SDC-90-00062

SDC
SOLENOIDAL DETECTOR NOTES

A SUPERCONDUCTING TOROIDAL MAGNET FOR THE ARGONNE NATIONAL LABORATORY SUPERCONDUCTING SUPER COLLIDER DETECTOR

Advanced Cryo Magnetics, Inc., San Diego

May 22, 1990

A SUPERCONDUCTING TOROIDAL MAGNET

for the

ARGONNE NATIONAL LABORATORY

SUPERCONDUCTING SUPER COLLIDER

DETECTOR

prepared by

ADVANCED CRYO MAGNETICS INC.

P.O. Box 910132
San Diego, CA 92191-0132

FINAL REPORT

MAY 22, 1990

A SUPERCONDUCTING TOROIDAL MAGNET for the ARGONNE NATIONAL LABORATORY SUPERCONDUCTING SUPER COLLIDER DETECTOR

SUMMARY

Advanced Cryo Magnetics Inc. has completed a conceptual design and preliminary cost estimate for the toroidal magnets required for the Solenoidal SSC Detector. The objectives of the design were to fulfill the physics requirements, minimize the cost, and keep the fabrication as simple as possible. In addition new technology requiring extensive development was avoided.

The magnets are designed to be wound with aluminum stabilized NbTi conductor that is bath cooled. By operating at a modest current density, and with the conductor fully exposed to the liquid helium, bath cooling provides complete stability and excellent reliability. A quench can occur in this type of magnet only if the liquid helium level is allowed to drastically decrease, and even for this unlikely event, the venting arrangement is such as to make the quench harmless. This is the design criteria used on the large bubble chamber magnets that have been so successful.

Both the vacuum vessel and the helium vessel are fabricated from aluminum to minimize the interference with the high energy particles. The magnetic pressure on the 2 flat ends is supported by carbon fiber loops that tie the ends together. All the stressed members, including the carbon fiber loops, operate at low stress relative to the material strength, further increasing the system reliability. The magnet has a complicated topography and considerable effort was devoted to developing an assembly procedure that did not require elaborate winding machines, fixtures, or precise machining, all of which can have a large impact on the cost.

This conceptual design meets all the physics requirements and is economical to build. Utilizing fully stabilized conductor, the operation of the coil to full field is assured. The overall reliability is further enhanced by the low stress levels of the force support systems of the coil.

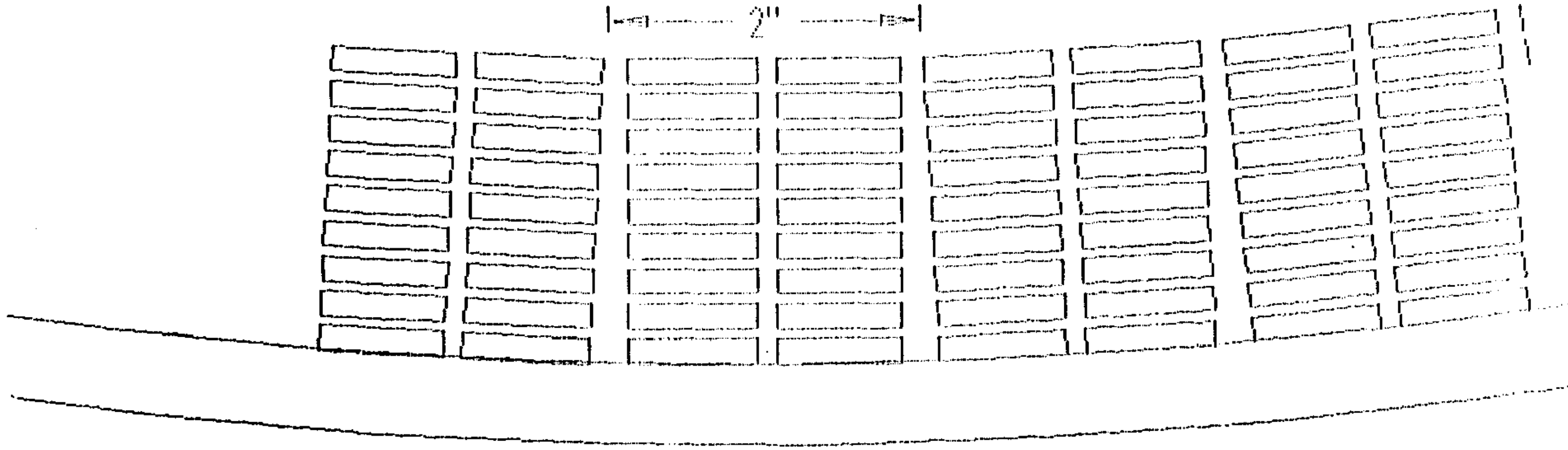
INTRODUCTION

A conceptual design of the toroidal magnet for the solenoid detector for the SSC is presented. The major physics parameters are the thickness of the aluminum end plates and the magnetic field X the particle path length. This design provides a field X length of 10 tesla-meters and the total end plate thickness is 12.5 cm of 6061 aluminum at the small diameter and 6 cm at the large diameter. The design is simple and will give excellent reliability. Due to the difficult geometry, considerable effort was spent on an assembly procedure to assure the magnet could be built. A parameter list for the design is presented on page 4 of this report.

CONDUCTOR

After considering the various methods of stabilization, a simple bath cooled concept was chosen. Indirectly cooled conductors are not at all suitable for this magnet because a large amount of conductor motion is unavoidable. Indirect cooling cannot provide the necessary stabilization for large conductor motion. Force cooled conductor could probably be made to work in this magnet but it is much more expensive and may require costly development. Also the reliability of force cooled magnets is more dependant on a continuous source of refrigeration than bath cooled. Bath cooled magnets can easily tolerate an interruption in liquid supply as long as the level in the magnet helium vessel is maintained.

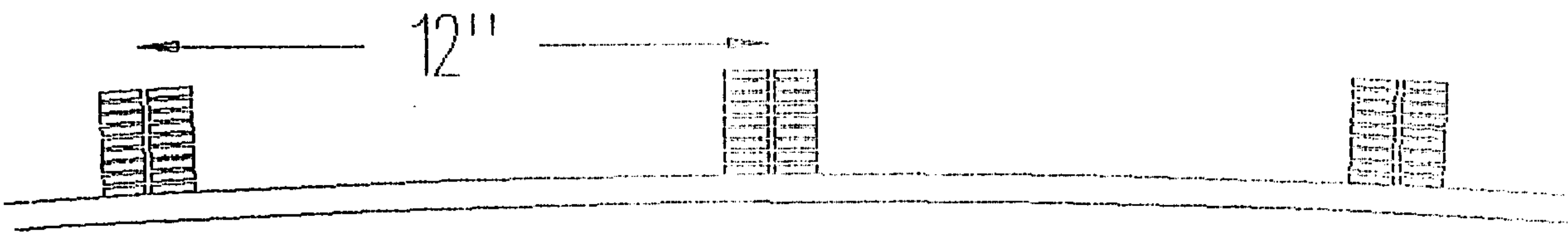
Monolithic aluminum stabilized NbTi, such as has been used in the "thin" solenoid detectors, is the chosen conductor. The aluminum minimizes the interaction with the high energy particles and provides low electrical resistance for good stabilization. The conductor is wound on a former that will become the inner wall of the helium vessel. The total winding consists of 120 bundles of conductor, with 18 turns in each bundle, as shown in Fig. 1 and 2. As the magnet is energized the conductor will be forced against the outer wall of the helium vessel. This will result in a considerable inelastic motion which means that the conductor must be very stable. An additional requirement on the conductor is that it can tolerate a small radius bend, less than 1/2 inch, at the corners of the magnet. This is an important cost feature because shaping a radius of even 1 inch at the corners of the structure is an expensive forming job. The bath cooled monolithic aluminum stabilized conductor, with good helium ventilation, meets all the conductor requirements very nicely.



