuated by the second bag after it becomes superconducting and is opened.

A flow of helium gas into the top of the insert dewar containing the second bag is used as a heat supply to evaporate any liquid helium rising into the bottom of the dewar. A desired flow rate of 7 liters/min was determined from the following calculations.

The heat capacity of helium gas is

$$C_p = 5/2 R$$

where $R = 8.31 \text{ joule/}^\circ\text{K/mole}$ and $C_p = 20.8 \text{ joule/}^\circ\text{K/mole}$. A change of gas temperature is assumed to be from 72°K (liquid nitrogen temperature) at the top of the dewar to 4.2°K at the liquid helium level, or approximately 70°K . Therefore, the heat is

$$Q = C_p \Delta T$$

$$Q = 1456 \text{ joules/mole.}$$

Since for helium, 1 mole = 22.4 liters

$$Q = 65 \text{ joules/liter.}$$

The area of the dewar bottom interface with the liquid helium is 20 cm^2 ; the heat required to evaporate the liquid helium is 0.2 watts/cm^2 (ref. c) which makes 4 watts or 4 joules/sec needed. Therefore, 0.06 liter/sec or 3.6 liter/min is the minimum helium flow rate required to evaporate the liquid helium rising from the bottom. Since it is critical that the second bag remain normal until fully inside of the first bag, the helium gas flow rate was maintained at approximately 7 liters/min. A helium gas supply incorporating a flow meter with a controllable by-pass for use in pre-cooling was used.

The procedure for inserting the second bag begins by pre-cooling the insert dewar, which has been assembled with the second bag supported from the vented stopper top. Allow the liquid nitrogen to rise inside of the insert dewar to 0.635 cm (1/4 in) below the bag top. With the flow meter adjusted to 7 liters/min, attach the helium gas line to the vented stopper and remove the insert dewar from the pre-cooling dewar. Quickly remove the excess liquid nitrogen from the bag by opening the flow meter by-pass which provides a large blast of helium gas. Quickly place the insert dewar and second bag in the shield dewar and slowly lower it into the liquid helium inside of the first bag.

After the second bag is fully in the first bag, remove the helium gas line from the insert dewar stopper vent tube. Lower the

second bag inside of the insert dewar (rotate at the same time, if possible) to the bottom of the first bag and unhook from the insert dewar stopper top. After about five minutes, when little helium vent gas is escaping from the insert dewar vent, remove the insert dewar being careful not to remove the second bag.

Now the first bag can be removed, as it has served its function of providing a low magnetic environment in which to place the second bag. To remove the first bag, lift it a few inches off the bottom of the dewar by its support rods and push the second bag, still folded and clipped, through the bottom of the first bag, puncturing it. Rotate the punctured bag's paddles clockwise, first the outside #1 and #3 support rods and then the #2 and #4 support rods, to roll up the bag so it may be removed. Remove the punctured bag by lifting it straight up, being careful not to remove the second bag at the same time. The second bag can now be opened using the same procedure as was used for the first bag.

Additional bags can be used if further attenuation of the residual magnetic field is required. Any bag that is to be added in the presence of an existing operating bag must be put in place using the insert dewar second bag technique.

The 10 cm (4 in) ID measurement dewar can now be placed into the final superconducting magnetic shield lead foil bag. First put the square cover plate with the spacer ring into place on the top closure plate and cover the hole with a lucite disc. After pre-cooling, quickly position the measurement dewar above the outer dewar, remove the lucite disc and lower the measurement dewar into the outer dewar about 30 to 38 cm (12 to 15 in). At this point, slowly lower it into the lead foil bag. This is best accomplished by lifting the bag up off the bottom a few centimeters so as to pull it over the measurement dewar. The rate at which the measurement dewar is lowered into the liquid helium filled foil bag is determined by observing the venting liquid helium boil-off plume to obtain a moderate amount of helium gas boil-off. When the bottom is approached, remove the paddle support rod extensions and lower the measurement dewar until it is completely inside the outer dewar. Now, attach the dewar to the top closure plate with screws. The superconducting magnetic shield is now ready for use.

A liquid helium boil-off rate of from 12-15 liters per day will be averaged for a room temperature environment in the measurement dewar. Heating or cooling the inside of the measurement dewar may result in a variation of the boil-off rate. When filling the outer dewar with liquid helium, a small block may be placed under the lip of the measurement dewar so as to provide an additional vent for the helium gas boil-off. This may be required if the back pressure in the outer dewar prevents the transfer of the liquid helium.

PERFORMANCE

This superconducting magnetic shield was assembled and put into operation in a magnetically dirty area. There was no attempt to lower or otherwise alter the background magnetic field or its gradients. A single-axis NOL fluxgate magnetometer sensor coupled with a NASA-ARC electronics package [0-0.1 Hz bandpass noise < 0.05 nT p-p (0.05 γ p-p)] was used to measure the residual field inside of the superconducting magnetic shield. A total of three cascaded lead foil bags was used to obtain the data shown in Figure 7. This figure shows that the magnetic field gradient in the bottom 25 cm (10 in) of the room temperature access dewar was 0.039 nT/cm (0.1 γ /in). The magnetic field at the center of this 25 cm (10 in) region was approximately zero while the magnetic field at bottom end and the top end of the 25 cm (10 in) length were approximately +0.5 nT (0.5 γ) and -0.5 nT (-0.5 γ) respectively for all three directions (X--north-south, Y--east-west, and Z--vertical).

In order to determine the effectiveness of the third bag, magnetic field measurements were made after the second bag and third bag cascading steps. Figures 8 and 9 show the results of the measurements, which were made in the bottom 30 cm (12 in) of a small diameter [4.45 cm (1.75 in) ID] measurement dewar. The differences between the curves in Figure 7 and Figure 9 occur because the larger 15 cm (6 in) OD room temperature access measurement dewar fully opens the lead foil shield bag while the small diameter measurement dewar does not.

Similar low magnetic field values can be obtained using only two lead foil shield bags if the background field is lowered at the point at which the first lead bag becomes superconducting. In other words, if the field trapped by the first bag when it becomes superconducting is low, then only a second bag is needed to lower the magnetic field to the desired low level. Two methods which can be used to lower the background magnetic field are: (1) a soft magnetic material shield which would be placed around the outer dewar, or (2) two sets of Helmholtz-type coils oriented so that one produces a vertical canceling field and the other a horizontal canceling field.

