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SHIELDING OF LONGITUDINAL MAGNETIC FIELDS WITH THIN, CLOSELY, SPACED, CONCENTRIC CYLINDRICAL SHELLS WITH APPLICATIONS TO ATOMIC CLOCKS

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ABSTRACT

Formulae for the longitudinal shielding effectiveness of thin, closely, spaced concentric cylindrical shells have been developed and experimentally tested. For shields which cannot be oriented, or which change their orientation in the ambient field, the shielding effectiveness for longitudinal fields is generally the limiting criteria and no design formulae have been presented for more than two shields. In this paper a general formula is given for the longitudinal shielding effectiveness of N closed concentric cylinders. The use of these equations is demonstrated by application to the design of magnetic shields for hydrogen maser atomic clocks. Examples of design tradeoffs such as size, weight, and material thickness will also be discussed.

Experimental results on three sets of shields fabricated by three manufacturers have been obtained. Two of the sets were designed employing the techniques described above. Agreement between the experimental results and the design calculations is then demonstrated.

INTRODUCTION

Shielding of magnetic fields is very important for the stable operation of atomic clocks. In the case of a hydrogen maser the requirements for shielding the cavity are quite stringent ($\Delta H \leq 10^{-10}$ tesla). Furthermore, for possible spaceborne applications, size and weight become added constraints. For these spaceborne applications a reliable method is required to accurately estimate the shielding effectiveness (ratio of internal to applied magnetic field) of concentric shields so that a design minimizing the size and weight of a shield set can be specified.

Formulae for shielding effectiveness, of open ended concentric cylindrical shells of high permeability material in a transverse magnetic field are readily available.[1-4] However, no general formulae exists for shielding longitudinal fields although Mager[4-6] has given a relationship between transverse and longitudinal shielding effectiveness for 1 cylinder (with and without end caps) and estimated a relationship for two open concentric cylinders. For shields which cannot be oriented, or which change their orientation in the ambient field, shielding effectiveness for longitudinal fields is generally the limiting criteria.

The general equation for the longitudinal shielding effectiveness G_N of N thin, closely spaced, high permeability cylindrical shields is given by[7]

$$G_N^{\ell} = \frac{1}{2} (u_{i+1} + v_{i+1}) \tag{1}$$

where

$$u_{i+1} = (1 + g_i^{\ell} s_{i,i+1}^{\ell}) u_i + s_{i,i+1}^{\ell} v_i$$

$$v_{i+1} = g_i^{\ell} u_i + v_i$$

with

$$u_1 = v_1 = 1$$

$$s_{N,N+1}^{\ell} = 0$$

and

$$g_i^{\ell} = \frac{\mu_i^{\ell} t}{b_i} = \frac{4D\mu_i t}{B_i} \times \begin{cases} 1 & \text{(open shields)} \\ [1+b/L]^{-1} & \text{(closed shields)} \end{cases}$$

$$s_{i,i+1}^{\ell} \approx \frac{3(b_{i+1}-b_i)}{4b_{i+1}} \times \begin{cases} [1+b/L]^{-1} & \text{(open shields)} \\ 1 & \text{(closed shields)} \end{cases}$$

Here, μ_i is the permeability of the i^{th} shield, t is the thickness of the individual shields, b_i is the radius of the i^{th} shield, D is the demagnetization factor of the cylinder, L and b are the average length and radii of the shield set, and u_i and v_i are symbols used to generate a recursive relationship. This formula is valid when

$t/b_i << 1$, $S_{i,i+1} << 1$, $g_i^{\ell} >> 1$, and $1 < L/b < 8$. The development of this equation, an easy method of pictorially representing the many terms in the recursive equation 1, and generalization to arbitrarily large L/b ratios are found in reference 7.

DESIGN CONSIDERATIONS

A shield set designed for a spaceborne hydrogen maser must provide shielding over the entire cavity such that the changing external field will not perturb the internal field to the extent that the consequent frequency shift will be outside the specifications for the maser. In this section the various parameters that determine the overall shielding factor will be discussed in the framework of design for an optimized shield set.

Design parameters in Eqs. 1 are the shield thickness t, shield spacing $s_{i,i+1}$ and shield number N. The inner radius b_1 is usually set by the particular application and the permeability is a property of the material. Optimum shield spacing is set by the condition

$$\mu_i^{\ell} \frac{s_{i,i+1}}{b_i} = \mu_j^{\ell} \frac{s_{j,j+1}}{b_j}$$

however, for closely spaced shields, such optimization gives slight improvement over equally spaced shields, and is not a significant design consideration in most instances.

