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A MAGNETICALLY SHIELDED ROOM

BY
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A MAGNETICALLY SHIELDED ROOM

by Harald Wesemeyer

Abstract: To facilitate the test of magnetometers, a magnetically shielded room was built and its performance tested.

Introduction

One purpose of the magnetically shielded room is to supply a medium with certain physical conditions similar to those far away from a city, from factories, from railroads, etc., as required for the testing of the performance of sensitive geophysical equipment, in particular, magnetometers. These conditions are:

(a) an extremely low level of electromagnetic radiation, in particular, at low frequencies, mainly 60 c/s;

(b) a fairly homogeneous earth's magnetic field with a gradient $< 10\ \gamma/\mathrm{cm}$.

Another purpose of the shielded room is to supply a magnetic field well below the local earth's magnetic field as well as to facilitate variations of the magnetic field from a lower value well below the local field to a higher value well above the local field. These facilities are often required for the test of the performance of magnetometers. Magnetic fields of the kind described can be supplied by a pair of Helmholtz coils inside the shielded room. Moreover, an attenuation of the earth's magnetic field will also affect the diurnal variations and micropulsations of the said field, and it is desirable that these should be very weak in a magnetically shielded room.

For the operation of magnetometers of the nuclear magnetic resonance type, a fairly homogeneous field is required. In a completely homogeneous external field the proton resonance line width as obtained from a liquid hydrocarbon sample would be about 1 γ. It is therefore desirable to reduce the inhomogeneity over the volume of the sensing sample to about the same value. In practice, a gradient of about 10 γ/cm is acceptable when a proton signal well above noise is to be detected. This gradient, however, is still large in comparison with the steepest gradient that was ever measured in Canada, namely 100 feet above the Marmara mountain with a gradient of 0.3 γ/cm.

In buildings containing steel constructions, local gradients of the earth's magnetic field are often as high as 300 γ/cm (when measured in about 1 m distance from a steel beam). Such an inhomogeneity of the field reduces the signal-to-noise ratio of a proton resonance line very considerably as a consequence of tremendous line broadening.

The desired properties of a magnetically shielded room will now be summarized:

(1) attenuation of low level electron magnetic radiations at low and high frequencies;
(2) attenuation of the earth's magnetic field and its variations;
(3) to facilitate variations of a fairly homogeneous magnetic field from a value well below the local earth's magnetic field to a value well above the earth's magnetic field;
(4) reduction of the local gradient of the earth's magnetic field.

The shielding material

As is well known, good shielding against electrostatic as well as alternating electromagnetic fields at high frequency can be obtained with any good conducting material whereby the shielding against the magnetic component of the high frequency radiation is due to skin effect losses. For the attenuation of low frequency radiation, however, the magnetic field vector is little affected by the electric conductor, and for a good attenuation a material with a large magnetic permeability is required.

It is not easy to find an inexpensive ferromagnetic material which has a very high permeability in the magnetic field of the earth or in lower fields but does not saturate in the earth's field. The local field inside the laboratory building is slightly smaller than 0.4 Oe. A commercially available ferromagnetic alloy which has the trade name "Conetic AA"[x]) was chosen as shielding material. It consists of 76.1% nickel, 20.1% iron, 1.3% chromium, 0.9% manganese and has cobalt and aluminium as minor constituents. It has a maximum permeability of about 300,000 at a polarizing field of 0.02 Oe. The permeability drops to about μ = 25,000 near 0.20 Oe. The initial permeability is not known. The magnetization material starts to saturate in a polarizing field of 0.3 Oe, with an induced flux of about 5.3 k gauss. The retentivity is about 2.5 kilo gauss. The material is available in foils of 5/1000" thickness with a width of 15".

It is obvious that the foil would just saturate in the local field which is about 0.4 Oe. In a magnetically closed box one layer of this foil would, nevertheless, leave a reduced field inside whose strength would be below the saturation field strength. A second layer when placed at some distance from the first would then effectively attenuate the remaining field.

It is assumed that weak radiation of magnetic fields at low frequencies and of amplitudes well below the saturation field would be attenuated by the same factor as a d.c. magnetic field.

Choice of the size of the magnetically shielded room and means of generating magnetic fields inside.