CONDUCTOR LAYOUT AT THE MINIMUM DIAMETER
EACH CONDUCTOR BUNDLE TAKES A SPACE 2"X2"
AND CARRIES 120,000 AMPS

ANL DETECTOR

Fig. 1



CONDUCTOR BUNDLE SPACING
AT THE MAXIMUM DIAMETER

ANL DETECTOR

Fig. 2

Stability

The monolithic, aluminum-stabilized conductor is 2 X 0.39 cm and operates at 7,000 amperes. It is a fairly common conductor and the one chosen is listed in literature from Hitachi. High purity aluminum, with some degree of work hardening, has a resistance ratio of about 400 to 1 at the operating field. This gives a resistivity of 6×10^{-9} ohm-cm which results in a resistance of 7.7×10^{-9} ohm per cm length. A current of 7,000 amperes in the normal conductor produces 0.377 watts of heating per cm length; with 50% of the surface exposed to the liquid helium, the required heat transfer is 0.188 watts/square cm. With such a low heat transfer rate the conductor is completely stable. It is imperative that the conductor in this magnet be very stable because as the magnet is charged, the conductor will move to transfer the magnetic load to the outside wall of the helium vessel and thus to the support structure.

The coil will be well ventilated with a large volume of liquid available to absorb any energy release due to conductor motion. Turn-to-turn insulation will consist of a 1/16 inch thick strip of linen-filled phenolic with slots machined in the surface to provide good conductor support and expose 50% of the aluminum surface to the liquid helium. Thicker phenolic will be packed around the conductor bundle to space it well away from the metal trays that hold it in position. The spacers will provide electrical insulation and still allow good helium circulation.

Quench Considerations

The total stored energy of 130 megajoules in the coil is enough to warm about 10% of the conductor to room temperature. Helium vessel vent size and position need to be designed to ensure that during a quench the liquid level is lowered enough to expose at least 10% of the conductor. The normal region will then propagate throughout the exposed conductor volume and distribute the energy, resulting in a safe temperature rise for the hot spot. This was the technique used to protect the FNAL 15 foot bubble chamber magnet and it survived a quench with no damage. The FNAL magnet had considerable more stored energy, about 400 megajoules.

It was beyond the scope of this study to design a vent system that would provide complete safety in the event of a quench, however, it is not a difficult task and will be part of the final design.

A SUPERCONDUCTING TOROIDAL MAGNET
for the
ARGONNE NATIONAL LABORATORY
SUPERCONDUCTING SUPER COLLIDER DETECTOR

PARAMETER LIST

1.	Minimum radius	1 meter
2.	Maximum radius	5.95 meter
3.	Length	3.3 meter
4.	Peak field	3 tesla
5.	Self field of 2" X 2" conductor bundle	1 tesla
6.	End plate thickness at I.D., total	12.5 cm
7.	End plate thickness at O.D., total	6 cm
8.	Torus internal volume, carbon	1/8 %
9.	Stored energy	130 MJ
10.	Operating current	7,000 amps
11.	Conductor	Al stabilized NbTi
12.	Conductor size	0.39 X 2 cm
13.	Current density	9,000 A/cm^2
14.	Type of stabilization	Bath cooled
15.	Ampere turns	15 X 10^6
16.	Conductor length (@ 7,000 amps)	32,000 meters
17.	Conductor weight	16,500 lbs.
18.	Cold weight including conductor	98,000 lbs.
19.	Warm weight	28,000 lbs.
20.	Total weight	130,000 lbs.
21.	Liquid helium volume	15,000 liters

STRUCTURAL DESIGN

The basic structure shown in Fig. 3 consists of a double skinned torus 12 meters maximum diameter. Its cross section is a quadrilateral giving it flat, washer-like ends and conical inner and outer surfaces. The first surface is built in six pieces (see Fig. 4). The conductor, wound in approximately 20 bundles, each 2" square, around the minor toroidal axis of each pie-shaped piece, is fitted into a retainer channel. The six pieces are joined and the outer skin added, boxing in the conductor between the two shells (see Figs. 5 & 6). The closed core of the torus can be accessed through various ports connecting the inner and outer skins, the walls of which pass between the conductor bundles (Fig. 7). The space between the two skins is the helium vessel. The conductor bundles are immersed in liquid helium.

The inner and outer conical surfaces of this body are both supported, against the conductor forces, by thick shells. The peak magnetic pressure is over 500 psi. The flat ends are also subject to this force and are supported by radial beams running along with each conductor bundle (Fig. 8). The beam reactions are provided by ties which pass through the core of the torus from end to end via connecting ports through the helium vessel. These ties are made of carbon fiber and are pre-loaded to a small percentage of their working load.

An aluminum heat shield is built entirely around this torus at a 2" nominal distance. It is maintained at this distance by 22 struts around the outer equator attached to 11 points on the vessel outer cone and 22 points, suitably reinforced, on the heat shield. These struts are 22" long. A further set of 22 struts, identical to the first, attaches to the heat shield at the same reinforced points but on the outside of the shield, serving to connect the cold mass to 11 points on the warm vacuum vessel shell (see Fig. 9).

The vacuum vessel consists of inner and outer conical shells connected at each end by hemi-toroidal concave heads (see Fig. 10). The considerable tension in these heads is reacted by compression rings at their inner and outer edges (see Fig. 11). The outer conical shell is strengthened, in its buckling mode, by the heavy ring required for the gravity support.