More important options are the choices between N, t, and b_N consistent with a required shielding effectiveness. Equation 1 has been used to generate a set of t and b_N values for N equally spaced closed shields with length $L \approx 3b_N$. The results are shown in fig. 1. Choices between b_N and t will depend on the physical limits imposed by a particular shielding application.

Often it is important to minimize the weight (or equivalently the amount of material) necessary for a given shielding requirement i.e. a shielding effectiveness criteria. The weight of a set of closed cylindrical shields is

$$W_N \approx 2\Pi t \rho \sum_{i=1}^{N} (b_i L_i + b_i^2)$$

where ρ is the density of the shielding material. For $L_i \approx 3b_i$ this equation reduces to

$$W_N \approx 8\Pi t \rho \sum_{i=1}^{N} b_i^2$$

Using this equation, the weight was calculated for N equally spaced shields as a function of t and b_N for a given shielding effectiveness. Figure 2 shows such a calculaton for 4 and 5 equally spaced shields where the shielding effectiveness criteria are indicated. It is noted that an optimum b_N exists for minimizing the weight. One can make shields physically smaller by reducing b_N but the thickness of the shields increases rapidly and the weight goes up. Likewise, the weight increases if b_N increases beyond the optimum value since the large b_N values more than offset the reduced t values.

For shielding to very low magnetic fields (10^{-10} tesla) the initial permeability μ_o of the material is an important material parameter, especially for the innermost shields. Since the permeability is a function of the internal induction field B inside the material, the value of μ will increase in the outer shields. For high permeability alloys, μ typically has a maximum μ_m near $B \approx 2000$ gauss which is more than 10 times μ_o. Induction B inside a cylindrical shell is approximately given by

$$B \text{ (gauss)} \approx (5/2) \left(\frac{bH_o}{t}\right)$$

where H_o is the field outside the shield. This relation along with the manufacturers published μ (B) curve, should be used to estimate μ of the outermost shield. Additional optimization can be obtained if the thickness t is selected to achieve μ_m in the outer shield.

The axial magnetic field profile within a partially closed cylindrical set of shields is usually dominated by the exponential decay of the external field as it enters the shielded region through the holes.[7]

$$H(x) \approx 1.1\left(\frac{L}{L_1}\right)^{1/2} \exp\{-k(0.75L-x)/2r\}+H_i \qquad (2)$$

where x is the axial distance from the center, H_o is the external field, L is the average length of the shields, 2r is the hole diameter in the end caps, and H_i is the internal field far from the entrance holes as determined by the shielding effectiveness, G_N. The profiles measured on two differently dimensioned magnetic shields and 3 different hole diameters were consistently fit to this equation using the theoretical value for k of 2.26. This equation can therefore be used to establish the minimum length of closed magnetic shields with access holes in order to maintain a specified shielding effectiveness for a given axial distance near the center of the shields.

SHIELD ACQUISITION AND EXPERIMENT TESTS

Using the above considerations, a set of shields was designed for the NRL passive hydrogen maser. The design shielding factor using the manufacturer's value of permeability was 6×10^5 over a centrally located 5" long region in the shield. This shielding would provide a more than adequate safety margin to insure that the maser's frequency stability specification of 1 part in 10^{14} would not be compromised by an external field change of $\pm 10^{-4}$ T ($\pm$ 1 gauss). Several shield sets conforming to the final design were purchased from two different manufacturers. In addition, a larger shield for an SAO VLG-11 ground based maser was purchased from a third manufacturer. Figure 3 shows the schematic design of the NRL designed shields along with an actual photograph of one set. The manufacturers' quoted values were approximately identical. Specifications of the shields including dimensions and manufacturer are shown in Table I. Shield set 3 was significantly larger than sets 1 and 2, the end caps were hemispherical instead of conical, and the entrance ports in the ends of the shields were different in size with no flared extensions.

Magnetic measurements of the shields were made in an 11.3 meter diameter Braunbek coil system at the Spacecraft Magnetic Field Site, Goddard Space Flight Center, Greenbelt, Maryland. (see figure 4). This coil system actively compensates for changes in the earth's magnetic field and is capable of nulling the earth's field to better than 1 nT over a 1.3 meter sphere. In addition, the system can apply a field, known to an accuracy of 1 nT, over this volume with a magnitude as large as 60 μT. Shielding effectiveness was determined by incrementally increasing the field in a specified direction while monitoring the internal field. Both longitudinal and transverse axial shielding effectiveness were determined using a fluxgate magnetometer with a 0.1 nT resolution. Prior to each measurement, the shields were depermed to a remanant internal field less than 1 nT.[8]

In set 1, each individual shield was measured in order to arrive at the experimental μ_i^ℓ value. Next the shields were sequentially assembled and measured - providing shielding effectiveness's for 1,2,3, and 4 nested sets. These measurements, shown in Table I, were used to verify the equation for G_N^ℓ. Also, shown in parenthesis for set 1 are the μ_i^ℓ values estimated using manufacturers published specifications. The G_4^ℓ calculations using these estimated μ_i^ℓ values are too high by a factor of 2.