Measurements of the attenuation of external magnetic field signals were not made. Brown's measurements (refs. a, b) of the attenuation factor on a smaller shield unit, having a smaller length-to-diameter ratio, gave attenuation values greater than 100 dB. It is assumed that the attenuation factor of this larger shield is at least as great.

The dewar system used for this superconducting shield was designed for a liquid helium loss rate of less than one liter per hour. Actually, the measured rate was 12 to 15 liters per day. Although the superconducting shield was only operated for 10 days during this initial run, an operating life greater than 100 days is expected before the boil-off rate becomes unacceptable. After this period the shield must then be prepared for operation again in accordance with the start-up procedure previously described.

POSSIBLE IMPROVEMENTS

Several improvements might be included in any new installation. They are:

1. A more adequate method for rotating the lead foil bag inside of the insert dewar while it is undergoing the superconducting transition. It is not certain how much improvement is gained by "flushing" the field from the lead foil, but it seems reasonable to incorporate and investigate this effect.
2. Obtain further attenuation by increasing the length-to-diameter ratio of the lead foil bag which would also require increasing the height of the outer and inner dewars. Room ceiling height was our limitation.
3. Reduce the initial earth's field values by using a mumetal magnetic shield around the outer dewar to provide attenuation of the starting field and thereby reduce the number of cascaded bag insertions required. A set of orthogonal Helmholtz coils could also be used to attenuate the earth's field at the point where the lead foil bag enters the liquid helium and becomes superconducting.
4. An automatic liquid helium level sensor for long-term operation. The dipstick resonance technique, however, is simple and very reliable.
5. Improvements in the lead foil bag opening devices. A more suitable material, i.e., unbreakable, rugged, minimum mass and heat capacity, for the former should be found. Brown's technique employing the manipulation of central strings (nylon fishing line) works well except during humid days. Modification of his bag-expanding technique, which reduces the risk of puncturing the lead foil bag, appears to be most promising.

SUMMARY

A superconducting magnetic shield with a 10 cm "hot hole" was designed and built by the Naval Ordnance Laboratory for the NASA Ames Research Center. Temperature in the hot hole is easily controllable from +70°C to -40°C. The residual field in the "hot hole" ranged from +0.5 nT (+0.5 γ) to -0.5 nT (-0.5 γ) over a 25 cm (10 in) region. Effect gradient in the working region is less than 0.039 nT/cm (0.1 γ /in). The liquid helium evaporation rate of this shield is low, i.e., 12-15 liters per day, which permits economical operation. Anticipated operating time before shutdown is greater than 100 days, limited only by dewar efficiency.

In addition to magnetometer development a large superconducting shield such as this one can be used for: (1) magnetic moment determination of lunar rock samples, (2) paleomagnetic dating, (3) screening for magnetic contamination, (4) shielding for superconducting

Josephson-effect magnetometers, and (5) providing a stable low magnetic field environment for numerous physical experiments.

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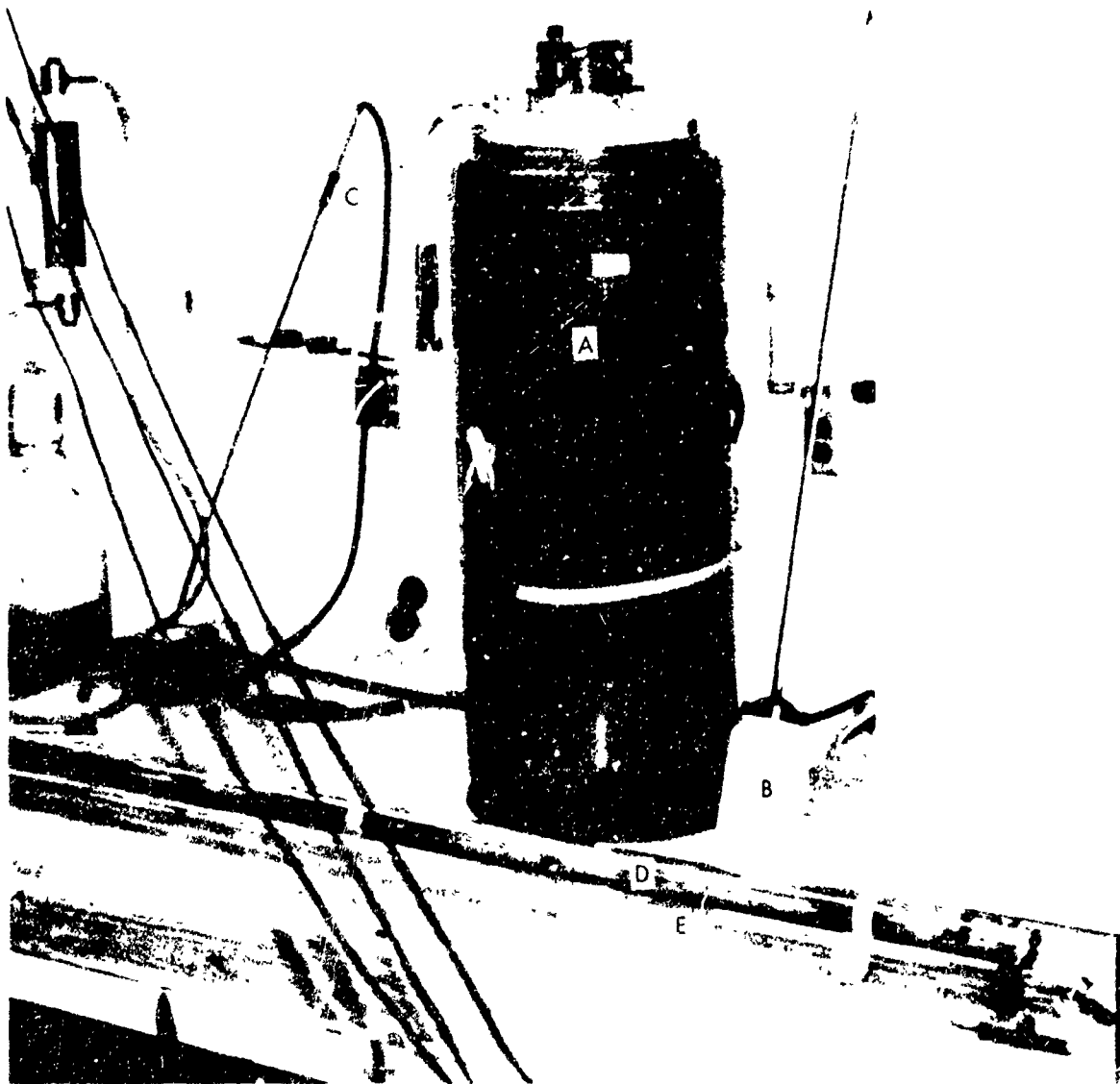