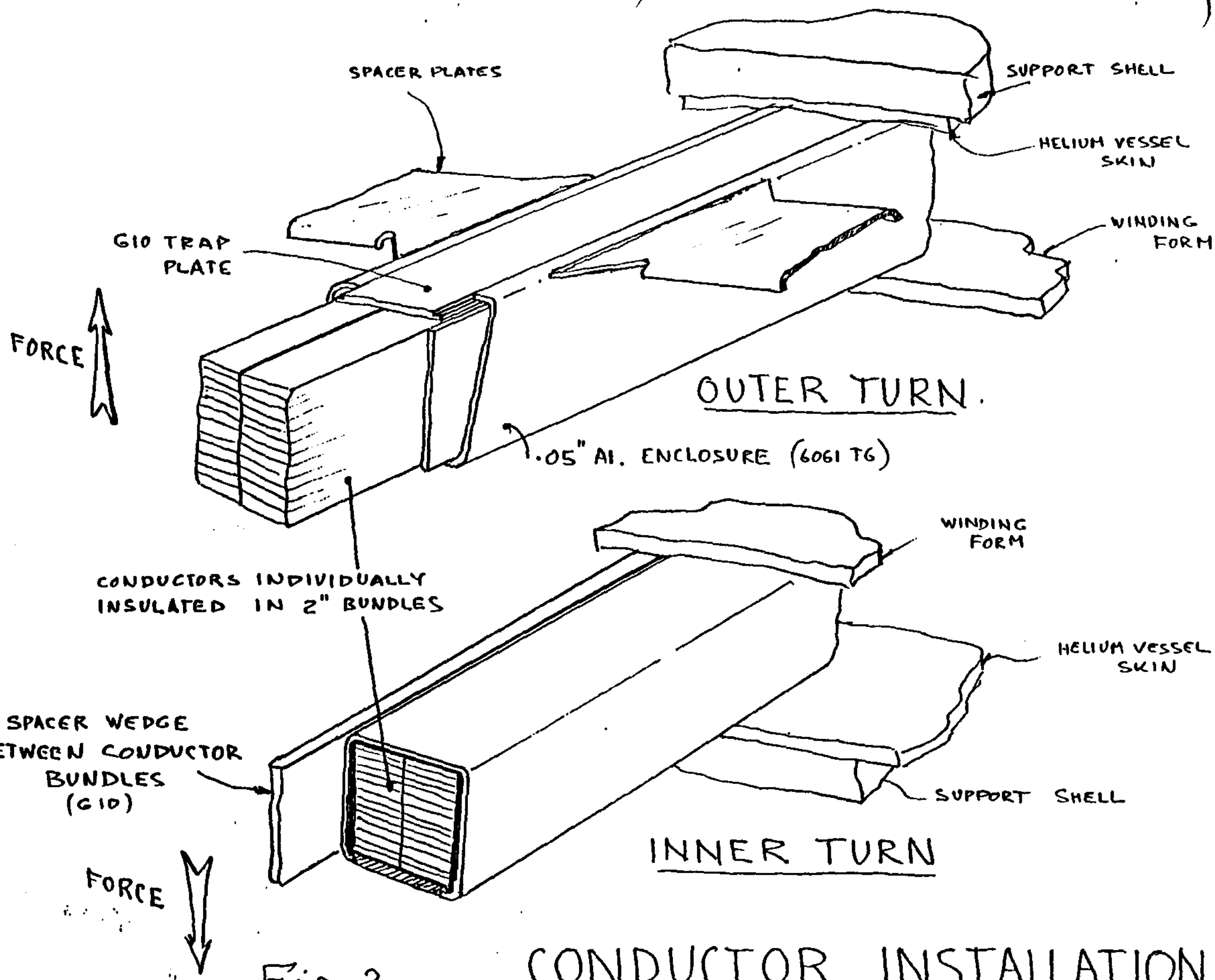
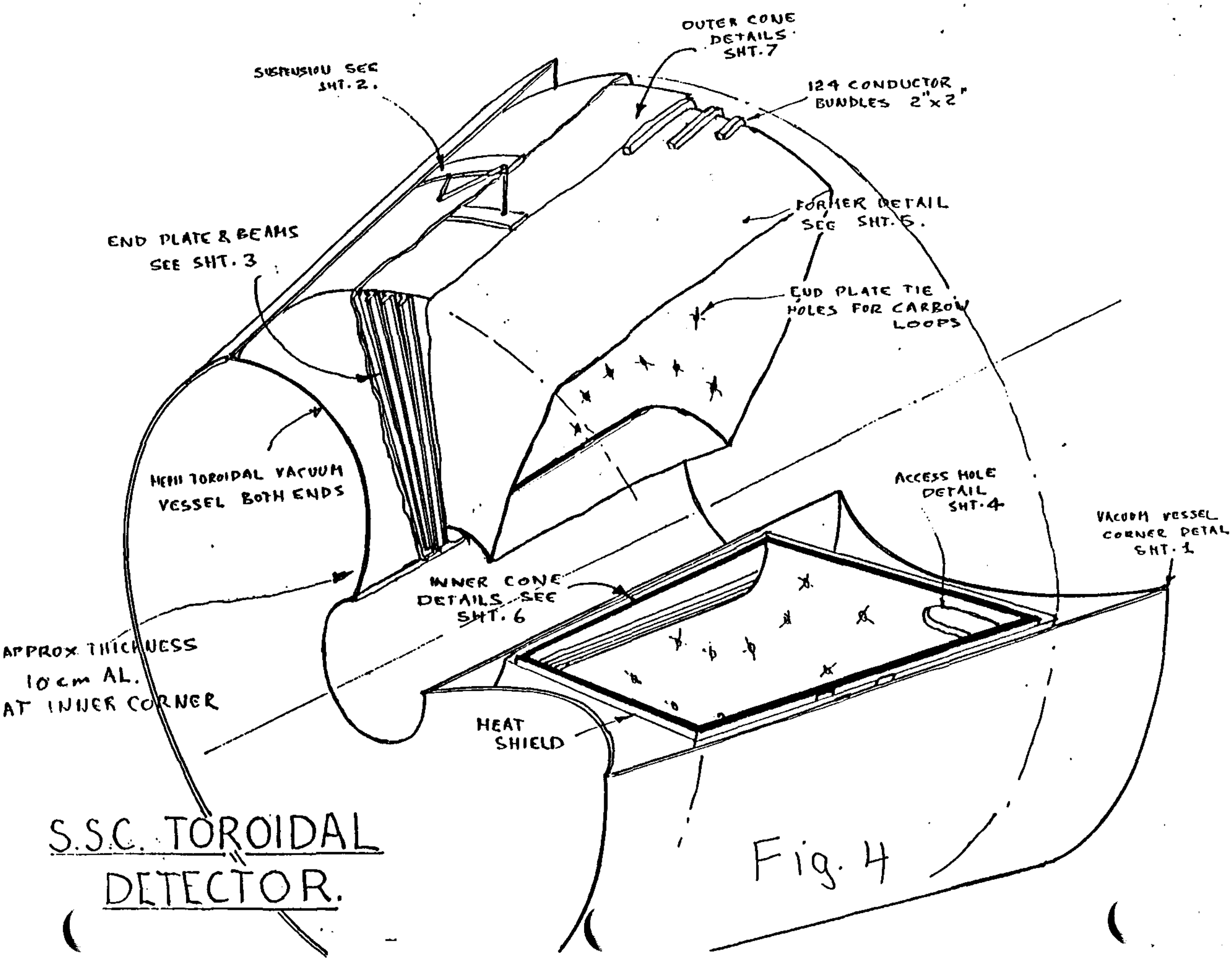