For the second set of shields, μ was experimentally determined at both high and low induction values for only one shield, and the results were assumed to apply for the remainder of the shields (i.e. the shields were not checked for material variability). Equation 1 was then used to calculate the measured G_4^ℓ and the result was experimentally verified (Table I). Again estimated μ_i^ℓ values for these shields using manufacturers specifications are shown in parenthesis. For this set, the calculated G_4^ℓ using estimated μ_i^ℓ values are almost an order of magnitude too high.

For the 3rd set of shields only the manufacturers values were used. The calculated G_4^ℓ value is almost double the experimental value.

It has been our experience that the μ(B) value supplied by the manufacturer is an upper limit that is not practically obtained in fabricated shields. The μ(B) plots are generated by measurements with a permeammeter on a small test piece, rather than on a fabricated cylinder in a uniform magnetic field. It is not surprising that the permeabilities determined by measuring the shielding of cylinders in uniform fields are lower than predicted on the basis of the manufacturers graphs. This must be taken into account when designing a shield set either by measuring the μ of a cylinder or by adding an adequate safety margin to the design calculations.

Figure 5 shows the measured axial field profiles for shields 1 and 3. The solid lines represent Eq. 2 for the appropriate shield length and hole diameter with k = 2.26.

CONCLUSION

Formulae presented here for the shielding effectiveness and the field profile of a closed set of N concentric cylindrical shields with access holes can be readily used to design and optimize magnetic shields for specific applications. Such design considerations have been successfully employed in the development of magnetic shields for hydrogen masers. The largest uncertainty in designing magnetic shields relates to the variability of quoted μ values. The only certain way to obtain reliable values for precise shielding calculations is to actually measure μ for at least one shield.