FIG. 1 SUPERCONDUCTING SHIELD ASSEMBLY BUILT BY THE NAVAL ORDNANCE LABORATORY FOR THE NASA AMES RESEARCH CENTER

- A. OUTER DEWAR
- B. BAG OPENING FORMER
- C. LIQUID NITROGEN REMOVAL TUBE
- D. SMALL MEASUREMENT DEWAR
- E. INSERT DEWAR

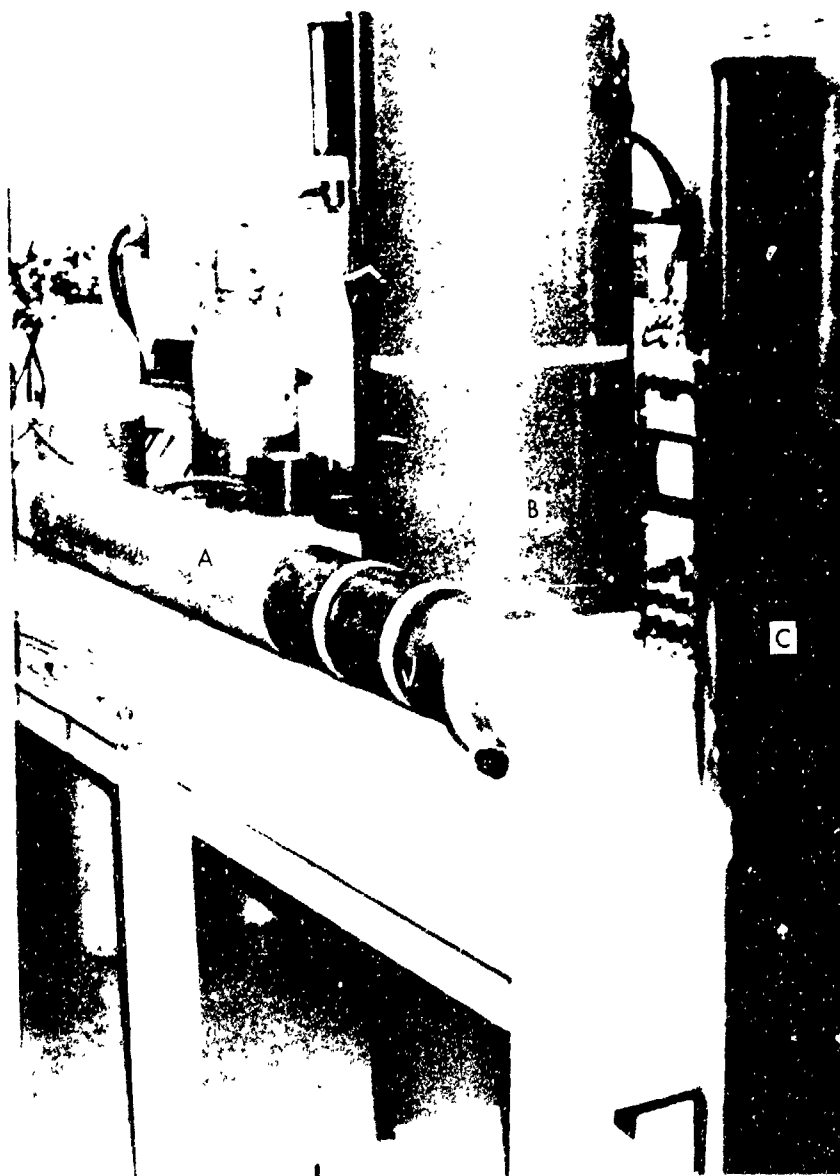


FIG. 2 DEWARS USED FOR SUPERCONDUCTING SHIELD
A. ROOM TEMPERATURE ACCESS DEWAR
B. LIQUID HELIUM FILLED OUTER DEWAR
C. POT DEWAR FOR PRE-COOLING