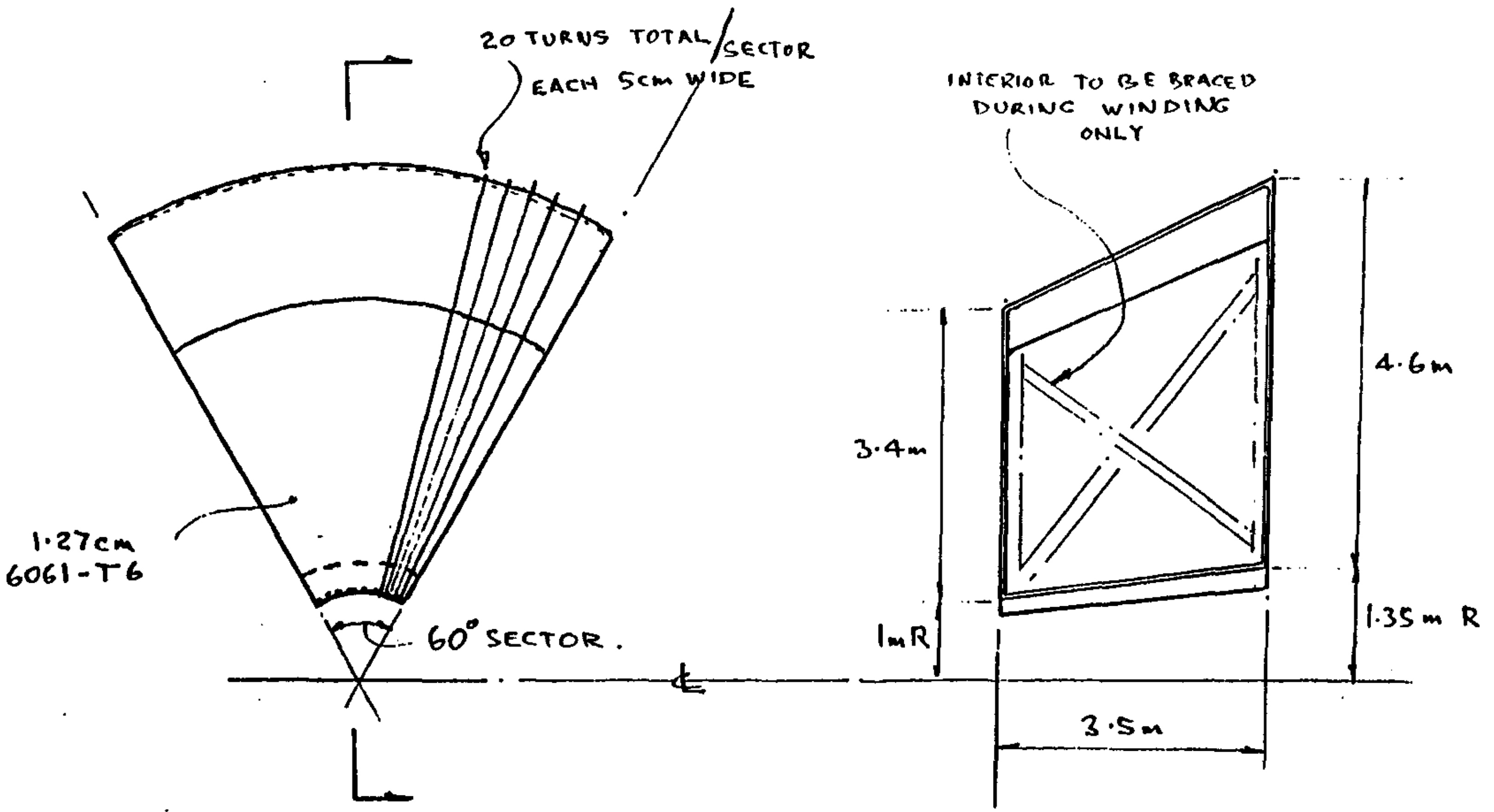
Fig. 3

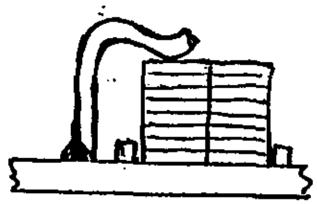
CONDUCTOR INSTALLATION



S.S.C. TOROIDAL DETECTOR.

Fig. 4





TEMPORARY CONDUCTOR
CLIP

TOROID FORMER
(6 REQ)
Fig. 5

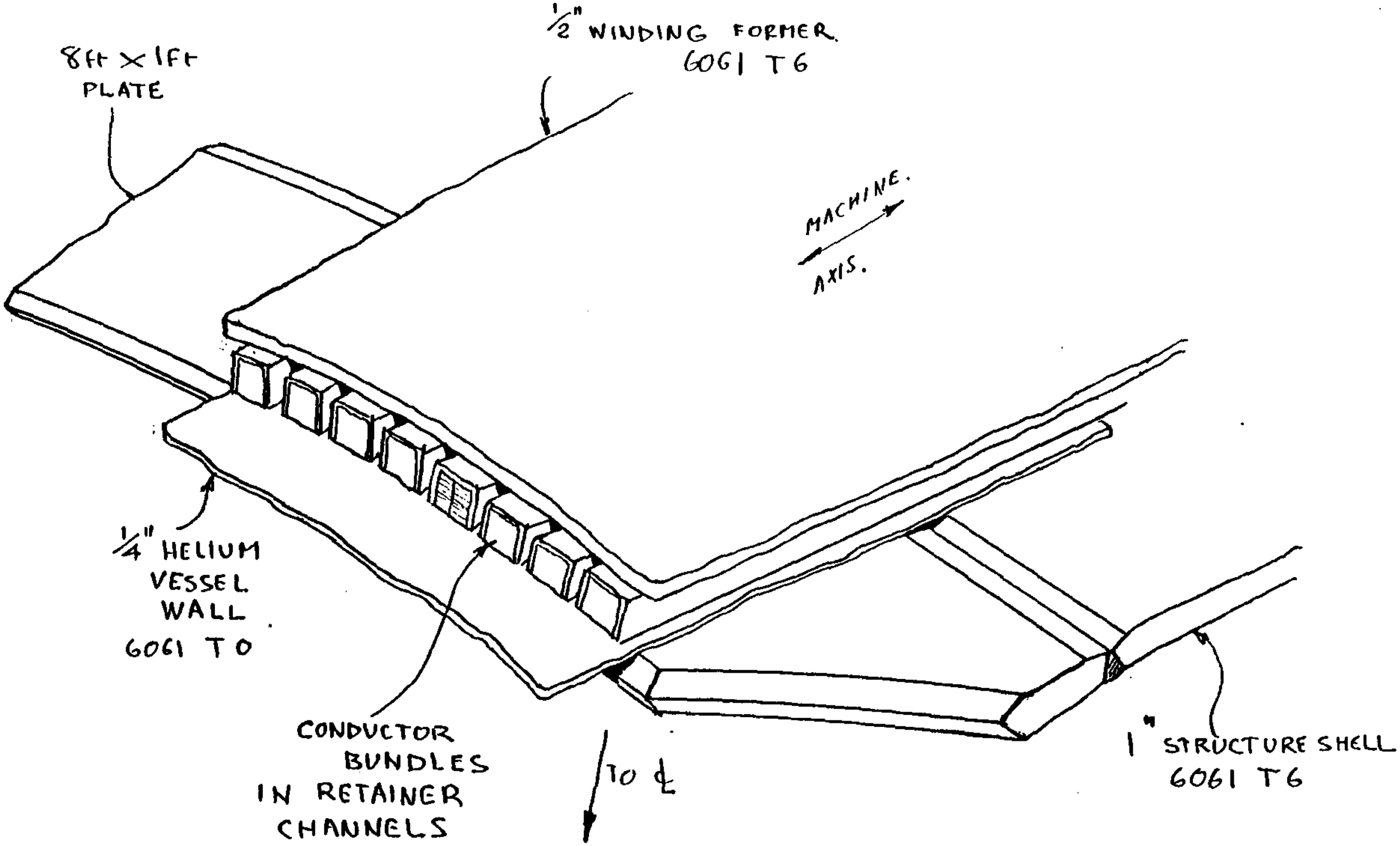
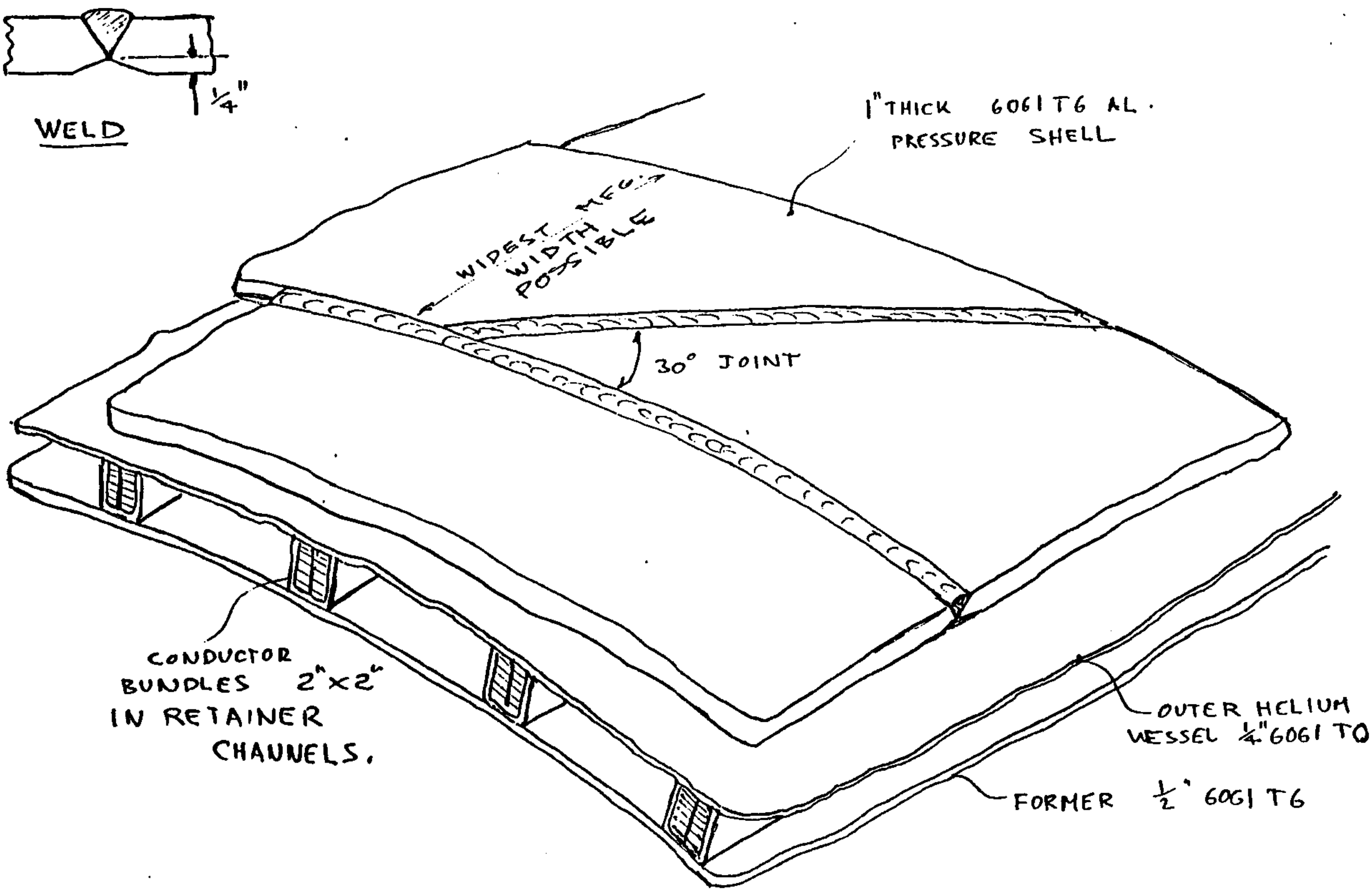