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REFERENCES

1. T.E. Sterne, Rev. Sci. Instr. 6, 324 (1935).

2. W.G. Wadey, Rev. Sci. Instr. 27, 910 (1956).

3. S.M. Freake and T.L. Thorp, Rev. Sci. Instr. 42, 1411 (1971).

4. A.J. Mager, IEEE Trans. Mag. MAG-6, 67 (1970).

5. A. Mager, J. Appl. Phys. 39, 1914 (1968).

6. A. Mager, Z. Angew. Phys. 23, 381 (1967).

7. D.U. Gubser, S.A. Wolf, and J.E. Cox, Rev. Sci. Instr. to be pubished.

8. S.A. Wolf and J.E. Cox, NASA Tech. Memo. 78104, p 371 March, 1978.

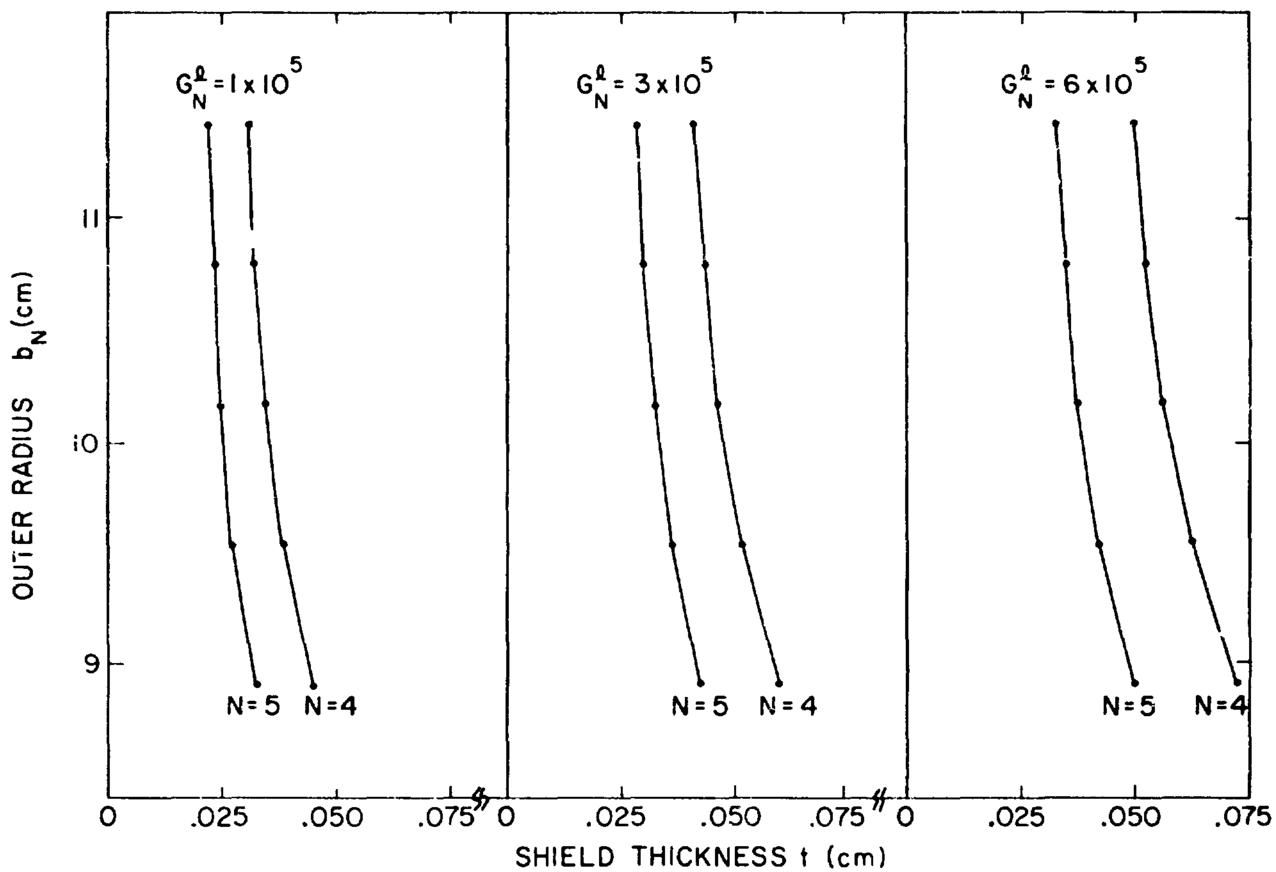


Fig. 1. Variation of outer shield radius and shield thickness for various G_N values.

