UCRL-20398
c.2

UNCLASSIFIED
LAWRENCE
RADIATION LABORATORY

JUN 30 1971

LIBRARY AND
DOCUMENTS SECTION

University of California

Ernest O. Lawrence Radiation Laboratory

SHIELDING OF LOW MAGNETIC FIELD WITH MULTIPLE CYLINDRICAL SHELLS

S. M. Freake and T. L. Thorp*

January 1971

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

Berkeley, California

UCRL-20398
c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to Review of Scientific Instruments UCRL-20398

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

SHIELDING OF LOW MAGNETIC FIELD WITH MULTIPLE CYLINDRICAL SHELLS

S. M. Freake and T. L. Thorp*

January 1971

37

Shielding of Low Magnetic Field with Multiple Cylindrical Shells

S. M. Freake and T. L. Thorp*

Department of Physics, University of California
and
Inorganic Materials Research Division,
Lawrence Radiation Laboratory,
Berkeley, California 94720

ABSTRACT

The factors which determine the minimum magnetic field inside a set of cylindrical shields of high permeability material are summarized. Using this information a three-cylinder system was designed and constructed to screen out the earth's magnetic field inside the dewar of a dilution refrigerator to less than 5×10^{-5} Oe.

The screening of magnetic fields with high permeability alloys has been extensively investigated.[1-5] However, the information required to successfully design a screening system is dispersed throughout many journals published over a long period of time. In this paper we will summarize the factors which limit the lowest field obtainable and will give details of a system which we have constructed to screen out the earth's field to less than 5×10^{-5} Oe.

Mumetal (77% Ni, 16% Fe, 5% Cu, 2% Cr by weight) is widely used as a screening material because of its high initial permeability ($\sim 10^5$) and low coercivity (0.03 Oe). After fabrication the metal has to undergo a controlled annealing processs, after which it must be handled with reasonable care.

For a cylinder of diameter D, length L, wall thickness d, made from material having permeability μ, the shielding factor for transverse fields S_t is given by[4]

$$S_t = H_{ot}/H_{it} \simeq \mu d/D, \tag{1}$$

for $\mu d \gg 1$, and $d/D \ll 1$, where H_o, H_i are the external and internal fields respectively. The longitudinal shielding factor S_ℓ is given by[4]

$$S_\ell = 1 + N\mu d/\pi D = 1 + (N/\pi)S_t \tag{2}$$

where N is the demagnetizing factor for an ellipsoid with axial ratio L/D. For a number of coaxial cylinders, the resultant transverse shielding factor is[5]

$$S_t = S_{1t} + S_{2t} + S_{3t} \ldots + \left[S_{1t}S_{2t}S_{3t} \ldots (1 - \frac{A_1}{A_2})(1 - \frac{A_2}{A_3})\ldots\right] \quad (3)$$

where S_{jt} is the shielding factor for the jth cylinder given by Eq. (1). A_j is the cross-sectional area of the jth cylinder, and $A_j < A_{j+1}$. Thus for cylinders with an extremely small spacing, $S_t = \sum S_{jt}$, and for well-spaced cylinders, $S_t = \prod\left[S_{jt}(1 - \frac{A_j}{A_{j+1}})\right]$. This makes it clear that adequate spacing between the cylinders is necessary for efficient shielding. We would expect similar relations to hold for the resultant longitudinal screening factor.

The treatment above neglects the penetration of the field at the open ends of the cylinders. This fringing field decays approximately exponentially[2] with distance x into the cylinder, i.e. for transverse fields

$$H_{it} = H_{ot} \exp[-k_t\, x/D]. \quad (4)$$

The factors k_t (~7.0) and k_ℓ (~4.5) are not dependent on cylinder diameter. Thus transverse fields are attenuated by a factor of about 10^3 per diameter distance from the end and longitudinal fields by about 10^2. The resultant field in a cylinder is the sum of the fringing field and the field determined by the shielding factor.