Fig. 6

INNER CONE DETAILS.



OUTER CONE DETAILS

Fig. 7

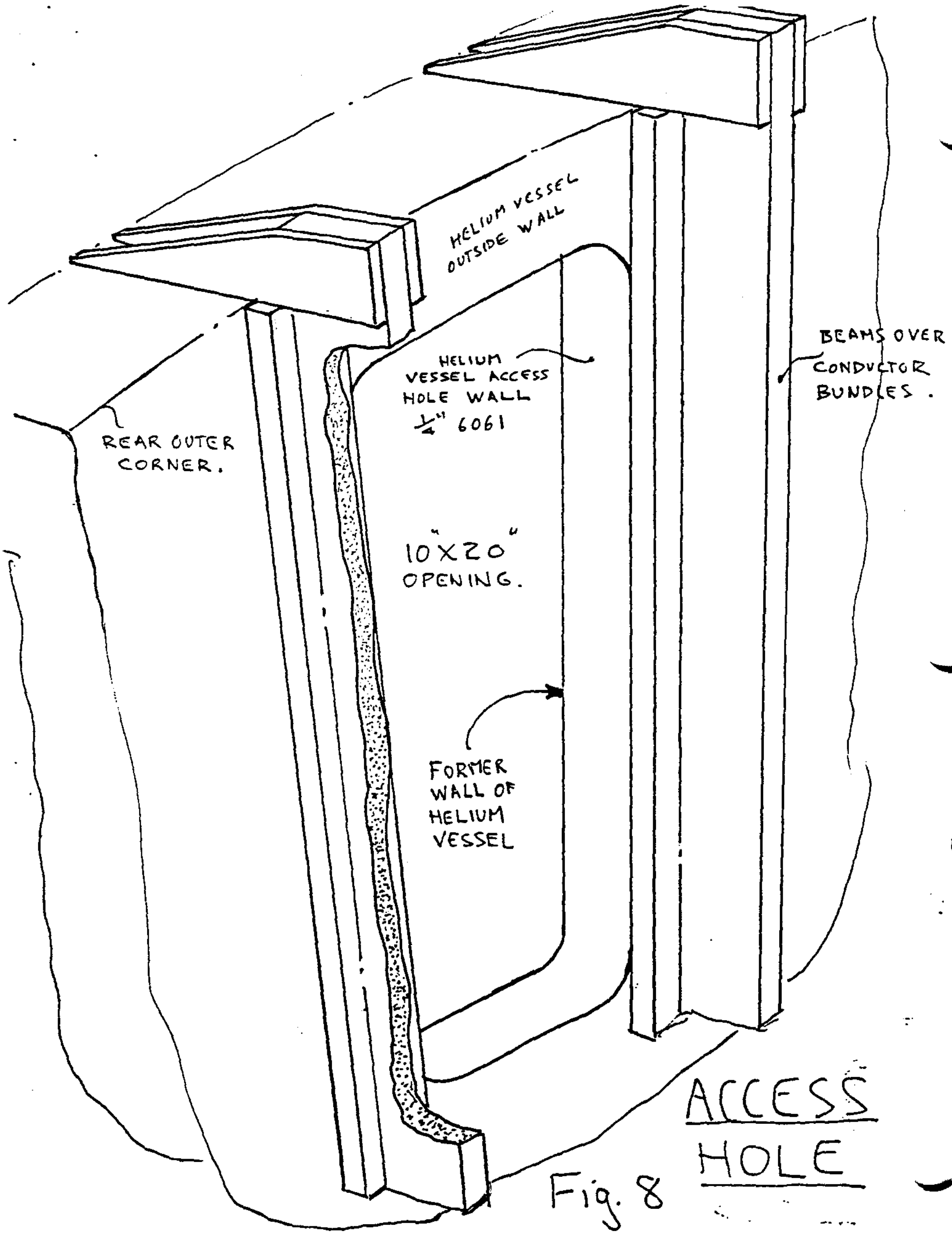

HELIUM VESSEL
OUTSIDE WALL
HELIUM
VESSEL ACCESS
HOLE WALL
1/4" 6061
BEAMS OVER
CONDUCTOR
BUNDLES.
REAR OUTER
CORNER.
10"X20"
OPENING.
FORMER
WALL OF
HELIUM
VESSEL
ACCESS
HOLE