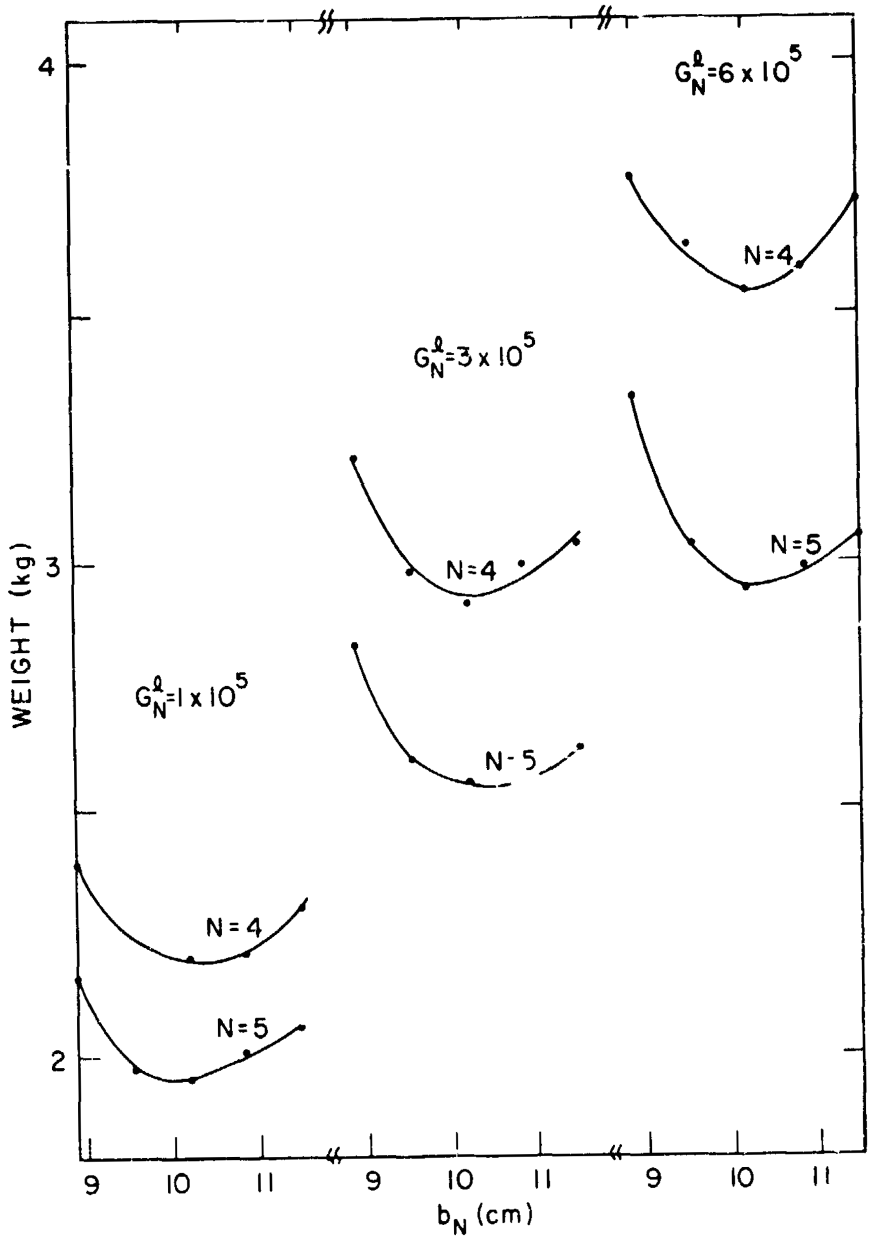
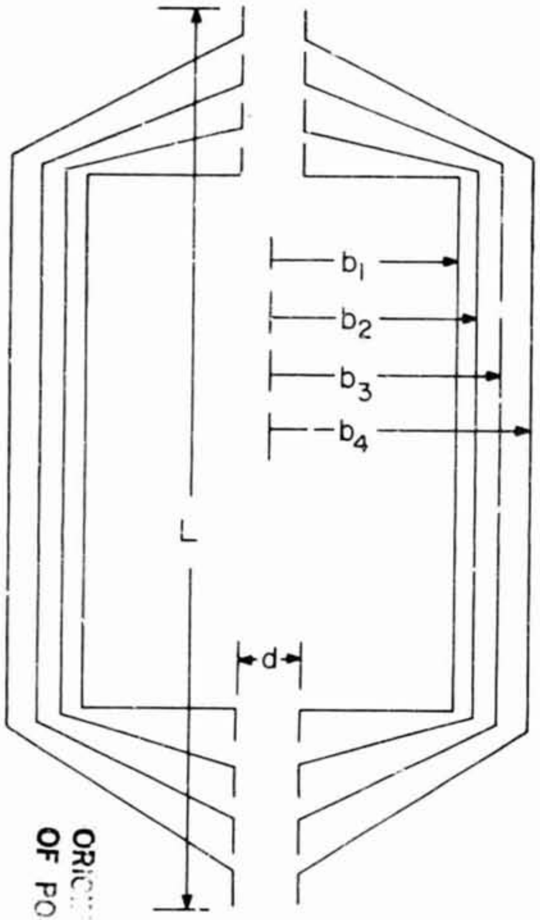


Fig. 2. Variation of total shield weight as a function of outer shield diameter for various G_N values.



