Fermilab

SDC SOLENOID DESIGN NOTE #200

TITLE: 1) Isogrid vacuum shell for large superconducting solenoid
2) Finite element study of the quench behavior of a solenoid for SSC detector

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This design note consists of two papers relating to the SDC solenoid which were presented at the 1993 Cryogenic Engineering Conference, July 13 - 16, 1993.

ISOGRID VACUUM SHELL FOR LARGE SUPERCONDUCTING SOLENOID*

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ABSTRACT

An aluminum isogrid outer shell of an annular vacuum vessel for a superconducting solenoid has been designed. The shell was about 4 m in diameter and 9 m long. Isogrid was used to reduce the effective or weight average thickness of the shell. The design requirement was a calculated collapse pressure of 2 atm. If solid aluminum plate were used, the shell would be 27 mm thick; using isogrid lowered the thickness to 10.5 mm. An isogrid shell 4.12 m OD by 2.34 m long was designed, fabricated, and tested as the outer shell of the vacuum vessel for a prototype of the solenoid.

INTRODUCTION

A 2-T superconducting solenoid approximately 3.7 m in diameter by 8.3 m long is being designed by a KEK+-Fermilab team for use with the Solenoid Detector Collaboration (SDC) experiment at the SSC. The solenoid consists of a superconducting coil and outer support cylinder inside an insulating vacuum vessel. The vacuum vessel is formed by cylindrical, coaxial inner and outer shells between flat annular bulkheads. Because the calorimetry is outside the solenoid, all reaction particles must pass through the superconducting coil and vacuum vessel and therefore, the amount of material in the solenoid must be minimized in terms of radiation and absorption lengths. The design requirement for the magnet is a total thickness of 1.2 radiation lengths (X_0), or 0.25 absorption lengths, normal to the colliding beams.[1] The engineering result of this requirement is that, with the exception of the Nb-Ti/Cu superconductor, only aluminum and some composites may be used in the coil and vacuum vessel.

The thickness of the superconducting coil and outer support cylinder are determined primarily by quenching considerations and for the SDC solenoid, cannot be less than about one X_0. The outer vacuum shell, if made of solid aluminum plate, would be 27 mm or 0.30

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+ National Laboratory for High Energy Physics, Tsukuba, Ibaraki, Japan

X_0 thick, too thick to achieve the desired calorimeter performance. Therefore, more sophisticated materials and methods had to be developed for the outer shell.

The KEK half of the solenoid design team, with industrial partners, investigated brazed aluminum honeycomb and reported encouraging results from a prototype shell.[2]

Fermilab and a group of industrial partners investigated *isogrid*--integral, grid-stiffened structures in which the grid forms an equilateral pattern.[3] Isogrid has an exceptionally high stiffness-to-weight ratio and has been used in aerospace structures since the 1970s. Metal isogrid shells are typically fabricated in steps: the grid pattern is first CNC machined in flat plates, then the flat plates are formed on a press brake into cylindrical sections which are welded to make up the shell. The investigation of isogrid included designing the shell for the detector solenoid and fabricating a prototype full-diameter shell about 2 m long. The prototype shell was assembled by Fermilab into a complete vacuum vessel and shipped to Japan. A prototype coil built by Toshiba for KEK will be installed into the vacuum vessel and tested in 1993/4.

DESIGN OF ISOGRID SHELL

Design of Full-size Shell

The design standards for the isogrid shell were a calculated collapse pressure differential of at least 2 atm[4] and stresses less than those allowable by the ASME Pressure Vessel Code.[5] The non-heat treatable aluminum alloy 5083-H321 was chosen because it has a reasonably high allowable stress (71 MPa, 10.3 ksi) which is unaffected by welding and because it is readily available at low cost. The dimensions of the outer vacuum shell for the insulating vacuum vessel of the SDC solenoid are 8.778 m in length and 2.050 m in outer radius.[6]

In the SDC magnet design, the cold mass, i.e., the coil and outer support cylinder, and the electromagnetic forces are reacted to the vacuum vessel with a system of epoxy-glass composite supports that attach to the annular bulkheads. The design loads for the support system are: upward, 20 tonnes; downward, 60 tonnes; left/right, 40 tonnes; and axial, ±40 tonnes.[7] These loads on the bulkheads affect the design of the isogrid and inner vacuum shells. The vacuum load on the bulkheads (~85 tonnes) puts both shells in axial compression.