The magnetically shielded room should be large enough to accommodate

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[x] Supplied by the Perfection Mica Company, Chicago

a table with a pair of Helmholtz coils, and there should be room enough inside so that a person can walk around this table. The size of the room was also determined by the influence of the magnetic shielding material on the magnetic field generated by the Helmholtz coils, and it is desirable that this influence should be small.

To determine this influence experiments were made for the two dimensional case of the magnetic field of broad bar magnets, and the effect of the shielding material on the field distribution observed. By means of analogy between the field of a broad bar magnet and that of a pair of Helmholtz coils, it was concluded that the distance of the walls of the room from the coils should not be shorter than the coil radius.

Because of homogeneity requirements, the radius of the Helmholtz coils was made 0.59 m large. The pair of coils was mounted on a tiltable table so that the magnetic field direction of the coils was either parallel and adding or anti-parellel and opposing to the residual magnetic field inside the closed shielding hut. The height of the table which supports the coils was chosen so that the centre of the Helmholtz field approximately coincided with the geometrical centre of the hut which is of cubic shape. The inside dimensions of the hut are 2.4 m by 2.4 m by 2.4 m, whereby leaving about one coil radius distance between the outer part of the coil bobbins and the magnetic foil.

Each coil has 700 turns of enamelled copper wire No. 20 (A.W.G.), and the current is supplied by batteries. The magnetic field of the coils can be controlled from outside. It can be scanned through a desired range by means of electronic devices and also sinusoidally modulated at frequencies up to 400 c/s.

The inhomogeneity in the centre of the Helmholtz coils when they generate a field of 1 Oe is $\leqq$ 1.95 γ/cm in a cubic volume of 10 cm edge length.

To obtain the resultant inhomogeneity the inhomogeneity of the residual field in the hut has to be added.

Construction of the magnetically shielded room.

The shielding hut was made by ½" thick plywood plates and is reinforced with studdings of 2" by 4" size. The hut is of cubic shape with an inner wall distance of 2.4 m. It has two walls. The outer one is spaced 10 cm away from the inner one. On both the inner and the outer one a single layer of magnetic foil is attached each time from inside.

To obtain both tightly closed magnetic and electric circuits for all foil sections, a clamped lock-seam joint was used in which the sections of the foil widely overlapped. The mentioned lock-seam is mechanically very rigid (see illustration).

The corners in which three faces join are carefully shielded with double overlapping pieces which were put underneath and over the foil sections.

The doors were made with extreme care. The magnetic circuit between the doors and the walls was pressed together whereby foam rubber strips underneath the foil distributed the pressure evenly and secured a smooth contact surface (see illustration).

To facilitate the control of electrical equipment inside from outside, cable entrances were built in the centre of a side wall. With special attention to good magnetic shielding, cables and pipes were wrapped in magnetic material and then put through holes of both walls. The outside of the wrapped cables and pipes were further enclosed with foil collars which provided the magnetic contact with the foils on the inner and outer walls. Attention to wide overlapping was paid everywhere on the cable entrances. Details of the cable entrances are illustrated in Fig. 3. There are four double conductor cables ending in amphenol radio frequency connectors, one six-conductor cable ending in an emphenol cannon connector, one pipe of 1½ inches diameter and 2 copper tubes of ½ inch diameter. The cables and pipes are under tension towards outside in order to keep the foil collars pressed onto the walls as indicated in the picture. The foils of both the inner and the outer wall are grounded at the cable entrances.

All control equipment was arranged outside the hut near the cable entrances on an aluminum dexion shelf.

Performance of the magnetically shielded room.

(1) Shielding against electromagnetic radiation in the low frequency range.

(1a) Attenuation of the residual "hum" level of the laboratory.

For the measurement of this no excess noise from transformers, motors or fluorescent lights was present as they were all switched off, and little "hum" was expected from the rest of the building in which the shielded room was built as the building contains only offices.

A parallel resonance circuit comprising a large pick-up coil (1.3 Henry, 2,500 turns) and several high quality paper condensers was tuned to a frequency of 60 c/s, and the voltage across the coil measured by means of a battery operated "Balantine" vacuum tube voltmeter. Measurements were taken at several places outside the shielded room and at several places inside the shielded room with the coil axis in various orientations so as to give maximum readings. The comparison between values of the measured voltages of 60 c/s background as obtained from places inside and outside the shielding hut before and after the hut was built, was made.