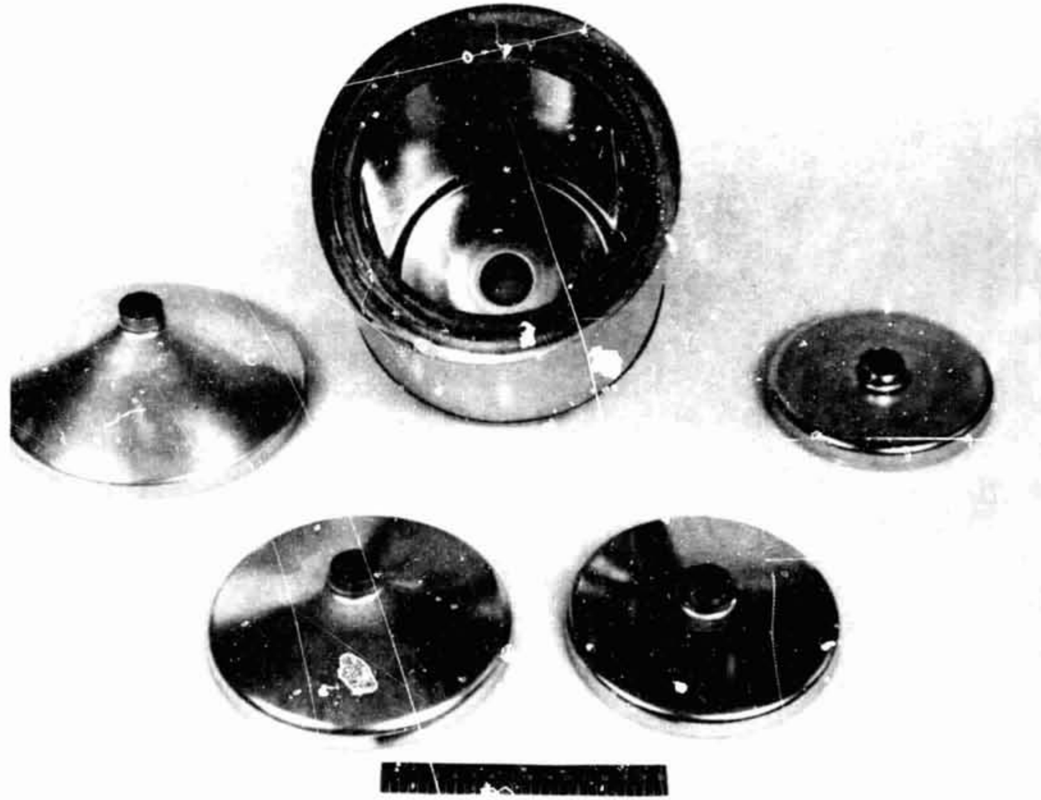


Fig. 3a. A schematic design of the two smaller sets of shields.

b. Photograph of a nested set of shields and their end caps.

