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PRODUCTION OF ULTRALOW MAGNETIC FIELDS FOR GRAVITY PROBE B (GP-B)

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ABSTRACT

The procedures for the production of a very low magnetic field of 10^{-11} tesla in a full scale prototype dewar have recently been completed. The GP-B Relativity Gyroscope Experiment will provide a controlled test of Einstein's General Theory of Relativity by making observations of the precession of nearly perfect gyroscopes in Earth orbit. The gyroscopes consist of highly spherical and homogeneous fused silica rotors which are coated with a thin superconductor and operated at a temperature of 2 K. Readout of gyro precession is accomplished by measuring the orientation of the magnetic dipole moment (London moment) which is generated by the spinning superconductor and is aligned with the spin axis. The GP-B experiment requires an ambient field of $\leq 2 \times 10^{-11}$ tesla (2×10^{-7} gauss) in order to minimize trapped flux in the rotors and thereby insure the proper operation of the SQUID-based gyroscope magnetic readout. The process to reach the required low field level is by iterative expansion of superconducting lead foil shields. The methods developed to effect the lead shield expansions and to accurately measure the low field are presented along with the final results.

THE GP-B EXPERIMENT

Experimental Objective

The Gravity Probe-B Relativity Gyroscope Experiment (GP-B) will provide a precise and controlled test of Einstein's General Theory of Relativity by observations of the precession of nearly perfect gyroscopes with respect to a distant guide star (e.g., Rigel) while in Earth orbit. For gyroscopes in a circular polar orbit with the gyro spin vectors in the direction of the guide star and the guide star in the orbital plane, the theory predicts two orthogonal effects, the geodetic and frame-dragging precessions.[1] For a 650 km orbit, the former has a calculated rate of 1.0×10^{-12} rad/sec (6.6 arc-s/yr.) and occurs in the plane of the orbit, and the latter has a predicted rate of 6.5×10^{-15} rad/sec (.042 arc-s/yr.) and causes the gyros to precess out of the plane of the orbit. The goal of the experiment is to measure the geodetic effect to better than 0.01% and the frame-dragging effect to better than 1%.

Experimental Technology

The extremely small values of the precession rates to be measured put severe constraints on the experimental design and on the choice of technologies.[2] Two of the important technology choices are those of the gyroscope rotor and its readout. The GP-B gyro rotor consists of a highly homogeneous and spherical 3.8 cm diameter fused quartz sphere.[3] The direction of the spin axis of the gyro can be determined by means of the co-aligned London magnetic dipole moment[4] produced by a thin superconducting niobium coating on the surface of the rotor. A component of this dipole vector is measured by a dc SQUID (Superconducting QUantum Interference Device) which is coupled to the gyro by a superconducting pickup circuit.[5]

All critical components of the experiment including the telescope,[6] four gyroscopes and a proof mass are constructed of fused silica and are optically contacted into the Quartz Block Assembly (QBA). The low thermal coefficient of expansion of fused quartz together with the