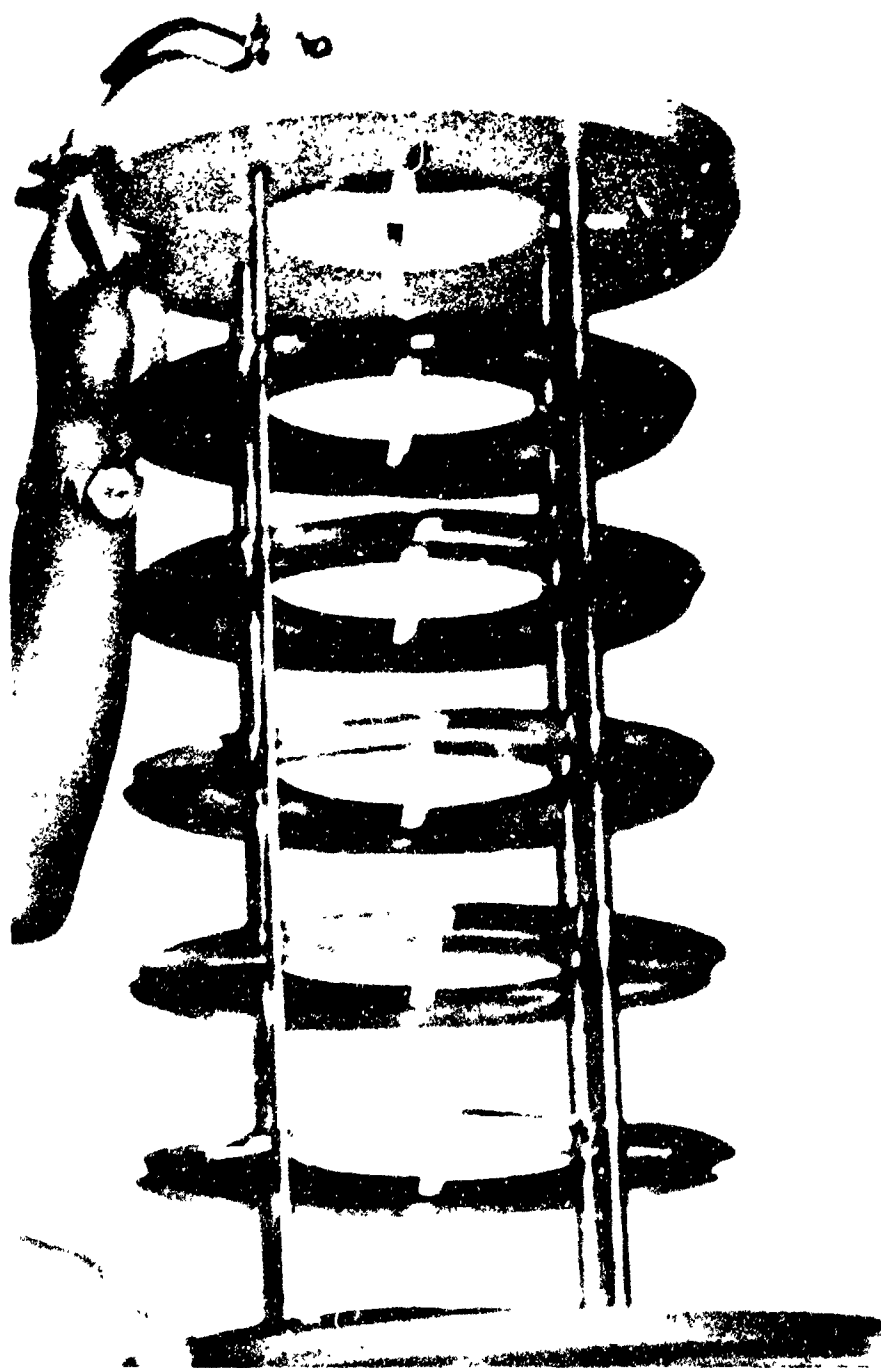


FIG. 3 BAFFLE ASSEMBLY WITH TOP CLOSURE PLATE

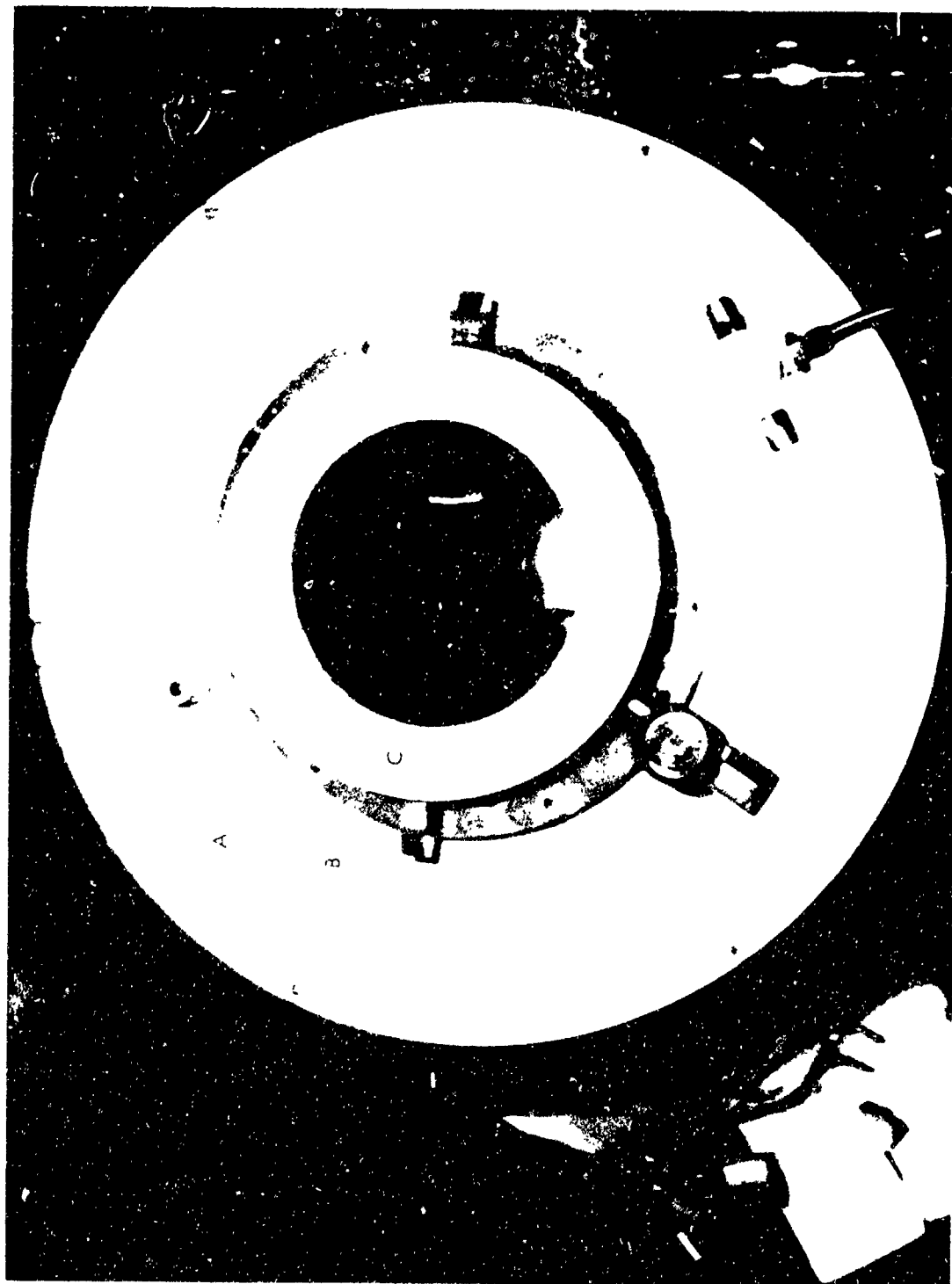


FIG. 4 TOP VIEW OF SUPERCONDUCTING SHIELD

- A. TOP CLOSURE PLATE
- B. SQUARE COVER PLATE
- C. ROOM TEMPERATURE ACCESS
DEWAR





FIG. 5 LEAD FOIL BAG WITH ATTACHED PADDLES