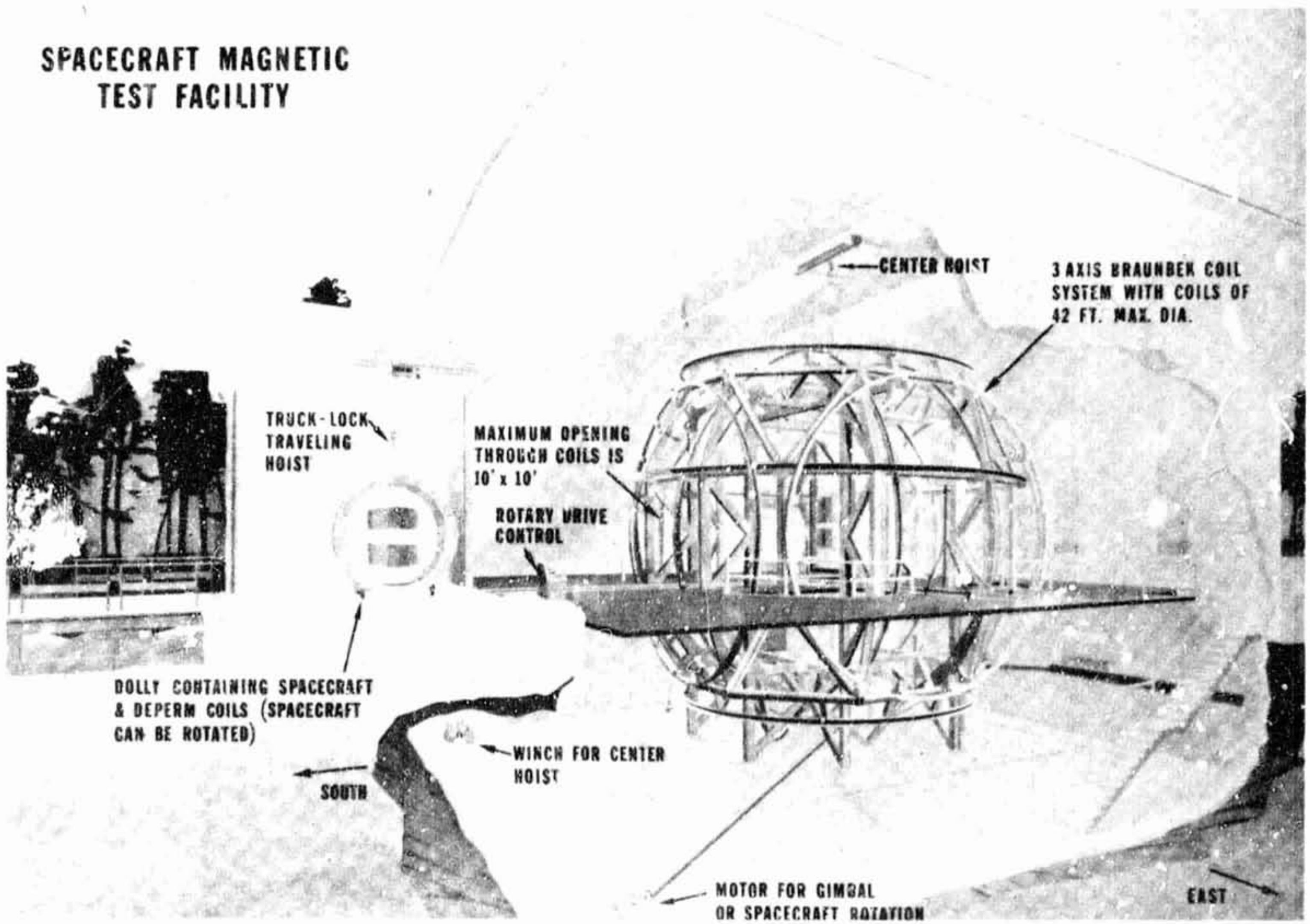


Fig. 4. Braunbek coil system at the Spacecraft Magnetic Field Site, Goddard Space Flight Center, Greenbelt, MD.

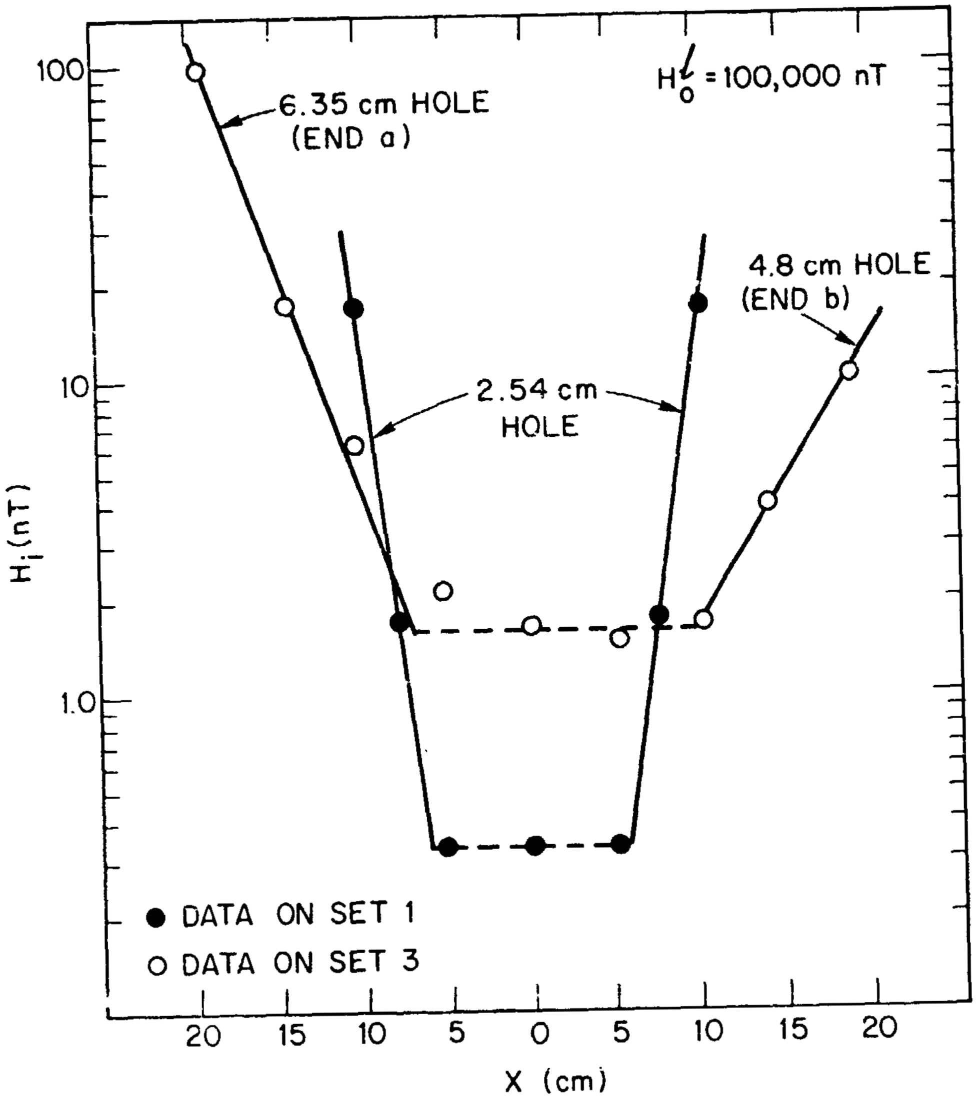


Fig. 5. Axial field profiles for shield sets 1 and 3 (Table I).