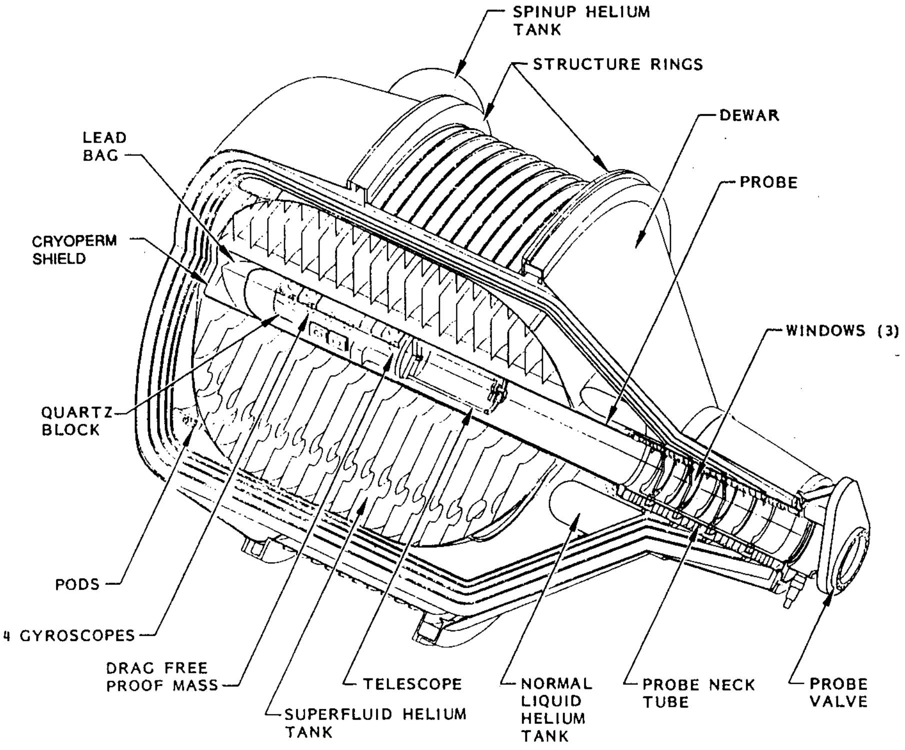

Figure 1. The integrated payload consisting of the probe in the science mission dewar. The Cryoperm shield is located outside the dewar well in the superfluid helium tank, and the supeconducting Pb shield is located inside the well.

thermal stability and uniformity afforded by operation at superfluid He temperature (1.8 K) assure the mechanical stability needed for the experiment. The Science Instrument Assembly (SIA, which includes the QBA, telescope, and SQUID assemblies) is mounted in a cryogenic probe enclosed by a vacuum shell. The probe provides vacuum and thermal isolation, optical access to the telescope, and mechanical, thermal and electrical support for the SIA. The probe is inserted into the central well of the dewar[7] (Fig. 1) which maintains the 1.8 K thermal environment by means of an annular tank of superfluid He.

The ambient dc magnetic field in the vicinity of the gyro should be maintained at ~10 pT (0.1 μG) in order to keep trapped flux in the rotor and magnetic torques to a tolerable level. In addition, external ac magnetic fields (e.g., the Earth's field modulated by satellite roll) must be attenuated by a factor of 10^{13} at the pickup loop to avoid signal contamination. These requirements can be met by means of a combination of a high-permeability shield (Cryoperm[8]), a defluxed superconducting lead-foil shield[9] (which is the subject of this paper), and a local superconducting Nb shield around the gyro.[5] Flux trapped in superconducting components inside the probe (including the local shield and the gyro rotor coating) can be flushed by uniformly heating these components above their critical temperatures and slowly recooling in the 10 pT ambient field maintained by the Pb-foil shield.

The Pb-foil shield is 254 mm dia. x 1.7 m long (10 x 67 in.), is closed at the bottom, and lines the interior of the dewar well. Its installation is an elaborate and lengthy process (which we outline below) that must be accomplished prior to integration of the probe into the dewar. Once the shield.is established, the dewar must be kept continuously cold. This imposes a subsidiary requirement that the probe be cooled down by insertion into the cold dewar while maintaining normal-boiling-point liquid He in the well and tank. This is accomplished by means of a large airlock and piston arrangement[2] which avoids convective mixing of the helium vapor with atmospheric gases and the subsequent deposition of solid air in the dewar well. Once the probe is fully inserted, complete mechanical and thermal integration is accomplished by means of three clamping mechanisms located at the bottom of the neck region of the dewar and spring-loaded thermal links located at heat exchangers situated on the neck of the probe.[10] At this point, the liquid helium remaining in the well can be pumped out. The Pb shield is mechanically clamped against the interior of the dewar well by the lead shield retainer which consists of a circumferential array of sixteen elongated BeCu leaf springs (shaped like slats from a venetian blind) which are pushed outward by the probe. This device also provides additional mechanical support for the probe and thermal isolation between the probe and shield.

The GP-B Testing Program

The overall GP-B hardware development program is based on an approach of incremental prototyping involving three generations of probes and two generations of dewars. The first generation probe and dewar are designated Probe-A and the Engineering Development Dewar (EDD), respectively, and are being used in current testing. Probe-A and the EDD are both full-scale prototypes with a mature probe/dewar interface, but other aspects are of varying prototypicality.[2] For example, Probe-A supports only two gyros instead of a full complement of four, has only a partial complement of SQUIDs, and has no telescope. In the case of the EDD, there is no guard tank, the liquid helium tank volume is only 400 L instead of 2400 L, and its outside diameter (~1 m) is consequently less than half that of the flight dewar.