<u>Result:</u> The 60 c/s noise background is attenuated approximately by a factor 7.

(1b) Attenuation of a direct radiation at 60 c/s.

A transmitter coil of the following dimensions, length 12.5 cm, diameter 18 cm, 112 turns, was placed in front of the hut at a distance of 2.2 m from the outer foil. The aforementioned receiving coil was placed in the centre of the hut. Both coils were initially aligned co-axially and then adjusted in angle with respect to each other to obtain a maximum reception of the radiation. Measurements of induced voltages from the receiving coil were taken for different fields of the transmitting coil and the readings were compared with those obtained with the same orientation conditions outside the hut when no shielding material was present between the transmitter and the receiver.

Result

Transmitter, 60 c/s

peak-to-peak intensity at the coil end facing the magnetic hut	Attenuation approximately
5.5 gauss	15
8.5 "	11
11 "	7

Remarks:

A saturation effect is clearly noticeable for the last case. The described transmitter represents a comparatively strong 60 c/s radiator, which would usually be switched off when investigations on apparatus inside the hut are made.

(2) Attenuation of the local earth's magnetic field.

The local field inside the laboratory is about 0.4 Oe. Outside the laboratory it is about 0.5 Oe. The difference is due to the screening effect of steel constructions in the building of the laboratory.

The residual field inside the shielded hut was measured by the following absolute methods:

(a) by means of the induced voltage in the rotating coil of an earth inductor (horizontal and vertical component in a magnetic meridian);

(b) by means of the period of oscillations of a magnetic needle (horizontal and vertical component in a magnetic meridian);

(c) by means of a proton precession magnetometer which actually measured the sum of the residual field and the field generated by the Helmholtz coils. Subtraction of the known Helmholtz field leaves the field which is attenuated by the magnetic hut.

Result: Comparison of measurements of the field in the laboratory outside the hut with measurements inside the hut, showed for places near the centre inside the hut an attenuation factor of 4.

		Attenuation
outside the hut and before the hut was built	0, 38 Oe	approximately 4
inside the hut	0, 10 Oe	

(3) Reduction of the local field gradient.

A gradient survey both inside the magnetically shielded hut and outside the hut in the laboratory was made. The gradients were computed from measurements with:

(a) a rotating earth inductor coil;

(b) a proton free precession magnetometer (with this instrument only measurements inside of the hut could be taken because of the high gradients and noise levels outside).

In addition to these measurements it was desirable in some cases, to measure the gradient directly. Therefore, a simple laboratory type of fluxgate gradiometer was built (see the appendix).

Gradients in the laboratory at an average field of 40,000 γ.

(a) 100 cm distance from a steel filing cabinet 110 γ/cm.
50 cm " " " " " " 185 γ/cm
25 cm " " " " " " 253 γ/cm

(b) on a shelf 30 cm from a window (no iron is present except hidden steel constructions inside the concrete walls of the building) 155 γ/cm

(c) on the floor 100 cm from a window 52 γ/cm

(d) the smallest gradient was found at a place on the floor in the centre of the laboratory 42 γ/cm

The relative error in these measurements was about 10%.

Gradients inside the shielded hut at a residual field of 10,000 γ.

(a) in the geometrical centre of the shielded room 8.5 γ/cm ± 15%

(b) 30 cm distance from a wall 35 γ/cm ± 15%

It is noteworthy to mention that at a field of 1 Oe the magnetization of the foil is saturated, and one would expect a field as inhomogeneous as in the laboratory without any magnetic shielding.

(c) the gradient in the centre of the hut and inside the Helmholtz coil at 100,000 γ was found to be 47 γ/cm ± 15%.

Comparison of gradients and result.

(a) The smallest measured gradient in the laboratory at a total field of about 40,000 γ is 42 γ/cm ± 10%.

(b) The average gradient in the centre of the hut inside a cylindrical volume of 25 cm length coaxial with the Helmholtz coils and about 20 cm in diameter at a total field of 100,000 γ is 47 γ/cm ± 15%.