The third factor which affects the lowest field obtainable is the remanent magnetization of the mumetal. This depends on the history of the material and on the dimensions of the cylinder. For a cylinder the

effective value of the permeability, μ_{av}, is[3] $\mu_{av} = 1 + 4\,(\mu - 1)\,d/D$ giving a magnetization $M_{av} = H_o/N(1 + \varepsilon)$ where $\varepsilon = \pi D/Nd\,\mu$. For a long thin rod ($N \ll 1/\mu$) subjected to a large field the magnetization left in the material after reducing the field to zero is $\alpha\, M_{sat}$, with $\alpha \sim 1/2$. For a finite rod we consider this 'permanent' moment is modified by $\chi'\,H$ where χ' is the differential susceptibility and H_i is the demagnetizing field. Thus,

$$M = \alpha\, M_{sat} + \chi'\, H_i$$

$$= \frac{\alpha M_{sat}}{1 + \chi' N}$$

and the internal field $H_i = -NM = -\dfrac{N\alpha\, M_{sat}}{1 + \chi' N}$. For the case when the material has not been subjected to a large field, we take a lower value than M_{sat}. For the Mumetal cylinders we find

$$H_i = -\frac{N\,\alpha\, M_{av}}{1 + \chi' N} = -\frac{\alpha\,\varepsilon\;\; H_o}{(1 + \varepsilon)^2} \qquad \text{(assuming } \chi' \approx \chi\text{).} \tag{5}$$

This field can easily be reduced by degaussing the cylinder in situ; that is, one applies a sinusoidal magnetic field and steadily reduces its amplitude. This process increases the effective permeability by helping the realignment of the magnetization in the ambient steady field. It is found that both toroidal and solenoidal windings are necessary for effective degaussing.

Finally, it is necessary to insure that the magnetic material is

not saturated in the ambient field. This requires the condition $d/D \gg H_o/B_{sat} = 2 \times 10^{-4} H_o$, since the saturation flux density B_{sat} for Mumetal is 5×10^3 gauss.[6] In practice this condition is easily satisfied. Nevertheless, it should be noted that μ is field dependent;[6] for example, for fields below the coercivity, μ drops. This should be taken into account when using Eqs. (1), (2), and (5).

The system that we have constructed was designed to screen out the earth's field to less than 5×10^{-5} Oe over a length of 15 cm inside the 25 cm o.d. dewar of a dilution refrigerator. The low fields were required for investigations of low temperature superconductors and Josephson effect phenomena. The dimensions of the three cylinders used are shown in Table I. The middle cylinder was made shorter than the outer to reduce cost and so that its ends would be screened to a certain extent from the external field; the inner cylinder was made shorter than the middle one for a similar reason. 1/16" sheet Mumetal was used in order to give the cylinders sufficient mechanical strength that they would not become unannealled with normal handling. A solenoidal coil was wound on the middle cylinder and both solenoidal and toroidal coils on the inner. Each coil could produce a field of about 10 Oe at 60 Hz, which was sufficient to produce the saturation flux density in the Mumetal.

In Table I we also show the calculated fields at the centers of the cylinders due to the shielding effect and due to fringing fields in both longitudinal and transverse external fields of 0.3 Oe. It can be seen that in all cases the residual longitudinal field is higher than the transverse and we will therefore confine our attention to the experimental results for longitudinal fields.

In Fig. 1 we show the axial field profiles obtained with these cylinders. The open inverted triangles, open squares, and open circles are results for the inner, middle, and outer cylinders before degaussing. Each point represents the mean of the fields measured with the cylinder parallel and antiparallel to the external field. These profiles indicate limiting fields of about 2.5 mOe, which are in reasonable agreement with the values calculated from Eqs. (3) and (4), and shown in Table I.