Probe-A and the EDD are being used in a series of rehearsals and tests known collectively as the First Integrated System Tests (FIST). FIST-A, -B, which consisted of a warm probe/dewar integration followed by the cool down of the integrated system, was completed in 1990 and successfully demonstrated the operation of almost all of the key

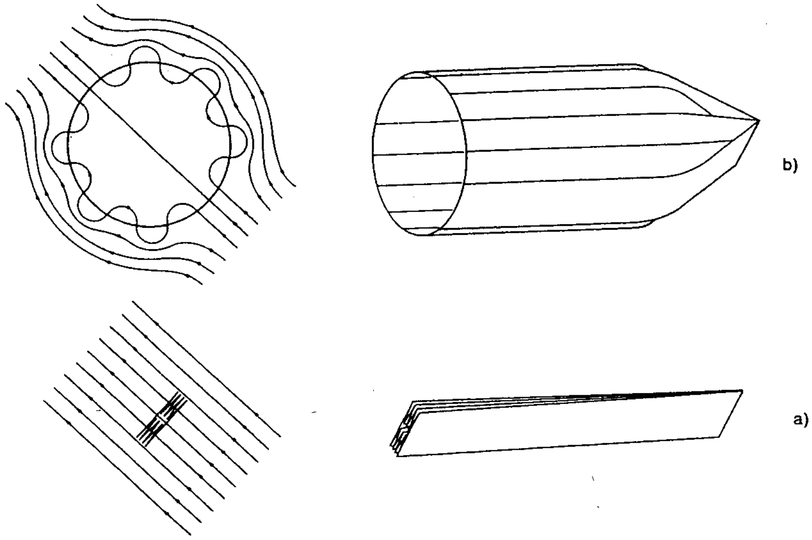

Figure 2. Lead foil shield and magnetic field, (a) prior to expansion and (b) after expansion.

features of the system with the major exception of the ultralow field aspects.[11] We are currently involved in FIST-C, which has the primary objective of demonstrating the ultralow field aspects of the system. As part of the FIST-C activities, we have verified the probe/dewar integration process by successfully integrating an Integration Rehearsal Test (IRT) probe containing a Quartz Block with the cold EDD. This test took place in the presence of a rehearsal lead shield with an internal field of 0.7 nT (7 μG), and at this level the field was found to be unaffected by the probe insertion process. Subsequent to this demonstration, we have proceeded with the process of establishing a flight-quality lead shield for use with Probe-A.

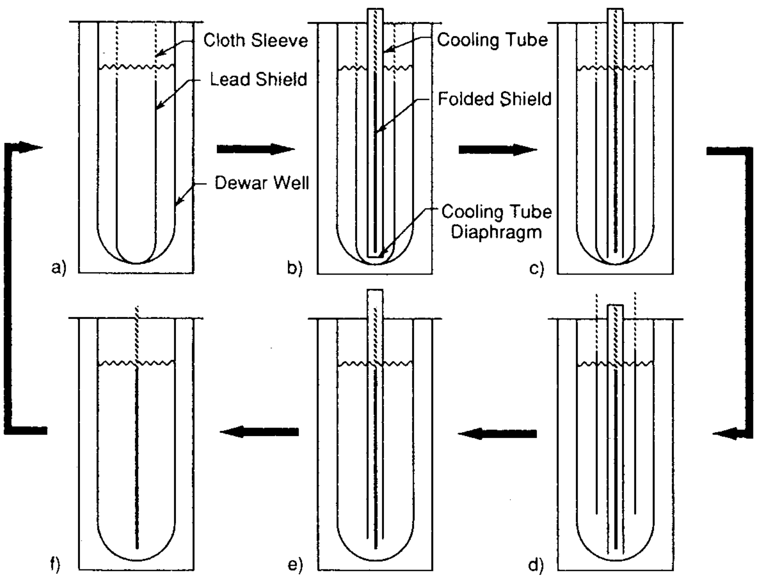

Figure 3. Lead Shield (LS) field reduction technique: a) previous LS positioned in dewar well; b) next LS enclosed in cooling tube under controlled helium atmosphere and installed inside the previous LS; c) cooling tube diaphragm cut out; d) removal of previous LS; e) removal of cooling tube; f) LS ready for expanding; a) LS expanded.