(c) The gradient in the centre of the hut at a field of 10,000 γ over a volume of 40 cm by 40 cm by 40 cm is 8.5 γ/cm ± 15%.

Deviations from this value only appear close to a wall.

(d) Then in 30 cm distance from a wall the gradient is 35 γ/cm ±20%.

As can be seen from these measurements the local gradient of the terrestrial field is reduced appreciably.

<u>Result</u>: The local gradient is attenuated by approximately a factor 5.

The homogeneity of the magnetically shielded room could further be improved by placing foil sections into certain places around a volume under consideration so that certain local poles are screened. This method is sometimes called "shimming".

Shimming could not be tried yet as the author had no more foil available when the hut was completed.

It is noteworthy that a large proton precession signal with a signal-to-noise ratio of 9:1, using a Varian proton magnetometer with kerosene in an effective sample volume of 350 ml, can be obtained inside the magnetically shielded hut, but not elsewhere outside the hut in the laboratory because the high noise level and the large gradient of the local field outside of the hut prevent the detection of a proton signal. This indicates drastically that the reduction of the local field inhomogeneity as well as the attenuation of low frequency electromagnetic noise was sufficient to obtain a proton precession signal.

(4) <u>Influence of the residual retentivity of the foil material on the field gradient.</u>

After strong magnetic fields had been applied, say about 2 Oe, a considerable magnetization of the magnetic hut was noticed as indicated with a dip needle. The resultant inhomogeneity was so great that a proton precession signal could not be obtained unless the hut was demagnetized before its use.

This indicates that the field gradient in the centre of the shielded room was at least of the order of 30 γ/cm after magnetization. See also paragraph 3 of this report under the section: gradients at a field of 10,000 γ.

The demagnetization of the hut was achieved by the cyclic reduction of the field of the Helmholtz coils from ± 2 Oe down to 0 Oe by means of rheostats and a reversing switch.

It was also observed from measurements of the decay time of a proton precession signal that the homogeneity of the field was greatest after a careful demagnetization of the hut.

The necessity of the demagnetization is no disadvantage as long as good homogeneity can be obtained by this process.

(5) Test of the continuity of the magnetic flux through the lock-seam joints and the magnetic joint between the inner door and the inner wall.

A small fluxgate gradient probe in which the two fluxgate coils were mounted close together was used for this test. This gradient probe was led in a distance of 0.5 cm over the joints under question, the sensitivity of this simple device was about 1 γ/cm.

Result: No discontinuities of the magnetic flux were observed near lock-seam joints, overlap joints, and corner edges.

When travelling passed the joint between the inner door and the inner wall, however, a change of the gradient of about 6 γ/cm was observed.

Conclusion

In the described magnetically shielded room the local earth's magnetic field is attenuated by a factor 4 (down to 10,000 γ). The local gradient is attenuated by approximately a factor 5 (down to 8.5 γ cm).

Low frequency electromagnetic radiations at weak intensities (up to amplitudes of about 5 gauss) are attenuated by a factor 10. Homogeneously magnetic fields up to 1 Oe can be supplied inside the shielded room by means of Helmholtz coils.

It is desirable to reduce the gradients inside the hut further. This could be done by the method of shimming unless a third wall inside is to be constructed.

The Perfection Mica Company, Magnetic Shield Division, is thankfully acknowledged for a price reduction on the magnetic foil.

Appendix

The fluxgate gradiometer

A gradiometer was built from a commercially available fluxgate magnetometer (Magnatest FM-201) which was equipped with two fluxgate probes. The two probes were mounted coaxially but antiparallel in orientation in the telescope axis of a theodolite with a distance of 24 cm between them. In a uniform field the reaction of one probe is cancelled by an equal and opposite reaction in the other probe and the fluxgate magnetometer reads zero. In non-uniform fields the magnetometer reads one-half the difference in field between the two probes, and when the probes are properly oriented the meter readings of the magnetometer are proportional to the gradients of the field. This orientation is achieved when the horizontal and vertical circles of the theodolite are adjusted until a maximum reading has been obtained.

The calibration of the gradiometer was done by using a small pair of Helmholtz coils over one probe and generating a small field there appropriate to the range of gradients to be measured. The radius of the Helmholtz coils has to be small in comparison to the distance of the other probe from the first mentioned one, so that their field at the other probe can be neglected.