Fig. 8

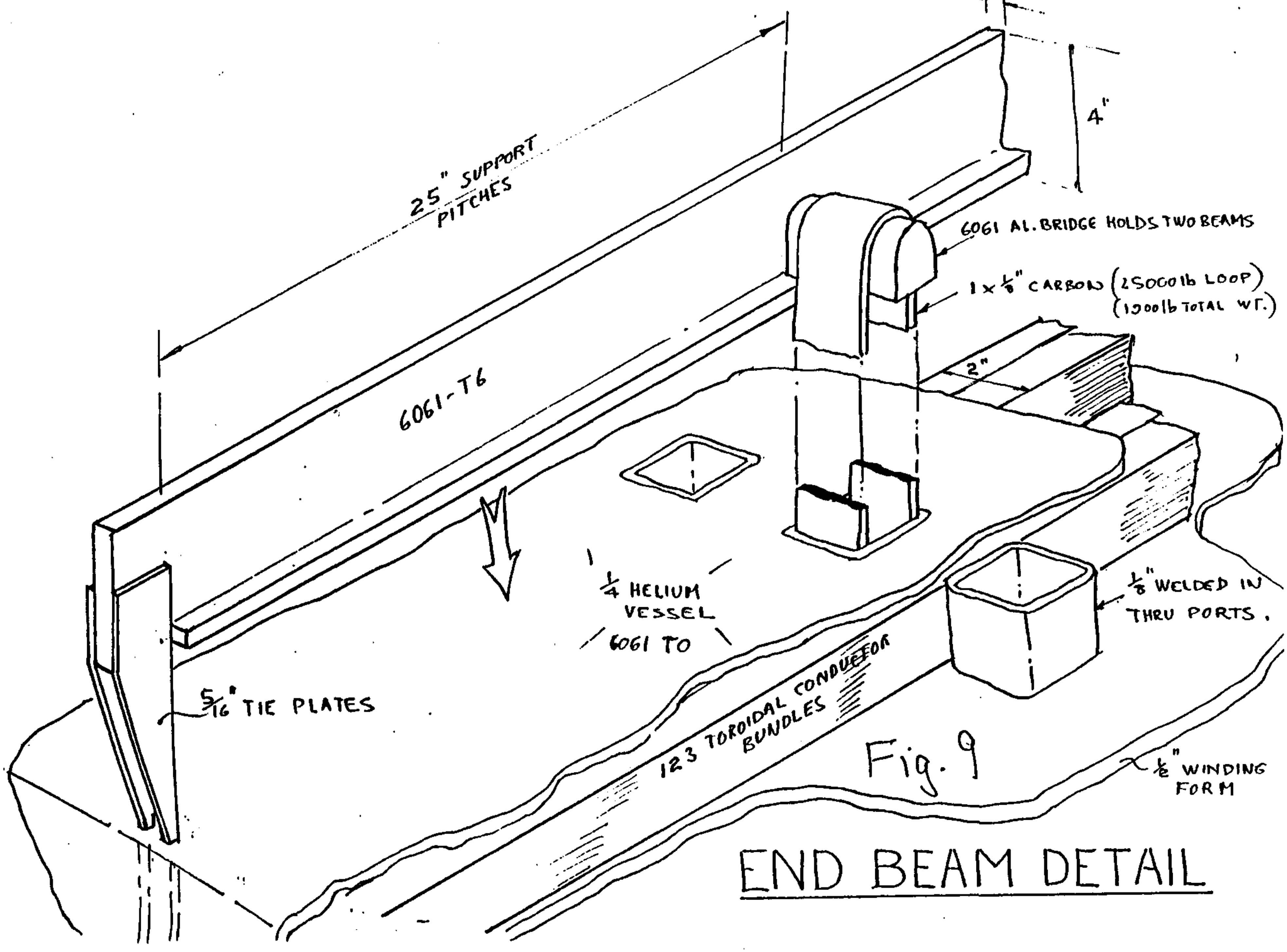
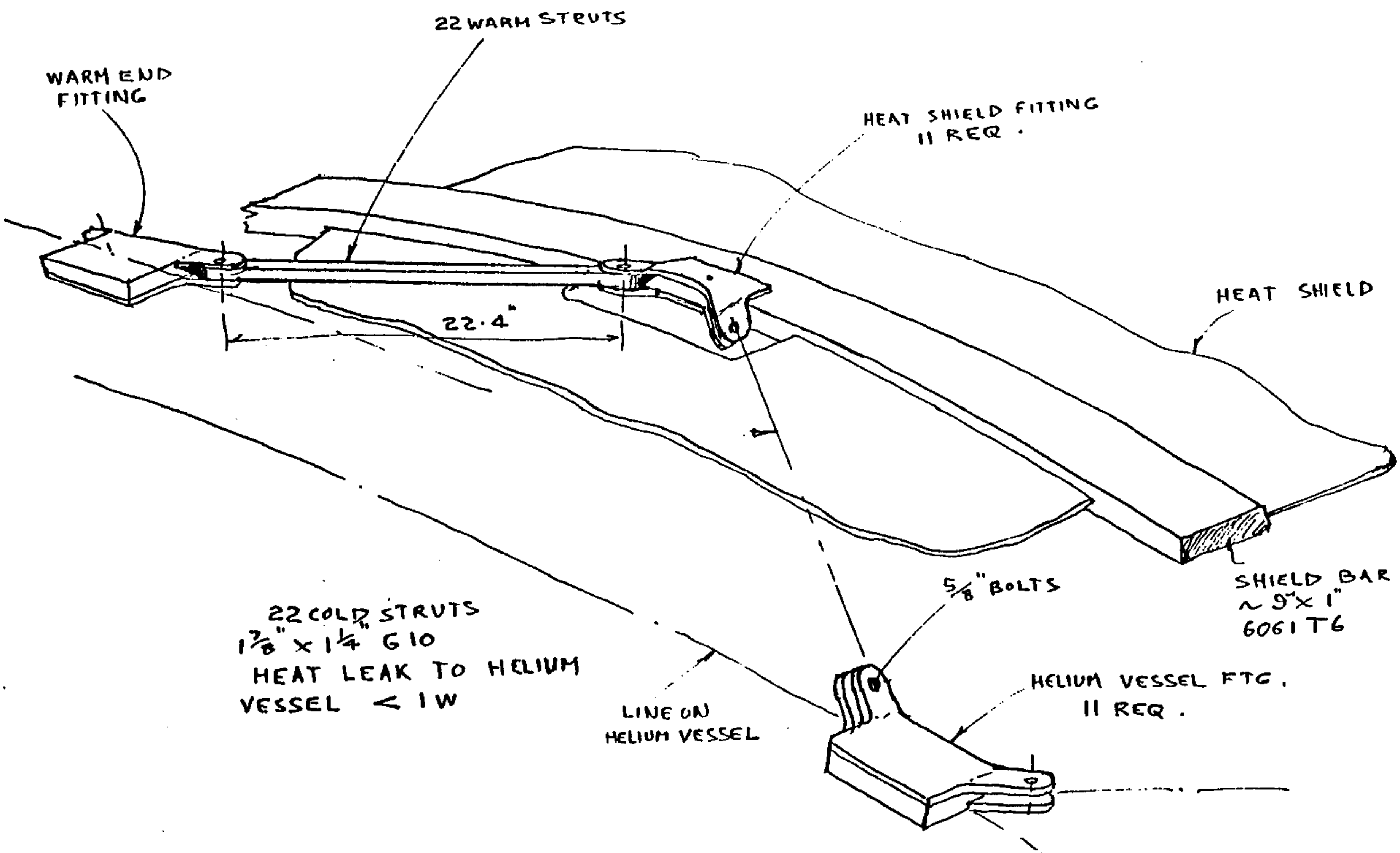