BASIC TECHNIQUES TO ATTAIN ULTRA LOW MAGNETIC FIELDS

Basic Shield Principles

The general techniques described here were first developed by B. Cabrera at Stanford University.[9] These techniques have been scaled up for use in GP-B, and a number of refinements and additions have been made in equipment and procedures.

The reduction of magnetic field by expanding superconducting lead shields is represented in Fig. 2. The tightly folded lead foil is slowly cooled to its superconducting state in the ambient field, ideally trapping only the flux penetrating the shield when it is cooled. In Fig. 3b the shield has been expanded, increasing the shield enclosed volume many-fold. The field reduction resulting from this operation can exceed 100:1. Iteration of this method using a sealed cooling tube is depicted schematically in Fig. 3. The procedure could ideally be repeated as many times as necessary to attain the desired field level, but there is a limit to this technique due thermoelectric currents generated by the thermal gradient coupled with residual anisotropy in the Pb foil. For this reason, the practical minimum field level is somewhat above 1 pT (10 nG).[9]

Materials Selection and Handling

It should be noted that even though the superconducting magnetic shield can provide an ultralow ambient magnetic environment, there is no guarantee that a sensitive experiment placed in that environment will be exposed to a field as low as the ambient. One reason is that materials used to construct an apparatus may have a significant level of ferromagnetic contamination despite the use of nominally nonmagnetic materials. At this level the problem often involves the concentration and distribution of (possibly unintended) magnetic species which are mostly uncontrolled in manufacture. Under these circumstances, considerable vigilance is required since significant sample-to-sample variations can occur. Contamination of parts can also occur anywhere in the fabrication and integration cycle due to the prevalence of tools made from magnetic materials. In addition to ferromagnetism,, magnetic fields can be generated by thermoelectric currents in normal metals subjected to thermal gradients.[9]

To combat these problems, the GP-B program has instituted a magnetic control plan which consists of: 1) a zone system to establish maximum allowable magnetic moments for parts in various regions of the probe and dewar, 2) a magnetic screening plan which details the screening procedure to be used for parts in the various zones, 3) sets of specifications to be included on all drawings to detail proper fabrication and handling procedures, and 4) control over the selection of materials.[12] This plan was originally instituted for Probe-A and the EDD but has subsequently been updated to stricter standards for Probe-B. Further modifications are likely when a new SQUID-based screening system which accepts whole gyro assemblies becomes available.

MAGNETIC SHIELD OPERATIONS

The principal operations used to arrive at the final shield configuration with a verified magnetic field ~10 pT (0.1 μG) are essentially those shown in Fig. 3. Some of these steps will be described in more detail here in order to convey the general nature of the operations involved. It should be noted that in order to simplify operations and reduce heat into the dewar, all lead shields except the final one have a smaller diameter of 152 mm (6 in.).

A primary concern while performing the many insertions and removals of hardware necessary for shield installation is the prevention of air contamination of the well. Air contamination can cause probe/dewar mating surfaces to freeze together or to have unacceptable mechanical and/or thermal properties. To prevent this, several pieces of dewar

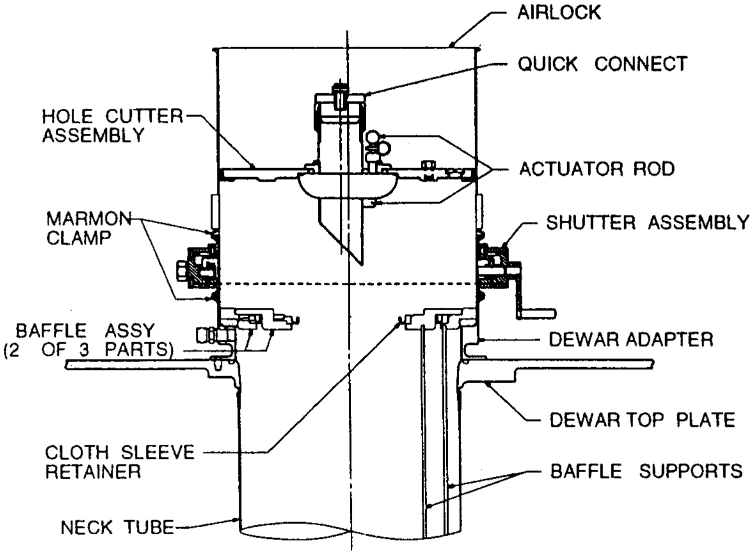

Figure 4. Lead shield hole cutter assembly in process of being installed through airlock and shutter into the dewar adapter. Dashed line represents the plane of the Mylar shutter film.