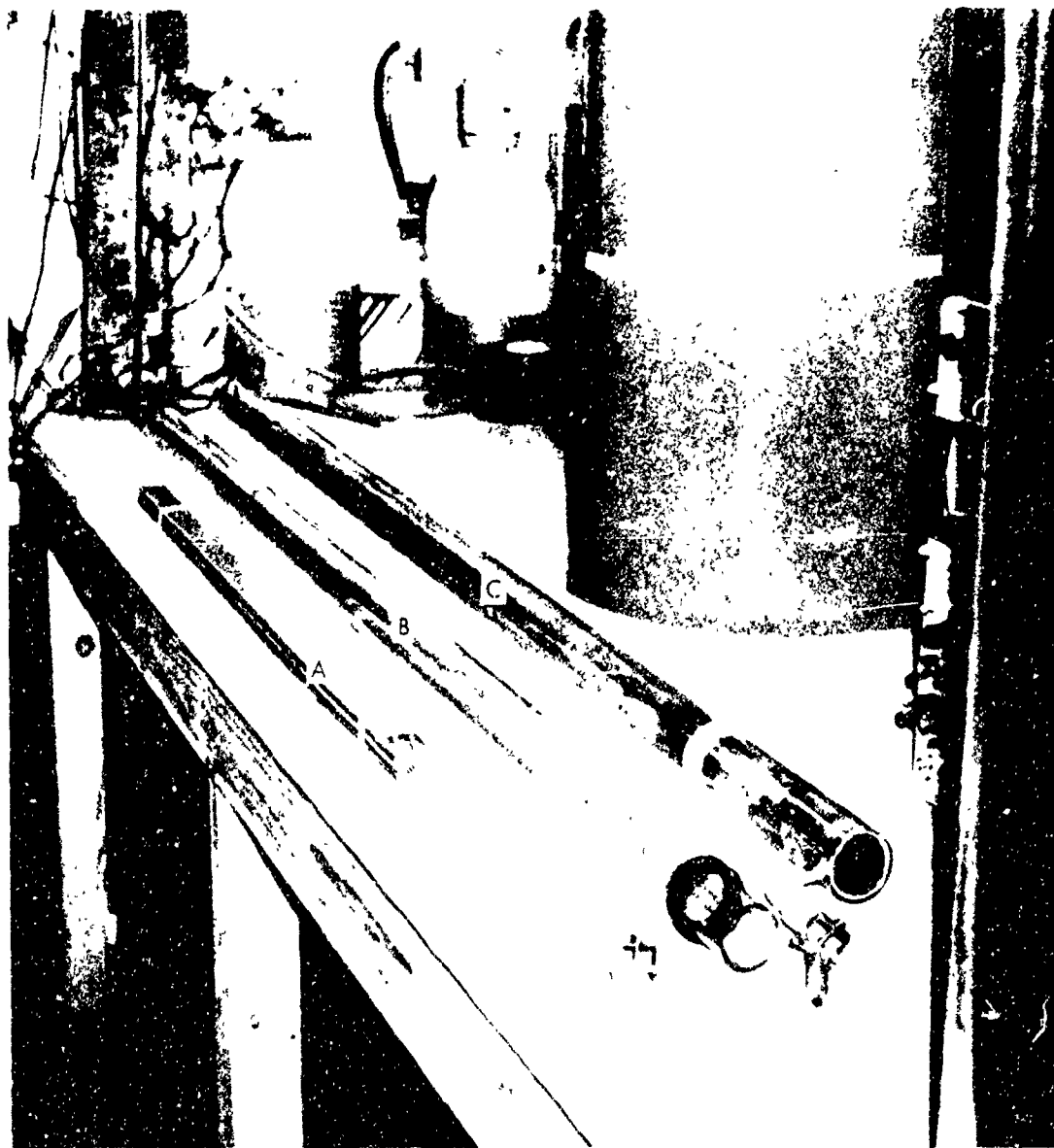


FIG. 6 INSERT AND SMALL MEASUREMENT DEWARS

- A. FOLDED LEAD BAG ASSEMBLY
WITH "ADDLES"
- B. INSERT DEWAR
- C. SMALL MEASUREMENT DEWAR

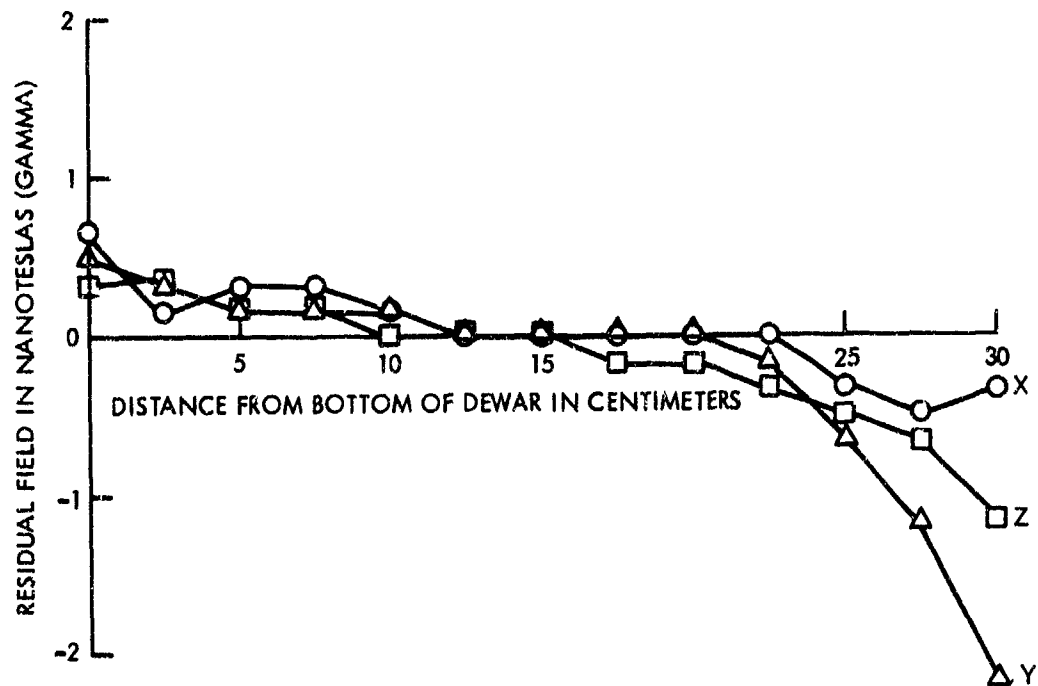


FIG. 7 MAGNETIC FIELD VALUES IN 10 CENTIMETER DEWAR AFTER 3RD BAG.