In general, the design of an isogrid vacuum shell consists essentially of solving simultaneous equations for general stability, local (rib and skin) stability, and stress loading with constraining equations (e.g., overall height). A consulting firm* designed the SDC shell for minimum effective (i.e., weight average) thickness under the constraint of a total radial thickness of 55.9 mm (2.2"). The design also had to satisfy formability requirements. For example, the skin was placed on the outer side of the shell so it would be in tension during forming and skin buckling would not be a problem. The locations of the forming centroidal planes were calculated to insure adequate crippling margins in the flanges and webs. The dimensions of the isogrid cross section are shown in Fig. 1(a). The effective thickness of this shell was calculated to be 10.5 mm (0.412") or 0.118 X_0.

The shell had a 324-mm hole 254 mm (10") from one end as a nozzle for attaching the vacuum jacket of the service chimney. The vacuum load on the chimney puts a punch load of about 1000 kgf on the perimeter of the nozzle. The general isogrid pattern and the reinforcement around the nozzle are shown in Fig. 1(b).

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* PS Associates Inc., San Diego, California

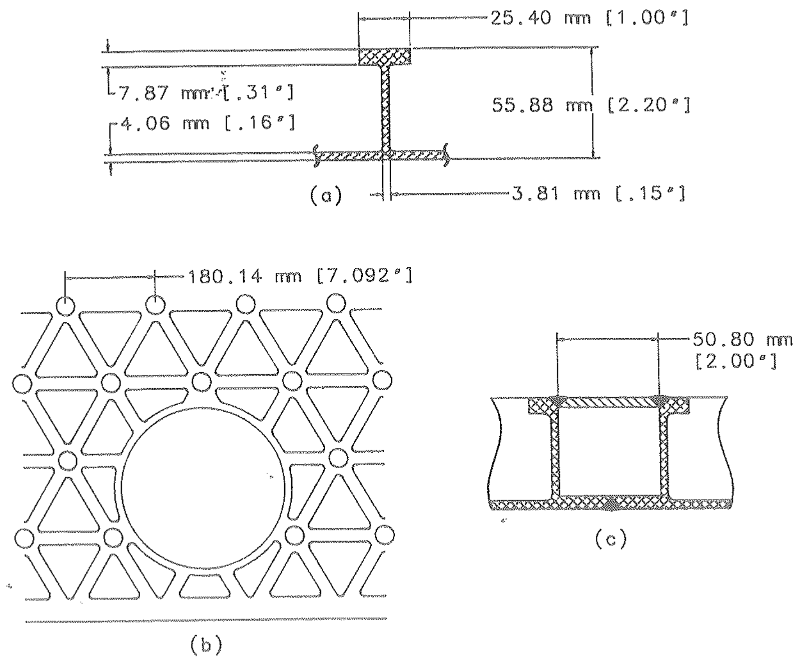

Figure 1. (a) Isogrid rib-skin geometry, (b) isogrid pattern and reinforcement around nozzle, (c) panel-to-panel weld geometry.

Because of the size of the aluminum plates that can be procured and machined, the shell must consist of a number of cylindrical sections welded together. The isogrid patterns along the edges of the sections were tailored to minimize the amount of non-optimal material and to provide structural continuity across the longitudinal and circumferential joints. Figure 1(c) shows the cross section of the welded joint. The isogrid pattern extended as close to the end of the shell as possible.

A study of the effect of the isogrid tolerances showed that the collapse pressure of the shell was more affected by the tolerance on the skin thickness than on the dimensions of the ribs.

Design of Prototype Shell

The KEK-Fermilab design team decided to design, fabricate, and test a full-diameter, quarter-length superconducting prototype of the SDC solenoid. The purposes of the prototype were to develop an aluminum-stabilized superconductor of high yield strength and RRR, to become skilled in the inner coil winding technique, and to develop the technique for fabricating an isogrid outer vacuum shell. The prototype coil will be energized to apply electromagnetic loads to the conductor and outer support cylinder equal to those expected in the detector magnet. Tests will be done to demonstrate that the coil can be quenched safely.