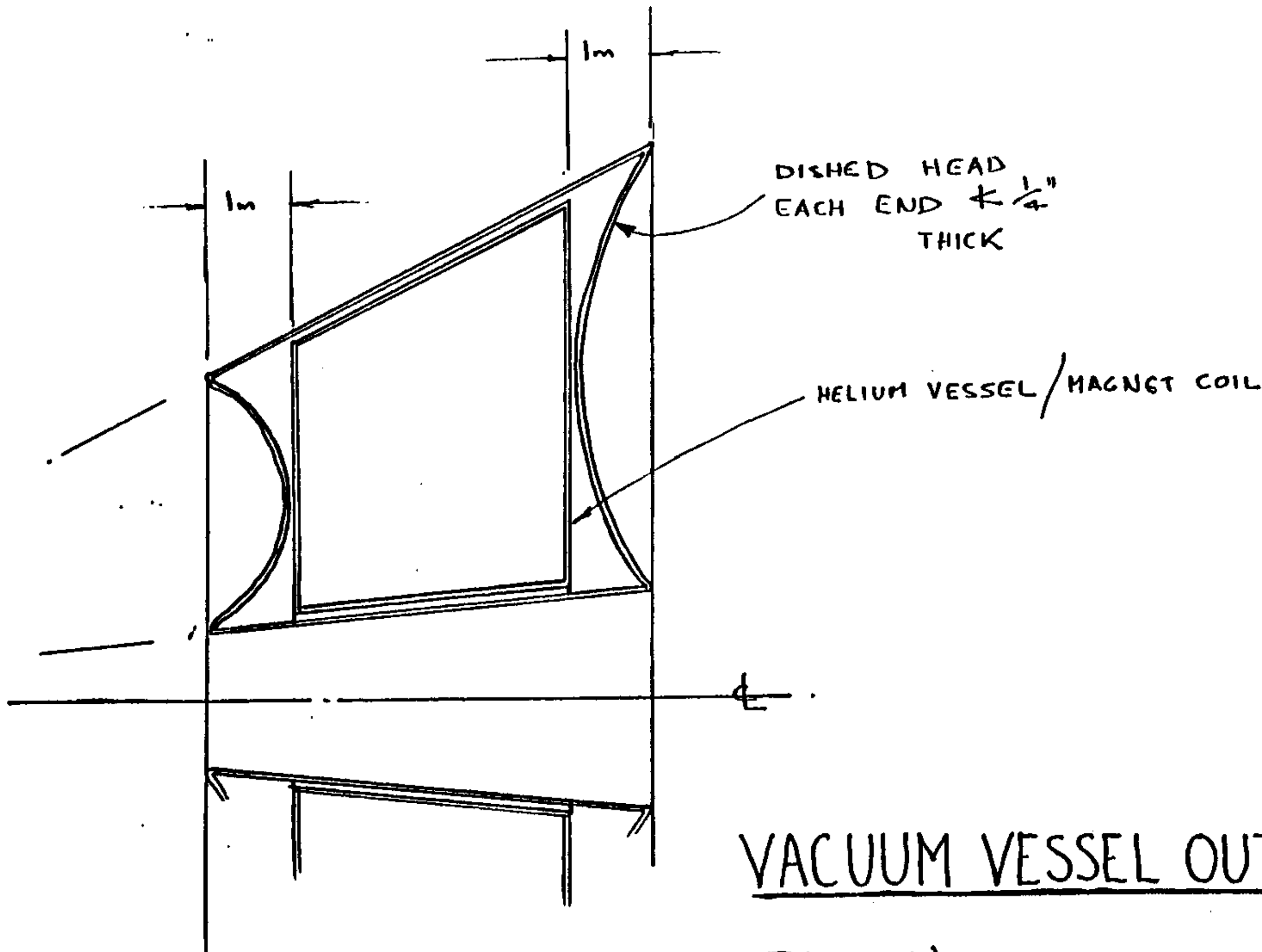
Fig. 9

END BEAM DETAIL



SUSPENSION DETAIL

Fig. 10



VACUUM VESSEL OUTLINE

Fig. 11

Except for the carbon fiber ties and the G-10 fiberglass-epoxy struts, the entire structure is 6061 T-6 aluminum. The outer helium vessel wall is T-0 temper and all the rest is T-6. The welds are arranged in noncritical directions to avoid the loss of strength associated with annealing at the weld. At this stage of the design, 0.62 times yield has been used as the design stress due to magnetic forces. This results in stresses as high as 27,500 psi for T-6 loaded only when cold and as low as 8,000 psi for material that has been annealed by welding. A factor of 3 against failure was used for general weight carrying loads, which are somewhat less predictable. It is apparent that we are not pressing the capabilities of these materials in relation to physics requirements, and, even if during detail design the loads become somewhat larger, the necessary metal thickness will be within the physics requirements.

The approximate critical physics thickness and material distributions are as follows:

inner corner each end	12.5 cm	6061 AL
outer corner each end	6 cm	6061 AL
torus internal volume	1/8% filled	Carbon

DESIGN ISSUES

An examination was made of the shape and structure types to determine which configurations would offer the least material in the regions of experimental interest. It was clear that the outer and inner cones should have a simple, structurally efficient geometry since their material content is large.

Helium Vessel

A practical problem which may arise is the achievement of a good fit between the helium vessel and the heavy conical shells which butt against its inner and outer cones. We are uncertain whether these shells can be easily fitted as "thin" cones to the helium vessel and have a sufficiently accurate matching of cone angles to support the thin helium vessel wall and the conductor behind it. A "lack of fit" of approximately 0.030" (0.75 mm.) would lead to undesirable local deflections and possible stick/slip thermal deposition at the conductor. Should further investigation show this to be a problem, then epoxy flooding of the helium vessel to load carrying shell interface appears to be feasible. Such epoxy fill crazes during cooldown, but is in confined compression of only 500 psi maximum during operation and is completely effective even after crazing.

The torus ends, however, need to be minimal and many types of structure are possible. We considered four major types of end conductor support with some subsets:

1. Simple plate support in bending from inner to outer cone, i.e. the large washer.

As with all beams in bending, this was found to be very inefficient. The average stress in the material was only 25% of the allowable working stress. The beam thickness was 28 cm. A third support cone through the middle of the torus, halving the span of the washer, was considered. This reduced the beam thickness by a factor of two but the large load had to be transferred to the beam through the helium vessel, a extremely difficult design task.

2. Honeycomb end plate - a similar setup to 1 above, but with efficient beams.

This configuration offers possible average stress levels up to 80-90% allowable, but the shears are very large and, due to temperature effects, glues cannot be trusted. Aluminum brazing would be needed. This development was felt to require substantial funding to assure reliability.

3. Balloon Ends.

The structural efficiency is very high for this configuration, approaching 100%. However, constraints on space available (only 1 m in length for a 4.6 m span) produce a large radius balloon. The wall thickness at 5 cm is entirely acceptable, but the edge rings are very large and require several hundred square inches of high performance aluminum in cross sections on a 12 m diameter circle. These were felt undesirable. In particular, local attachment of a "membrane" of 2" thickness is a very demanding task.

4. Multiple tie straps, the chosen method.

Since this configuration has the simplest conceivable load path, i.e. a straight line from applied load to reaction, it obviously has the least possible material. Geometric considerations dictate that the number of straps must be limited. We have chosen to place the tie points along the line of each conductor bundle with a pitch of 25 inches. This span of continuous beam does not call for very much material on the average, only 4.5 cm at the bore edge of the "washer" and 1/6 of that at the outer edge. The ties between front and rear washers pass through ports in the helium vessel and do not involve the vessel in the load path at all. To minimize the deflection and the material content of the ties, carbon is used at a fairly low stress. Its specific stiffness (strength divided by density) is seven times that of steel or aluminum.

Vacuum Vessel

The vacuum vessel is comparatively simple having an outer (buckling designed) shell, an inner tension shell and concave balloon ends. Due to the low pressure, these membranes are comparatively thin (< 1/2 cm) and the support rings are not excessive (Fig. 12).

Support System

The suspension of the 100,000 lb. cold mass is by means of a "Warren girder", curved and folded into cylinders between the outer 3 elements of the magnet. This was selected solely on the basis of experience and the design presented is very near final. It has the following features which make it desirable.

1. The assembly is progressive - no installation and alignment exercises are necessary, normal build techniques give excellent accuracy.

2. It is very stiff. Natural frequencies of systems of this sort have in the past been of the order of 18-20 Hz. Strap hung systems are often 3-5 Hz, right in the earthquake sensitivity frequency regions.