18

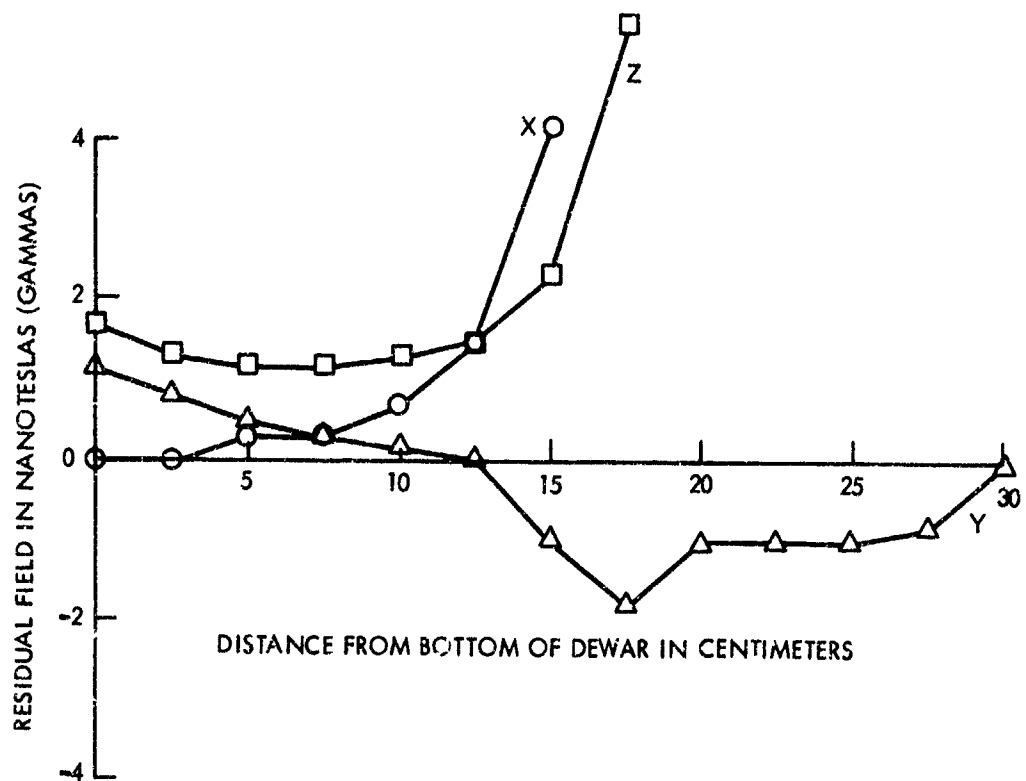


FIG. 8 MAGNETIC FIELD VALUES IN SMALL DEWAR AFTER 2ND BAG.

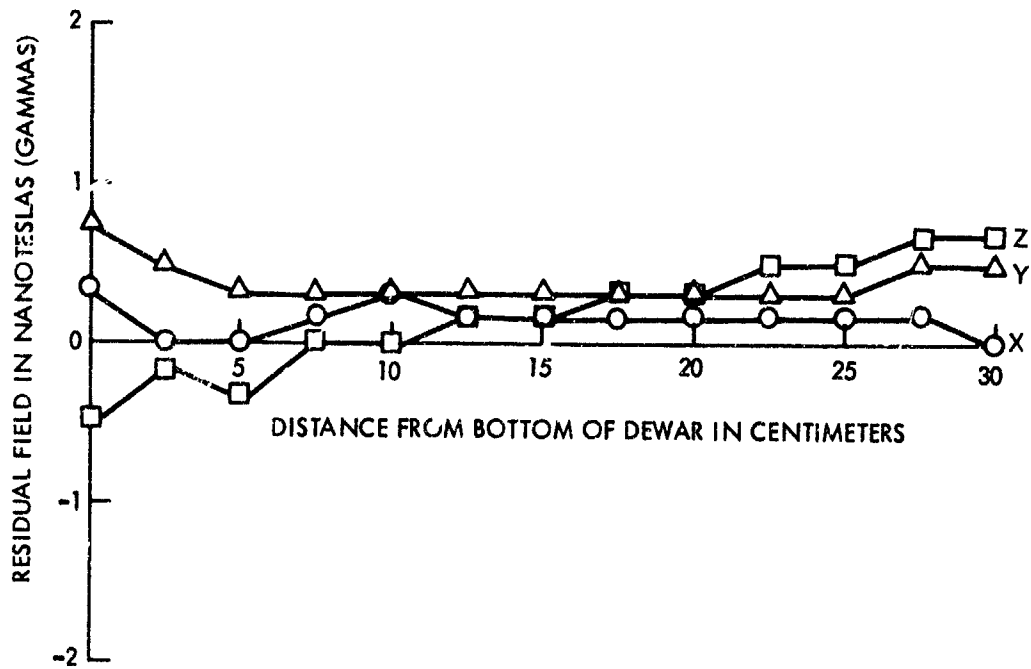


FIG. 9 MAGNETIC FIELD VALUES IN SMALL DEWAR AFTER 3RD BAG.

APPENDIX A

SHIELD LEAD FOIL BAG CONSTRUCTION PROCEDURE

1. Place a 60 cm x 120 cm x 0.635 cm thick (2 ft x 4 ft x 1/4 in) phenolic sheet on an open bench approximately 2-1/2 meters (100 in) long by 1 meter (40 in) wide. On the left side of the phenolic sheet place a roll and dispenser of 0.05 mm (2 mil) by 50 cm (20 in) wide lead foil.

2. Since the bag is to be 107 cm (42 in) long, roll off a piece of lead foil greater than 230 cm (90 in) to start. After inspecting it for tears and irregular marks, cut off a 230 cm (90 in) piece with care so as not to crinkle the foil.

3. Carefully fold the 0.05 mm thick (2 mil) lead foil piece in half so the bottom fold of the bag is formed. Now to cut the bag to size, two 125 cm (60 in) lengths of 3.8 cm x 7.6 cm (1-1/2 in x 3 in) wave guide material are used as cutting guides. Gently place one of the clean wave guide pieces approximately 10 cm (4 in) from one edge of the folded lead foil, square with the bottom fold. Place the second wave guide piece near the other edge and space it 38.4 cm (15-1/8 in) from the first wave guide piece. Check for squareness.

4. Using a sharp knife or single-edge razor blade, carefully cut the lead foil using the wave guide pieces as a cutting guide to produce a folded sheet 34.8 cm x 114 cm (15-1/8 in x 45 in). Try not to crinkle the foil when cutting. Now measure off 107 cm (42 in) from the bottom fold and mark the bag top (open end). Using a straight edge, carefully cut the bag to length. The bag has now been cut to size [a folded 34.8 cm x 107 cm (15-1/8 in x 42 in) piece].