support equipment have been built. These include a 0.7 x 0.6 x 2 m glove box, 0.38 m diameter airlock cylinders, and a 100 mm high sliding Mylar shutter mechanism.

The shield is made of 63 μm lead foil ($Pb_{99.8}Sn_{0.2}$) tightly folded in accordion fashion to a width of 28 mm. The expanded length of the 10-in. shield is 1.7 m, and it has a mass of 1.1 kg. One (or two) longitudinal seams are torch welded to complete the 6-in (or 10-in) diameter cylinder. The bottom is also closed off by welding.[13] The open top of the lead

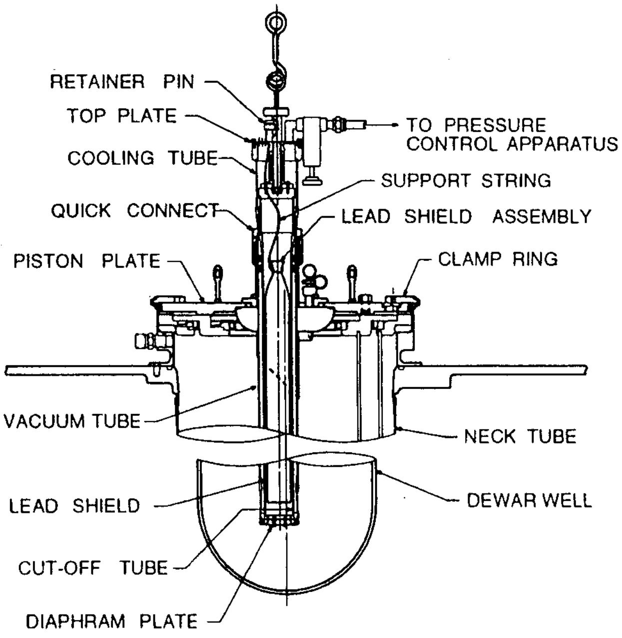

Figure 5. Cooling tube and lead shield fully installed through hole cutter assembly into the dewar.

shield is attached to a cylindrical cloth sleeve with dots of GE 7031 varnish. Grommets, set into the top of the cloth sleeve, serve as the support points for all lead shield handling operations.

The first operation of the sequence is the installation of the lead shield into the cooling tube assembly. This assembly (Fig. 5) has two concentric Pyrex tubes; the outer tube, the vacuum tube, isolates the shield from the helium bath. The inner tube is a cut-off tube which can be lowered to pierce and cut through a 25 μm thick aluminum diaphragm located at the bottom of the vacuum tube. The latter operation allows lead shield egress out of the cooling tube after the controlled cool down is completed. The lead shield cloth sleeve is supported by a string tied to a retainer pin that penetrates the top plate of the cooling tube. Another string ties to the diaphragm flange for later retrieval. After the lead shield is installed the cooling tube is vacuum leak checked and backfilled with 0.3 kPa (2 torr) of helium.

In preparation for the installing of the cooling tube, the center baffles are removed to give a clear 6-in bore through the neck tube area. The hole cutter is assembled into the airlock as shown in Fig. 4, and the airlock is purged with helium until an O_2 monitor indicates less than 1%. The shutter is then opened and the hole cutter assembly is mated to the dewar. The cooling tube can then be slowly lowered through a 2-in. diameter sliding seal in the hole cutter assembly to reach the configuration shown in Fig. 5.