3. The centroid of the magnet does not move at all during cooldown.

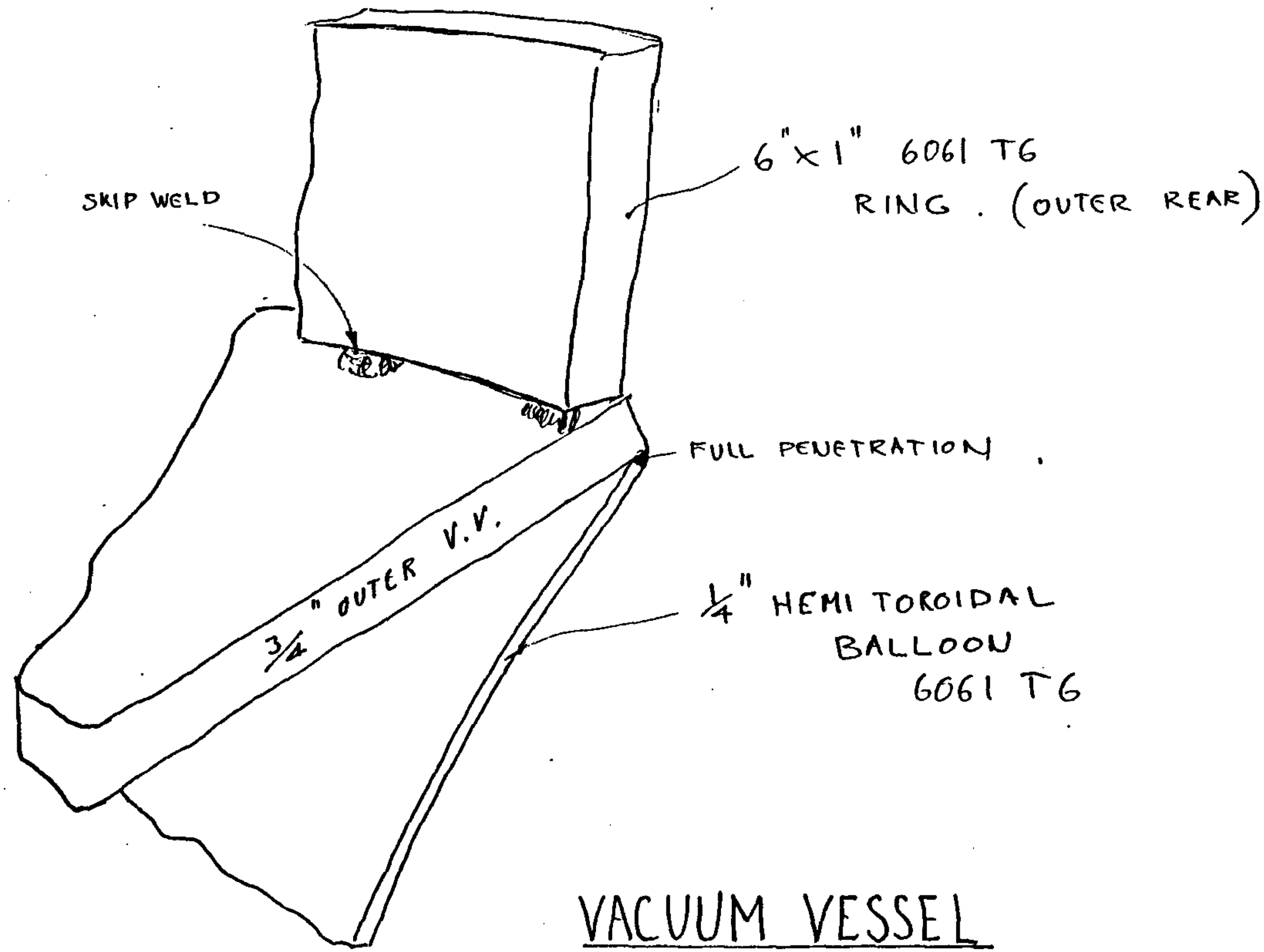
4. It is structurally redundant; its strength increases slightly if some members are driven to failure.

5. It is tolerant of cooldown shrinkage of the cold mass.

6. It is tolerant of the large operating dimensional changes in the coil.

7. It is economical in that it uses many cheap identical parts and does not break up the main structural element continuity.

8. Its heat leak in our design is presently less than 1 W from the 80 K shield to the helium vessel.



VACUUM VESSEL
TYPICAL CORNER
Fig. 12

9. By dividing the outer vacuum shell into 2 separate pieces, the necessary thickness for buckling resistance is reduced, saving about 13,500 lb. of aluminum against the single unbraced shell.

The only competitive suspension we considered was a similar Warren girder installed at the small end of the magnet. We thought that the loss of shell stabilizing and the magnet translation along axis during cooldown was not justified by the few tenths of a watt potential heat leak savings.

COST SCALING

Over small changes in size and field the cost will scale almost directly as the surface area of the assembly and directly as the field, i.e. total ampere turns of conductor. The cost of the conductor per foot will not vary much with changes in field because the size is determined by stability considerations and the amount of NbTi will only change slightly over the field of interest. Stored energy is probably not a good scaling parameter for this magnet.

ASSEMBLY PROCEDURE

Due to the complicated winding geometry the assembly sequence is critical to maintaining low cost. The following procedure is one solution to the problem.

1. Make 6 winding forms (1/2" Al.), including temporary internal bracing, conductor bundle guides, and port hole walls.
2. Electrically insulate winding form, wind coils, and finish electrical insulation.
3. Progressively remove temporary internal bracing.
4. Support forms on large end on cement blocks.
5. Join 6 coil forms into 1 large torus from 2 sets of 3.
6. Connect all the coils in series.
7. Add outside layer of helium vessel (1/4" Al.).
8. Leak check the helium vessel both inside and outside.
9. Install inner structure shell (1" Al.).
10. Install outer hoop load bearing shell (1" Al.).
11. Tack weld end beams.
12. Install carbon loops.
13. Fasten inner support struts to outer shell of helium vessel.
14. Change support position from end to inner bore temporary lugs.
15. Assemble outer and end thermal shields.
16. Fasten outer support struts to thermal shield.
17. Install superinsulation on shield.
18. Finish vacuum vessel outer cone and ends.
19. Change support from inner surface to outer cone.
20. Remove temporary lugs on inner surface and complete thermal shield and super insulation.
21. Complete vacuum vessel.

FURTHER DESIGN WORK NEEDED

The design presented is only conceptual at this point and considerable work is needed to produce a final design ready for fabrication. However, the design gives enough detail to determine that the magnet is certainly feasible and that the cost of the magnet and cryostat is a small portion of the total detector. The following is a partial list of the details that must be worked out.

1. Replacement of the outer cone with a cylinder of the same maximum diameter, i.e., make the magnet a cylinder instead of a cone on the outside diameter, should be investigated. This shell is nearly half the magnet weight and would be much cheaper to fabricate as a cylinder than as a cone. The layout of the carbon support loops would be much simpler in that they would only run from one flat end to the other. In the present design, part of the loops must tie from the large flat end to the tapered outside diameter of the cone to support the overturning moment of the magnetic force on the large flat end. Only about ten percent more conductor would be needed for the cylindrical arrangement.

2. Secondary stresses, in the ASME pressure vessel code sense, should be investigated at the vessel corners to ensure the helium vessel can accept the straining of its support structure for an appropriate number of cycles. Some reinforcement of the corners is to be expected.

3. The question of the installation angle of the carbon ties must be fully investigated. Presently an attitude normal to the end faces is proposed and will work, however it may not be the best configuration.

4. Pretensioning of the carbon tie straps must be worked out in detail.

5. The cryogenic neck and all magnet services are not defined. This is expected to be very conventional.

COST ESTIMATE
FOR THE
SSC DETECTOR TOROIDAL COILS

The cost for the toroidal coils of the SSC detector were estimated by an outside consultant. The estimate was based on the conceptual design by Advanced Cryo Magnetics Inc. Labor cost is assumed to be $80.00 per hour.

The cost for one torus is shown below:

1.	Engineering		$500,000
2.	First of a kind costs		$500,000
	Prototype scale model		
	Forms and tooling		
	Manufacturing engineering		
	Shop travelers and procedures		
	Inspection procedures and hold points		
3.	Materials		
	Toroid former	$420,000	
	Helium vessel	$230,000	
	Inner/outer cone and end plates	$240,000	
	Insulation	$120,000	
	Carbon loops	$500,000	
	Miscellaneous	$330,000	
	Subtotal		$1,840,000
	Contingency, 25%		$460,000
4.	Labor		
	Vessel forming	$420,000	
	Welding	$300,000	
	Coil winding	$640,000	
	Inspection and testing	$90,000	
	Rework	$290,000	
	Subtotal		$1,740,000
	Contingency, 20%		$350,000
GRAND TOTAL, LESS CONDUCTOR			$5,390,000
5.	Conductor (IGC estimate)		$1,000,000
TOTAL			$6,390,000