The minimum fields differed by about 1 mOe in each case for the two orientations of the cylinders, indicating the presence of small permanent magnetizations. The solid inverted triangles and solid squares show the profiles after degaussing the inner and middle cylinders. The effective permeability is increased by this process so that $H_{min}^{(1)}$ is reduced and the limiting field is determined by penetration of the field from the ends.

The field profile for the three coaxial cylinders after demagnetization of the inner two is denoted by the triangles in Fig. 1. The field at the center was in the opposite direction to the ambient field and has been plotted on the separated section below. Because the inner cylinder was in a non-uniform field its magnetization overcompensated

the applied field at the center. It was possible to reduce the absolute magnitude of the field at the center of the cylinders by passing a small steady current through the solenoid wound on the inner cylinder. The field profile then obtained is denoted by the open diamonds in Fig. 1.

One would expect to obtain a profile similar to the latter by using the outer cylinder alone and degaussing it. However, changes in the external magnetic field would only be screened out by the factor of $S_\ell = 110$. By using three cylinders, the screening of varying fields was greatly improved.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

* Present address: Royal Radar Research Establishment, Malvern, England.

1. W. G. Wadey, Rev. Sci. Instr. 27, 910 (1956).
2. A. Mager, Z. Angew. Phys. 23, 381 (1967).
3. A. Mager, Elecktrotechn. Z. A89, 11 (1968).
4. A. Mager, J. Appl. Phys. 39, 1914 (1968).
5. A. K. Thomas, IEEE Trans. on Electromagnetic Compatibility, EMC-10, 142 (1968).
6. Institute of Physics Handbook, (McGraw-Hill, 1957).

FIGURE CAPTION

Fig. 1. Longitudinal field profiles on the axes of the cylinders for a longitudinal external field of 0.3 Oe. Inner cylinder before degaussing ∇; inner cylinder after degaussing ▼; middle cylinder before degaussing □; middle cylinder after degaussing ■; outer cylinder (not degaussed) 0; all three cylinders together after degaussing the middle and inner cylinders Δ; as Δ but with current of 80 μA in the solenoid wound on the inner cylinder ◇. Note that the bottom part of the diagram shows fields in the opposite direction to the external field.

Table I. $H_t^{(1)}$, $H_\ell^{(1)}$ are the calculated fields at the center of the cylinders determined by the shielding factors, $H_t^{(2)}$, $H_\ell^{(2)}$ are those determined by fringing fields from the ends of the cylinders. The transverse results are for a transverse external field of 0.3 Oe, the longitudinal results for a longitudinal external field of 0.3 Oe, and we have taken $\mu = 2 \times 10^4$ (see Ref. 6). $H_\ell^{(3)}$ is the internal calculated field due to remanent magnetization produced by a longitudinal external field of 0.3 Oe, which was the ambient field in our laboratory.

Cylinder	D Cylinder diameter (cm.)	L Cylinder length (cm.)	N Demagnetizing factor	S_t Transverse shielding factor	S_ℓ Longit. shielding factor	$H_t^{(1)}$ (μOe)	$H_\ell^{(1)}$ (μOe)	$H_t^{(2)}$ (μOe)	$H_\ell^{(2)}$ (μOe)	$H_\ell^{(3)}$ (μOe)
Outer	29.2	147	0.7	220	50	140	6300	0.013	9	3900
Middle	27.9	107	1.0	230	70	130	4100	0.85	130	3100
Inner	26.0	76	1.4	240	110	120	2800	27	970	2300
O+M+I				1.5×10^5	4.5×10^3	2	66	0.013	9	

TABLE I.