Fermilab provided the vacuum vessel for the prototype magnet. The inner diameter of the isogrid shell was 4.008 m (157.804") and it was 2.340 m (92.126") long. The bulkheads were attached with O-rings and bolts so that they could be removed for inspection, modifications, or repairs. The isogrid pattern designed for the full-size solenoid was used for the prototype vessel so that relevant fabrication experience was gained. Because of its shorter length, the collapse pressure differential of the prototype isogrid shell was therefore quite high; it was calculated to be about 1 MPa (145 psi).

The prototype isogrid shell was designed to be fabricated from three, 120° cylindrical sections with three longitudinal welds joining the sections.

To gain experience in the forming of isogrid shells before finalizing the design of the prototype, a test panel, 0.620 m (24.4") x 1.025 m (40.35"), was machined in the Fermilab shop and brake formed to the 2 m radius.* To reduce post-forming cleanup, the isogrid pockets were not filled during forming. Although generally successful, this panel showed that a lead-in section was needed in the forming direction and that the panel edges in the cross forming direction needed to be stiffer to prevent the edges from rolling.

A second test panel, 2.365 m (93.126") x 1.276 m (50.25"), with a chimney nozzle, was designed, machined+ and formed.* Figure 2 shows this test panel after forming; the lead-in section and the stiffening skin over the nozzle can be clearly seen. Anticlastic, or saddle, deformations can be a problem when forming isogrid panels.[8] The detailed procedure for forming the isogrid plates and compensating for anticlastic bending was developed on this test panel. The panel-to-panel welding procedure was also demonstrated on the panel.

MANUFACTURING OF PROTOTYPE VESSEL

Isogrid Shell

Three plates 2.464 m (97") x 5.080 m (200") x 70 mm (2.75") thick were purchased for the prototype shell. Both sides of the plates were machined# to a thickness of 55.9 mm (2.2") on a gantry mill. The isogrid pattern was then machined (Fig. 3)--there are about 585 isogrid pockets in each plate.

The machined plates were formed* on a 1000-ton press brake, using a punch radius of 560 mm (22"), with the jaws 533 mm (21") apart, as shown in Fig. 4. After the panels had been generally formed, local bump forming was used to bring the panel to within 2.54 mm (0.1") of the desired inside radius of curvature (Fig. 5).

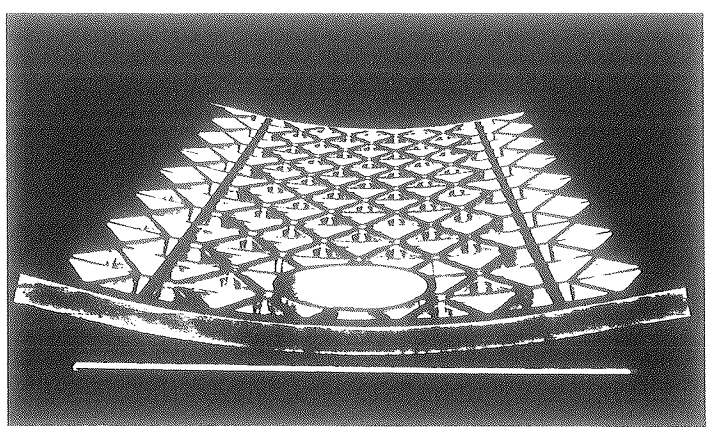

Figure 2. Isogrid test panel. The narrow longitudinal bands of unmachined material represent the location of the panel-to-panel welds.

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* Amro Fabricating Corp., South El Monte, California
\+ Dial Machine Co., Rockford, Illinois
\# Camarillo Dynamics, Inc., Montebello, California

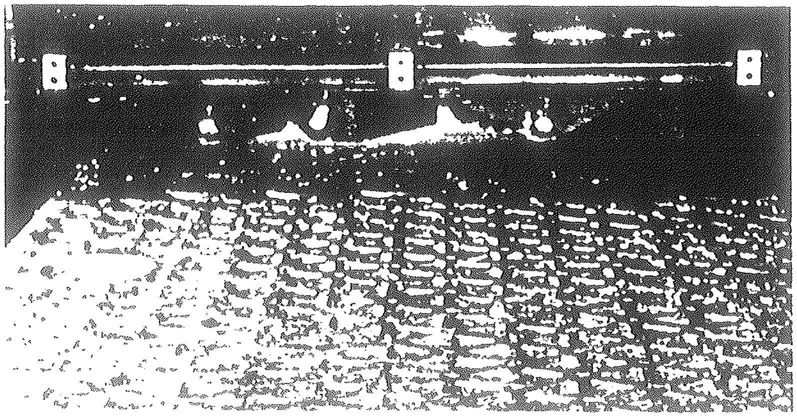

Figure 3. Machining isogrid pattern in aluminum plates.