The error of all readings of this gradiometer was $\pm 2\ \gamma$/cm due to incomplete balance of the two antiparallel probes.

Figure 1

Lock-seam

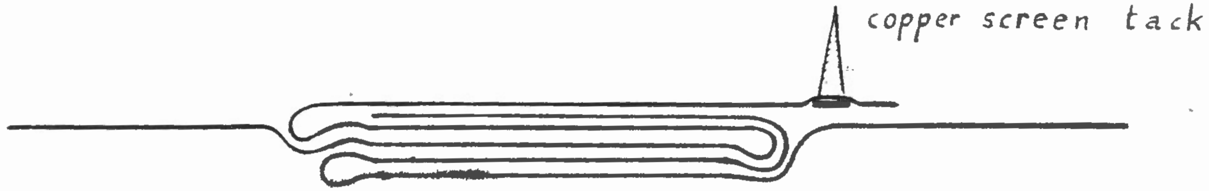


Figure 2

Inner and Outer Doors

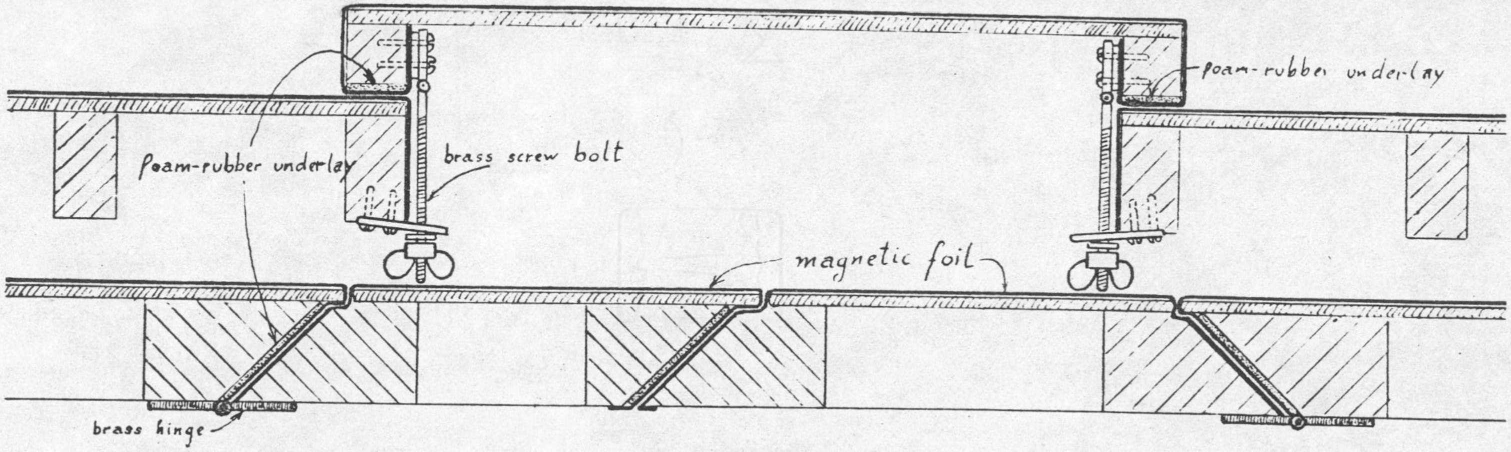
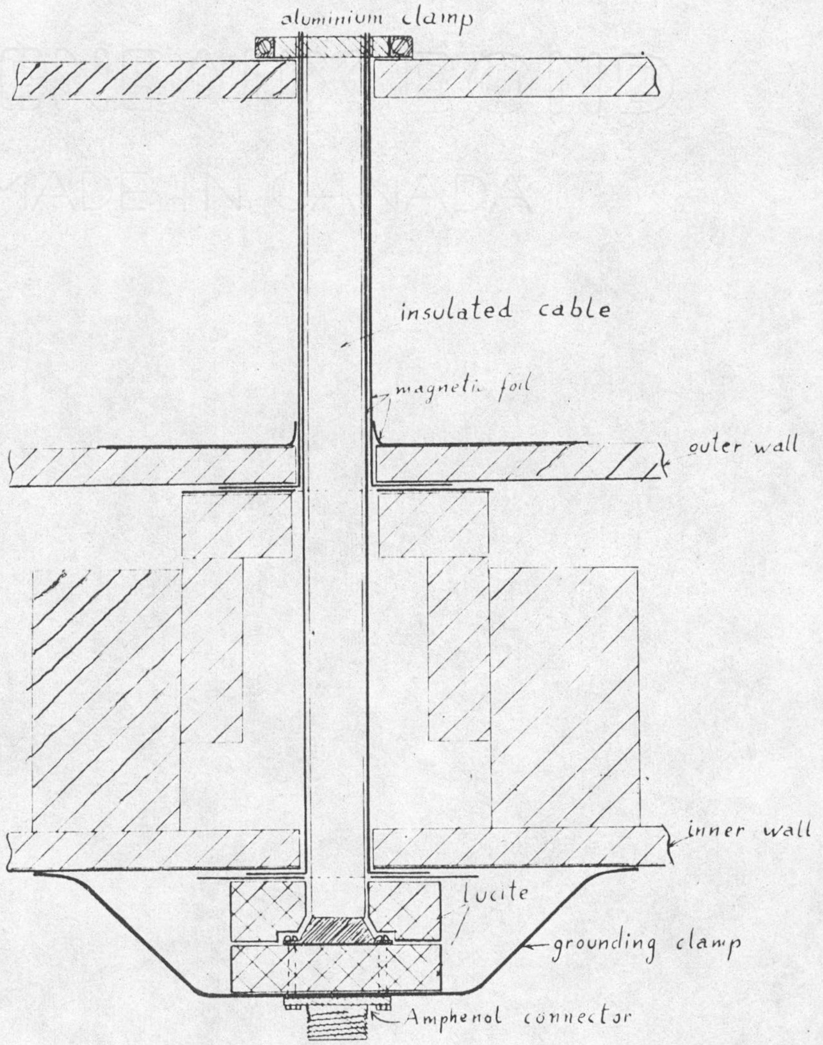