The next operation is the controlled slow cooling of the lead shield through the superconducting transition temperature (~7.25 K for the lead alloy employed). The temperature of the lead shield is determined by heat input from the cloth sleeve balanced by the cooling via gas conduction to the 4.2 K wall of the cooling tube. In hard vacuum the lead shield rises to about 15 K and, with a gas pressure of about 0.3 kPa (2 torr), cools to 4.2 K. Temperature control is effected by regulating the helium pressure at the top of the cooling tube. This is accomplished via a closed loop controller which uses the temperature output of a germanium thermometer, mounted on the lead shield, to drive a piezoelectric valve which meters helium into a turbo vacuum pump that continually pumps the cooling tube. The helium partial pressure is monitored with a helium mass spectrometer. A cooling rate of 0.2 K/hr is used, which, combined with a top-to-bottom temperature difference of 1 K, results in the cooling of the whole lead shield to a superconducting state in five hours. This slow cooldown is important as it minimizes the generation of thermoelectric currents and the consequent trapping of the flux generated by these currents in the shield. After the shield is safely cooled, the cooling tube diaphragm is partially punctured and a pressure equalization line is installed between the top of the cooling tube and the dewar well.

The removal of the previous lead shield is accomplished inside a helium-purged glove box as shown in Fig. 6. The actuator rod is lowered to position the hole cutter blade at the bottom of the cooling tube and just above the bottom of the previous lead shield. The cooling tube is supported from a guy wire anchored at the glove box cover plate, and the piston plate is removed. The previous shield is raised up with the cloth sleeve retainer ring, puncturing a hole in the shield bottom end. The cloth shield and lead are pulled up, compressed into the region above the cooling tube, a temporary split support plate is installed to support the cooling tube, the guy wire loosened and the old shield removed. The piston plate is then reinstalled and the glove box is removed. The hole cutter blade is retracted to its up position.

The cooling tube configuration is now the same as following the insertion except for the absence of the previous shield. The cooling tube is then removed as follows: 1) the inner cut-off tube is fully lowered to completely sever the diaphragm, 2) the retainer pin is secured to a fixed string anchored to the ceiling, 3) the instrumentation wires are cut, 4) the cooling tube is raised out of the dewar, 5) the two support strings are cut from the retainer pin and secured. The new unexpanded lead shield is now hanging by itself in the dewar well. The glove box is now installed and: 6) the support strings are secured outside the glove box, 7) the hole cutter assembly is lifted up and several cloth sleeve grommets are hooked to the shield support ring, 8) the diaphragm is recovered with the diaphragm string, 9) the hole

Table 1. Lead Shield Magnetic Field Measurements Results

Date	Shield	Field Value (10^{-10} T, μG)	Direction
11/19/92	Trial 10-in	7.2	Axial
12/15/92	Trial 10-in, post IRT probe	7.2	Axial
1/28/93	# 1, 6-in	Not measured	--
2/25/93	# 2, 6-in	1 .0	Transverse
3/14/93	#3, 6-in	0.32	Transverse
4/13/93	#4, 10-in	0.10	Transverse
4/14/93	"	0.07	Transverse
4/29/93	10-in w/ retainer	7.2	Axial
5/4/93	10-in w/o retainer	0.35	~Axial
5/13/93	10-in w/ retainer	7.2	Axial

cutter assembly is stowed on the glove box floor, 10) the remaining cloth sleeve grommets are hooked, 11) the shutter with cover plate is installed on the dewar adapter, and 12) the glove box is removed.

The lead shield expansion is accomplished by inserting triangular and spherical shaped formers into the shield. These tools are lowered through the airlock/shutter hardware and pushed by an evacuated hollow expander pole into the shield. Purging and pressure control steps similar to those previously described are used.

A SQUID-based flip coil magnetometer[9] is lowered into the lead shield and used to measure the transverse and axial fields at two or more axial locations. If the shield installed is a 6-in shield and the field exceeds a threshold of ~0.4 nT (4 μG), a new 6-in shield is prepared for installation. However, if the field is below the threshold, a 10-in shield is prepared for installation.