After forming, the lead-in edges were cut off and the weld preparations machined (Fig. 6). The three panels were then fitted together on a fixture and the panel-to-panel joints made using TIG welding (Fig. 7). The joints were checked for leaks using a helium mass spectrometer leak detector. The ends of the shell were then machined flat and to length, and the holes for attaching the bulkheads were tapped (1/2" x 13 threads per inch).* After all machining was completed, the isogrid pockets were cleaned with steam and detergent. The outside of the shell was grit blasted.

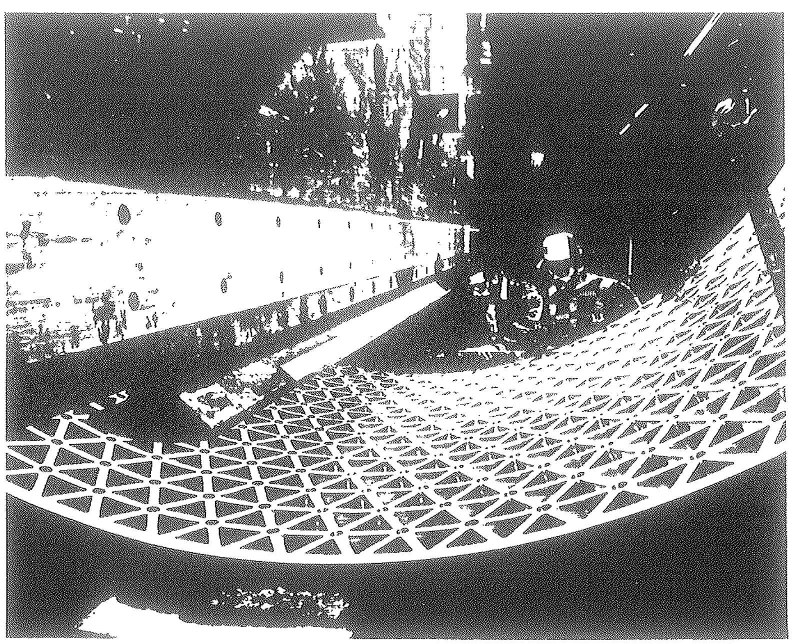

Figure 4. Forming of isogrid panel in press brake.

* Square Tool & Machine Company, Inc., South El Monte, California

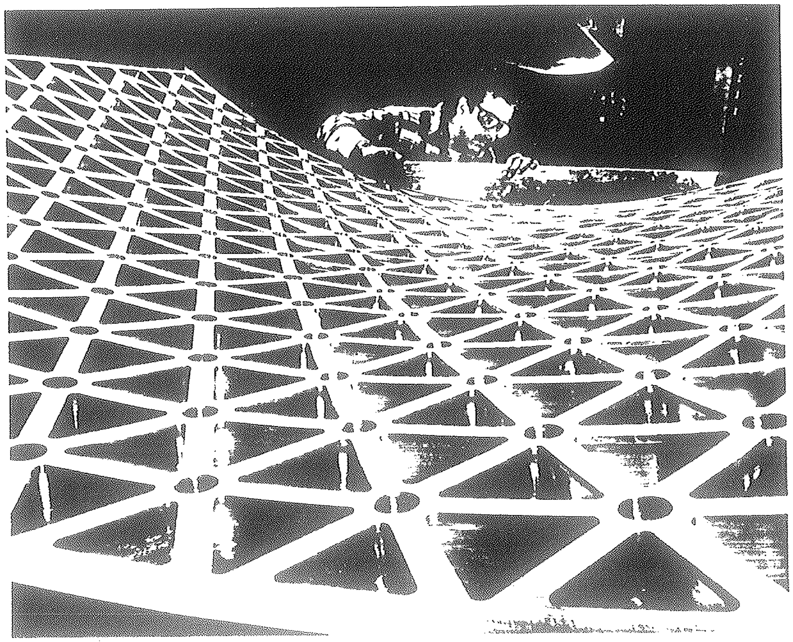

Figure 5. Checking radius of curvature of formed panel.