Figure 3



CROSS-SECTION OF A CABLE ENTRANCE

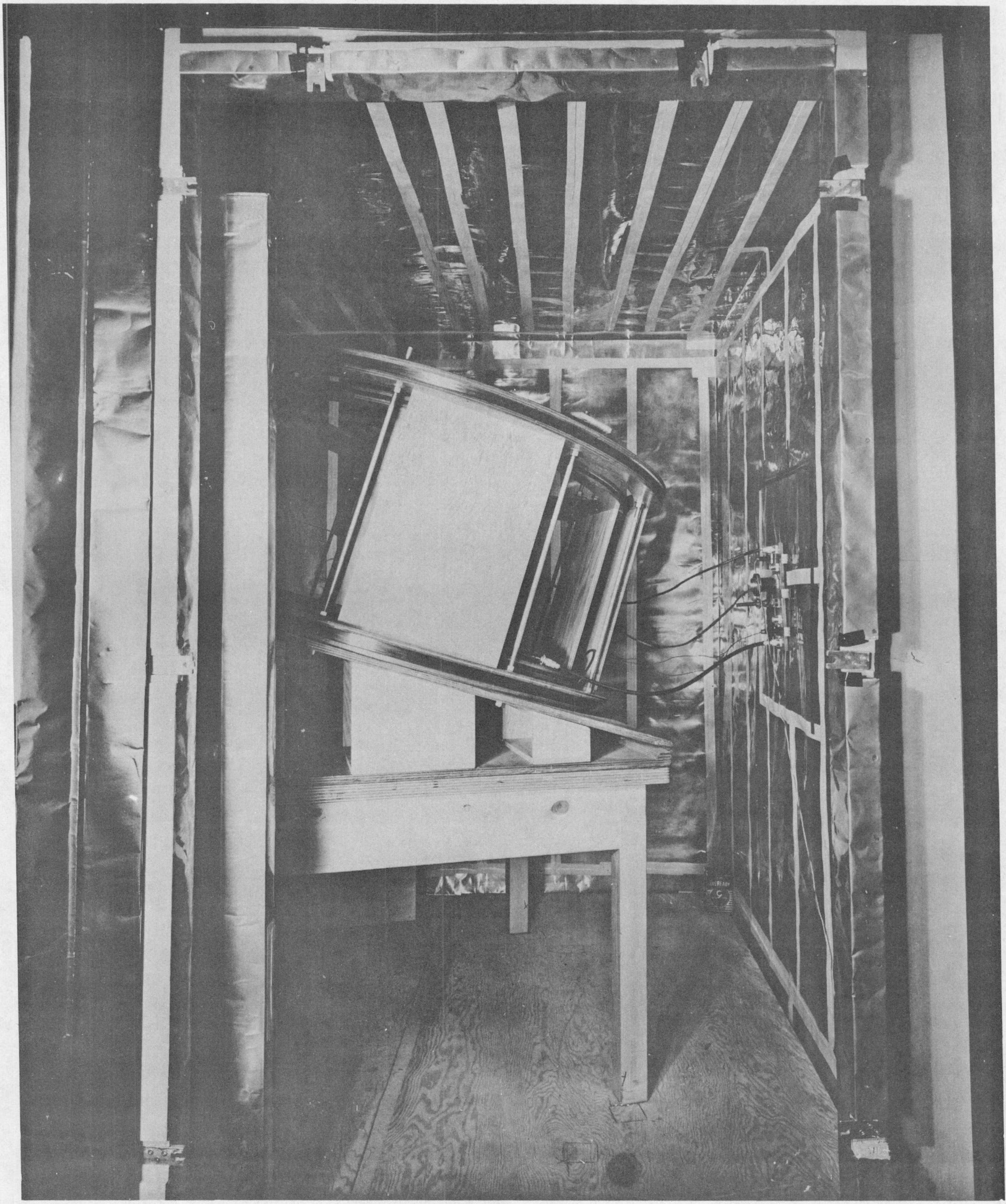


Plate I. The magnetically shielded room (open).

Plate II. The doors (one open).