5. Position one of the wave guide pieces on the front edge of the phenolic piece. Then carefully lay one side of the foil bag on the wave guide piece so that 0.158 cm (1/16 in) overhangs the edge of the wave guide piece. Clamp the foil bag in place with the second wave guide piece and an added lead weight, so that the foil bag is firmly held during the soldering operation.

6. With a 2.54 cm long by 1.9 cm wide (1 in x 3/4 in) pry card (piece of computer card) pry the foil open so that soldering flux (ruby fluid) can be put on the two edges to be soldered. Apply a small amount of soldering flux to the open edges using a small cotton swab. Close the edges together by using a short length of lucite [about 30 cm x 1.27 cm x 0.635 cm (12 in x 1/2 in x 1/4 in)] as a guide and the soldering flux soaked swab to flatten the lead foil tightly into place.

7. With a small torch which uses butane or propane and oxygen adjust the flame so it has a slight yellow tint at approximately

1 cm (about 1/2 in) from the nozzle. Solder the lead foil joint together with a continuous motion, observing the flowing melting foil. Hold the torch about 2-4 cm (~ 1-2 in) from the foil being careful not to melt too much of the foil. Solder the entire length of the bag side at one time. Inspect the soldered joint with a magnifying glass and mark on the wave guide all joint hole locations. With a pair of tweezers, close the holes after applying a small amount of soldering flux using a toothpick swab. Resolder these holes and re-inspect to assure that all holes have been soldered closed.

8. Remove the top wave guide piece and position the soldered bag side in the center of the bottom wave guide piece. Replace the top wave guide piece and press down on it with your weight so that the lead beads will be flattened. Re-inspect the joint.

9. The next step is to remove the soldering flux from the newly soldered joint with an alcohol-soaked paper towel. Both wave guide pieces should also be wiped clean.

10. The other side of the lead foil bag can now be soldered closed with the techniques of steps 5 through 9.

11. The finished bag should be stored between sheets of paper on a flat rigid surface. Care should be taken that nothing is placed on the stored bags as they are easily damaged. Any small holes in the lead foil bags may cause undesirable results due to flux leakage when the bag is used as a superconducting magnetic shield.

APPENDIX B

PROCEDURE FOR ATTACHING LEAD BAG TO SUPPORT PADDLES

In order to support and manipulate the lead foil bags in the liquid helium, four paddles made of 0.635 cm (1/4 in) thick non-magnetic phenolic were designed and are shown in Figure B-1. Each paddle has a screw fastener on its top end which fastens into a 0.952 cm (3/8 in) diameter thin-walled stainless steel tubing support rod and support rod extension.

The 60 cm x 120 cm x 0.635 cm (2 ft x 4 ft x 1/4 in) thick phenolic sheet used in the lead foil bag-making procedure (Appendix A) is also used in this procedure. The adhesive compound required to attach the 0.05 mm thick (2 mil) lead foil bag to the paddles is contact cement (Weldwood or equivalent) diluted 1:1 with toluene.

a. Place the phenolic sheet on a flat surface and wipe clean with a toluene-soaked cloth. All pieces of equipment must be kept clean of contact cement as well as any foreign particles. Mark off a reference line 19 cm (7-1/2 in) from the front edge of the phenolic sheet.

b. Place the lead foil bag on the phenolic sheet so that the open end (top) is to the left and inspect for any possible damage. Center the bag over the reference line so that one edge of the bag is aligned with the front edge of the phenolic sheet and the open end (top) of the bag is flush with the left edge of the phenolic sheet.

c. Align a small paddle 0.635 cm (1/4 in) from the reference line with the screw fastener to the left as shown in Figure B-2. Two straight edge lengths of phenolic can then be placed along the edges of the paddle as guides to facilitate the glueing. Apply a thin layer of diluted contact cement to both the paddle and the bag, leaving the bottom 20 cm (8 in) without adhesive. This unglued length allows for the shaping of the bottom of the lead foil bag as the inner dewar is inserted. Wait a few minutes until the contact cement sets and then starting at the bottom of the bag, leaving a 0.635 cm (1/4 in) overhang, lay the paddle down and press gently to make sure that the paddle adheres to the bag.

d. Lift the bag by one of the soldered edges and turn it over. Gently fold the lead foil bag along the first paddle so that the second small paddle can lay next to the first paddle as seen in Figure B-2. Again use one of the straight edge lengths of phenolic as a glueing guide and apply a thin layer of diluted contact cement to the second small paddle and the lead foil bag, leaving the bottom 20 cm (8 in) without cement. Place the small paddle on the glued portion of the bag and gently press it in place for good adhesion to the bag surface.

e. Cement a wide paddle on the top edge of the bag as shown in Figure B-2 using the above cementing techniques. Make sure that the bag's edge is completely covered by the wide paddle and that the bag is cemented along its entire length. Turn the bag over lifting by the wide paddle just attached. Cement the last wide paddle on the bag edge as was described above.

f. The lead foil bag with paddles is now ready to fold in an accordion-type pleat arrangement. Refer to Figure B-2 and use the following steps:

1. Fold in the 3rd paddle.
2. Turn bag over.
3. Fold in the 3rd and 4th paddles.
4. Turn bag over.
5. Fold in the 3rd and 4th paddles. Third paddle should be even with paddles 1 and 2.
6. Turn bag over.
7. Fold in 4th paddle to be even with paddles 1 and 2.
8. Carefully unfold the bag pleats from the top and inspect for any folds cemented together. If the pleats are glued together, clean with toluene and refold.
9. Put clips on the completed bag unit to maintain the folded arrangement.

During the bag-folding operation, care should be exercised so that the bag material does not extend beyond the paddle edges, so that the bag is protected from damage.