Table I Shield Parameters

	RADIUS (cm)				PERMEABILITY ($\times 10^{-4}$)				G_n^{ℓ} ($\times 10^{-3}$) (USING $f = 0.75$)	G_n^{ℓ} ($\times 10^{-3}$) EXPERIMENTAL
Set 1 [(a)]	b_4	b_3	b_2	b_1	μ_4^{ℓ}	μ_3^{ℓ}	μ_2^{ℓ}	μ_1^{ℓ}		
	9.65				3.5				0.093	0.093
	9.65	8.51			3.5	2.9			1.5	1.5
	9.65	8.51	7.62		3.5	2.9	2.0		17	18
	9.65	8.51	7.62	6.86	3.5	2.9	2.0	2.5	250	250
Manufacturer's estimate	9.65	8.51	7.62	6.86	(7.0)	(3.5)	(2.5)	(2.0)	(590)	---
Set 2 [(b)]	9.65	8.51	7.62	6.86	2.0	1.8	1.7	1.2	50	50
Manufacturer's estimate	9.65	8.51	7.62	6.86	(7.0)	(3.5)	(2.5)	(2.0)	(590)	---
Set 3 [(c)]	23.88	21.84	20.07	18.54					---	60
Manufacturer's estimate	23.88	21.84	20.07	18.54	(10)	(5.0)	(2.5)	(2.0)	(100)	---

(a) Mu Shield Corp. Malden, Mass. 02148 2.54 cm access hole, 0.051 cm wall thickness

(b) Perfection Mica Corp. Bensenville, Ill. 60106 2.54 cm access hole, 0.051 cm wall thickness

(c) Allegheny Ludlum Brackenridge, Pa. 15014 6.35 cm access hole one end
4.826 cm access hole other end
0.081 cm wall thickness

QUESTIONS AND ANSWERS

DR. VICTOR REINHARDT, NASA Goddard Space Flight Center:

I have a few questions. First of all, on your holes, I noticed that you had some little flanges. Did you experiment to determine if those flanges improved the shielding factor?

MR. WOLF:

Well, it turns out that we did experiment with that. On our initial design, we felt these flanges would make a difference. But we had a set of shields fabricated without the flanges, and it turned out that there was no difference.

DR. REINHARDT:

Okay. Another question: The variations in the μ. Did you find a lot of variation in the samples from the same manufacturer?

MR. WOLF:

We actually looked at three manufacturers. The μ values of two of the manufacturers were quite comparable once the shields were annealed to their best state. In one case, we had to have the shields reannealed a second time.

The third manufacturer, the μ value was about a factor of two lower than the other two, even though the original specifications were the same. I suspect that there would be a large variation in the μ that you could get from manufacturer to manufacturer.

DR. REINHARDT:

No, but within the same manufacturer, did you find reproducible μ's if you ordered the same set of shields?

MR. WOLF:

Yes. Once the shields were properly annealed, the permeability was quite constant.

DR. JACQUES VANIER, Laval University:

First, when you mentioned the part in 10^{14} that you required, what was the field fluctuation you assumed?

MR. WOLF:

Okay. I'm sorry; I should have mentioned that. We assumed a field variation, an external field variation, of ±1 gauss.

DR. VANIER:

Okay. What method of degaussing these shields did you use? Could you comment on that?

MR. WOLF:

We tried many. The best method was actually a twofold technique. We depermed the outer shields by placing them inside a ten-foot Helmholtz pair and put on an AC field of 30 gauss. And then after that, we took a wire and ran it through the inside and put on an AC field of about, again, 30 gauss, slowly decreasing the field. And we did it maybe two or three times, until the internal field was less than we could measure with our instruments. It was degaussed to about 10^{-6} gauss; a microgauss.

DR. VANIER:

Do you know the frequency of the degaussing?

MR. WOLF:

Yes. It was 60 cycles.

DR. GIOVANI BUSCA, Ebauches, Switzerland:

Did you find some problem in the joint of the shields? Normally, people say that the joint is the most critical part of the shields.

MR. WOLF:

Well, it turns out that we did not see any difference. The shields that we got for the SAO-VOG-11 shields were welded on one end with just a mechanical joint on the other. The fact that we got such good agreement with the profile for just taking into account the size of the holes indicated that there wasn't very much difference between the spot-welded joint, and just the mechanical joint.