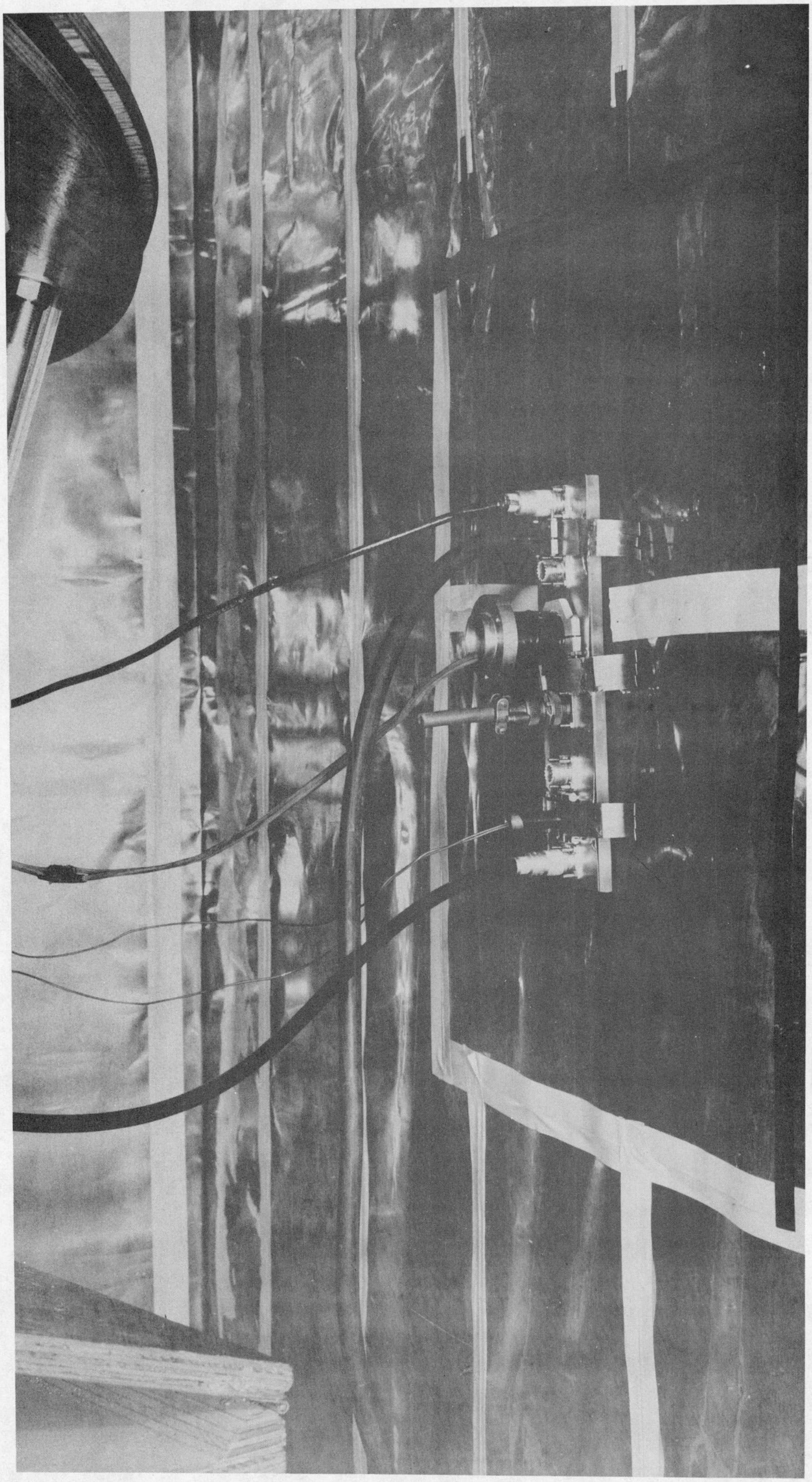


Plate III The cable entrances with connectors from inside.