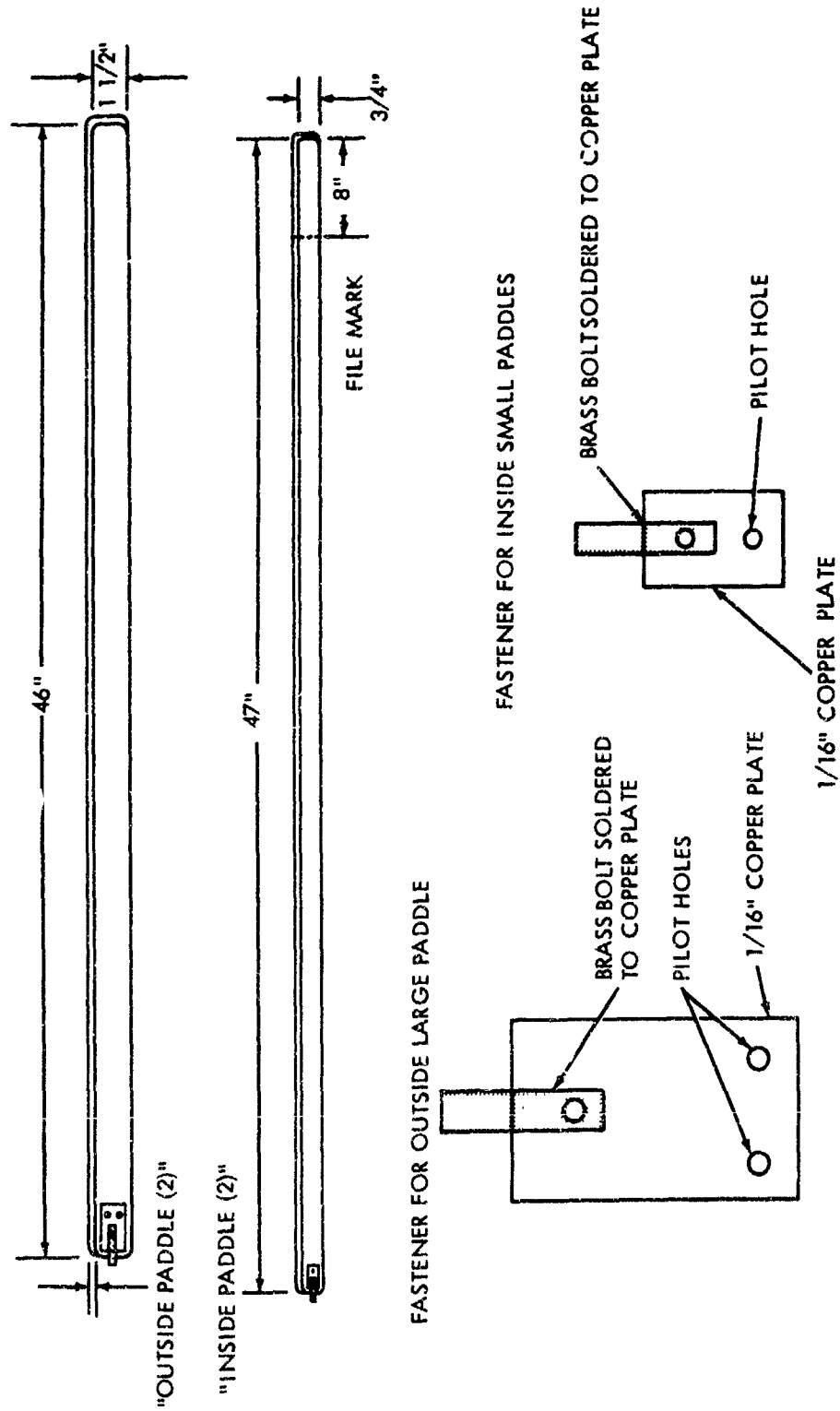
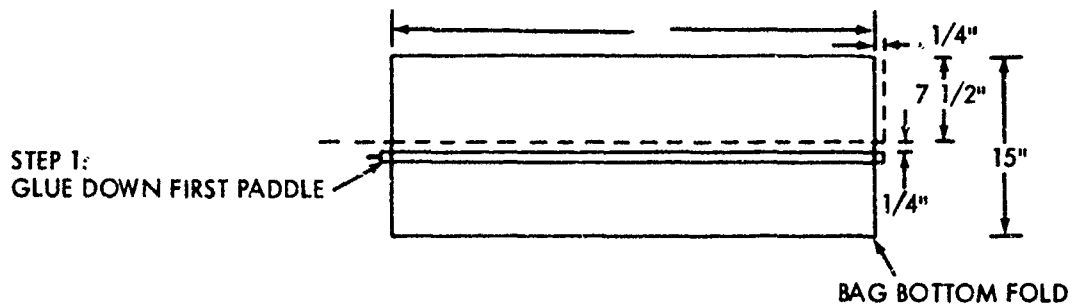
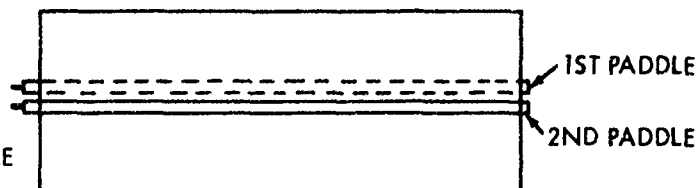


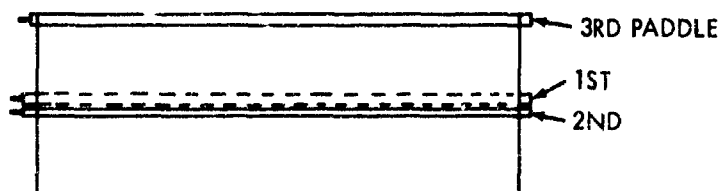
FIG. B-1 LEAD FOIL BAG SUPPORT PADDLES



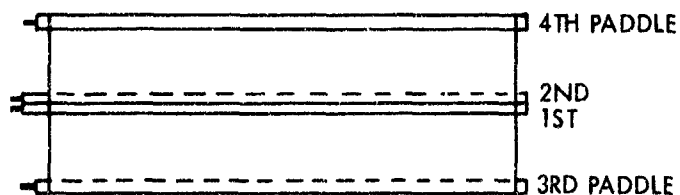
- STEP 2:
1. TURN BAG OVER
 2. FOLD SECOND PADDLE SO AS TO BUTT AGAINST FIRST PADDLE
 3. APPLY GLUE AND ASSEMBLE



- STEP 3:
GLUE 3RD PADDLE ON BAG AS SHOWN



- STEP 4:
1. TURN BAG OVER
 2. PUT ON 4TH PADDLE



- FOLD PADDLES AS:
1. FOLD IN 3RD PADDLE
 2. TURN BAG OVER
 3. FOLD IN 4TH AND 3RD PADDLES
 4. TURN BAG OVER
 5. FOLD IN 4TH AND 3RD PADDLES.
 6. TURN BAG OVER
 7. FOLD 4TH PADDLE TO BE EVEN WITH PADDLES 1 AND 2.

FIG. B-2 ASSEMBLY STEPS-PADDLES ON SHIELD BAG
(VIEWED FROM TOP)