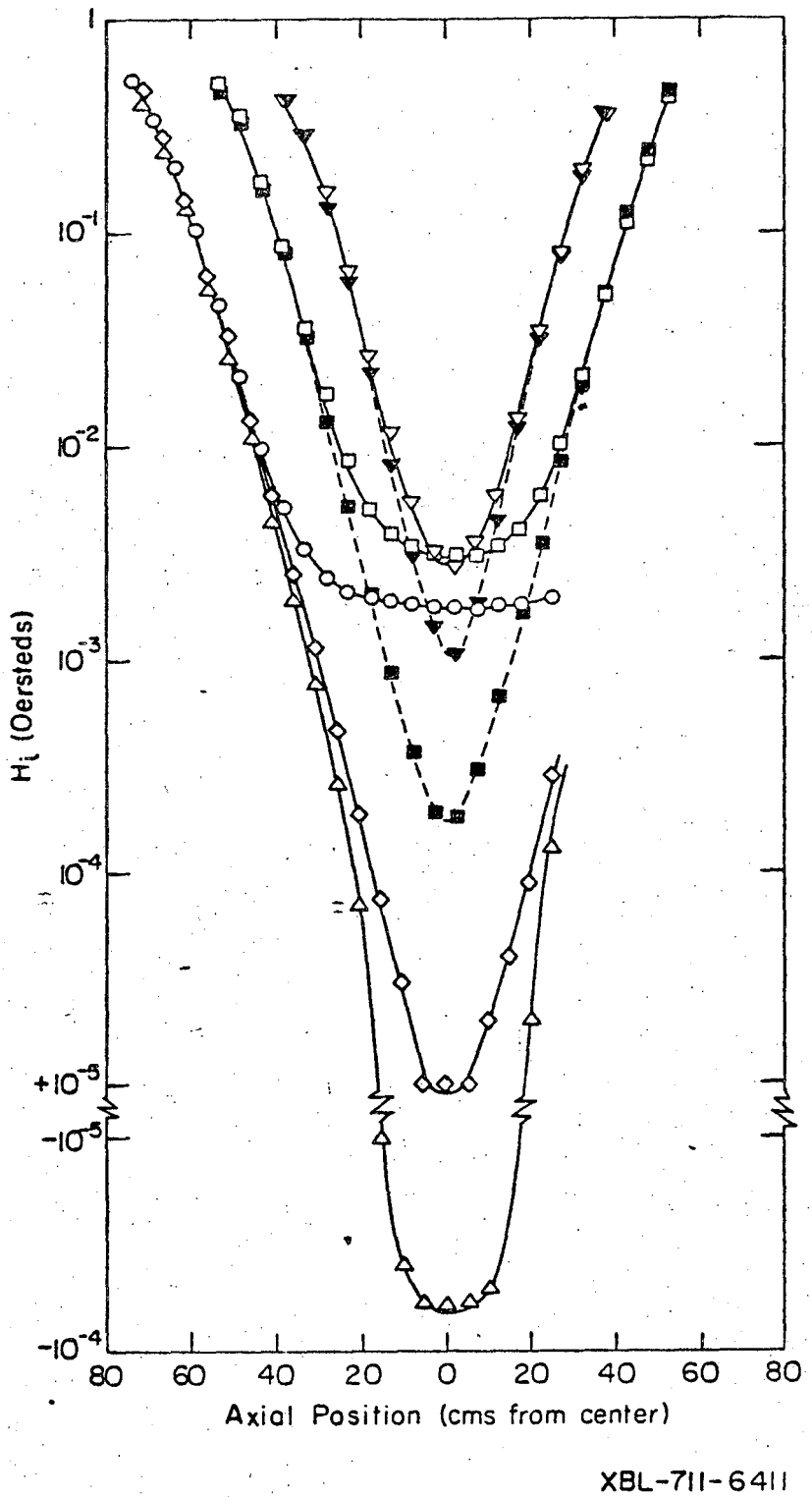
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$+10^{-5}$
-10^{-5}
-10^{-4}
H_i (Oersteds)
80 60 40 20 0 20 40 60 80
Axial Position (cms from center)
XBL-711-6411

Fig. 1

University of California

Ernest O. Lawrence Radiation Laboratory

Berkeley, California