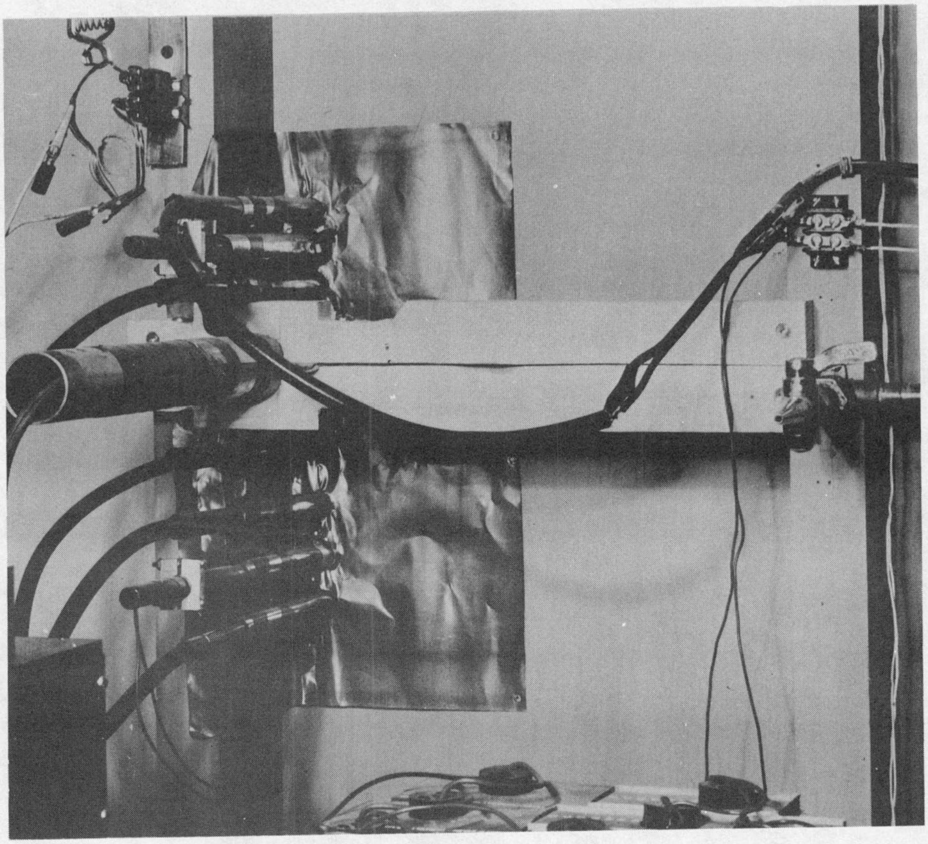


Plate IV. The cable entrances from outside.