The installation of a 10-in. shield is very similar to that of a 6-in. shield up through the measurement of the field with the flip coil magnetometer. If the shield is satisfactory, the 10-

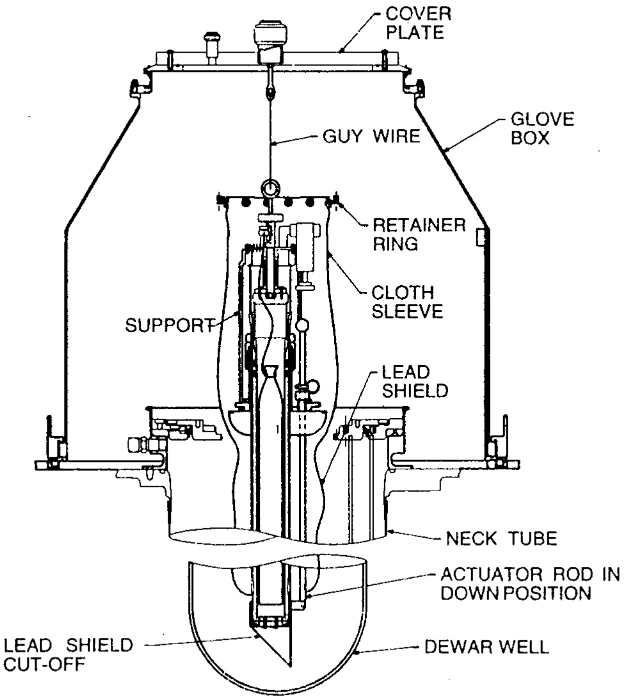

Figure 6. Removal of the previous lead shield inside of helium-purged glove box.

in spherical expander is reinserted into the shield, the cloth sleeve is removed (string pulls are used to shear the cloth from the shield), and the shield is seated into the dewar well. At 4 K, the lead foil is stiff enough to support itself without the cloth sleeve. At this point, the shield retainer is installed into the shield and the field checked with the flip coil magnetometer and with a scanning magnetometer. The latter can detect local field inhomogeneities, such as caused by holes in the lead shield. The dewar is now prepared for the insertion of the instrument probe.

RESULTS OF SHIELD PREPARATION FOR FIST-C

The recently completed lead shield operations have resulted in a magnetic field of 10 pT. The progression of the lead shield work is shown in the magnetic field measurements shown in Table 1. The trial 10-in configuration was a two-shield expansion used for the practice IRT probe insertion. The expansion sequence initiated early in 1993 culminated in the final 10-in. shield with field values which meet the GP-B requirements. However, these values were significantly degraded when the BeCu retainer device was installed. In fact, all of the measurements which show 0.72 nT are with the retainer installed. Investigation of the retainer material, using SEM and Auger microscopy, has suggested that the field contamination may be linked to randomly located 1-2 µm-sized inclusions with high (~50%) concentration of Co. Note that the final remeasurement with retainer removed shows a apparent degradation of the shield field with the field now appearing to be mostly axial. This is possibly due to an increase in the remanent field associated with the magnetometer itself, which is known to be nonzero. It should be noted that the flip coil magnetometer is capable of uniquely determining the ambient transverse field but is not able to distinguish axial ambient field from that arising in the magnetometer itself. Under typical circumstances, however, the ambient field should be transverse.[14] It is also possible that there has been a change in the field trapped in the shield, but this does not appear very likely since the critical field for lead is 0.08 T (800 G). Another remote possibility is the accidental introduction of magnetic particle(s) into the well.

CONCLUSIONS

The techniques and procedures for the installation of an ultralow magnetic field environment suitable for the GP-B gyroscope instrument have been developed and demonstrated. A problem in the use of BeCu hardware has been uncovered. The planned work around for the FIST-C test series is to trim off the bottom one-half of the retainer, reducing the field at the instrument to the required test levels. This is possible as the shield will exponentially attenuate any field (with a maximum decay length of $0.2716d$, where d is the diameter of the shield) arising from a localized source more than approximately one shield-diameter away in the axial direction.[14] A solution for the flight retainer will require different construction materials or improved screening.

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13. The specification of 0.2% Sn in the lead foil keeps the surface of the foil largely oxide free. This allows the welds to be carried out without the use of a flux which would contaminate the shield and act as an adhesive between layers of foil.
14. Both the trapped field and the fringing field from the open top of the shield should be transverse. The former because the shield expansion is transverse in direction, and the latter because the external axial field has a shorter decay length than the tranverse component. See B. Cabrera, Ph.D Thesis, Stanford University (1974).