Other Vessel Components

The inner shell was a weldment of cylindrical sections of 6.3-mm (0.25-inch) 5083-O aluminum alloy, with flanges on both ends for the tapped holes. The inner diameter of the inner shell was 3.400 m (133.9").

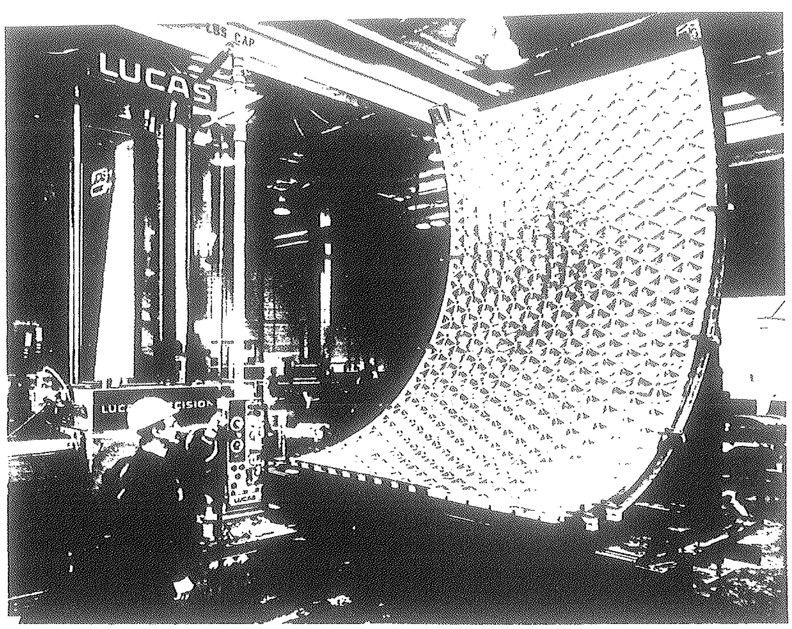

Figure 6. Machining weld preparation in formed isogrid panel.

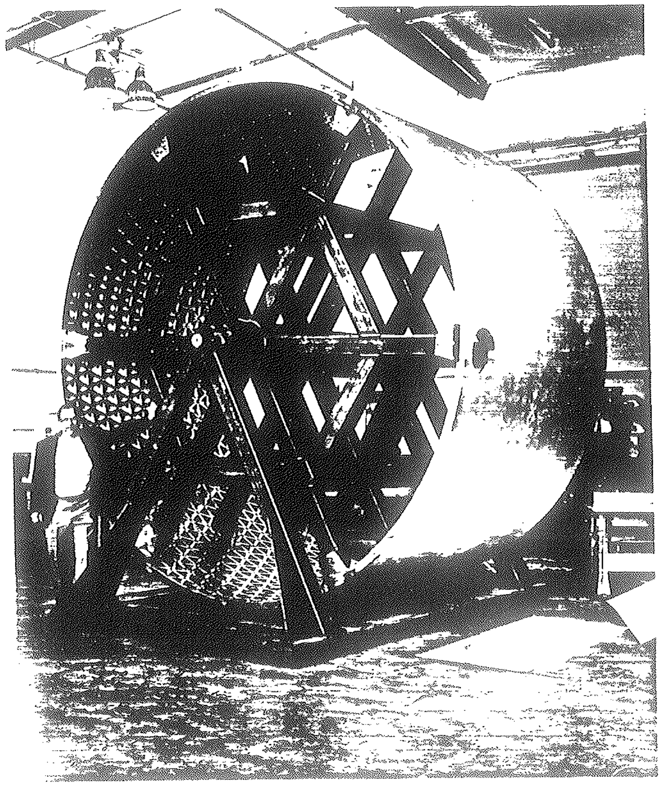

Figure 7. Welded isogrid shell on assembly fixture.

The annular bulkheads were fabricated from 5083-H112, machined to a thickness of 31 mm (1.22"). The radial extent of the bulkheads was 360 mm (14.173"). O-ring grooves, and attachment lands and access holes for the cold-mass supports, were machined in the bulkheads.

Testing Of Prototype Vessel

The components of the vacuum vessel were assembled (Fig. 8) and the annular space evacuated for leak testing. Substantial effort was required to get the O-rings to seal properly, but the leak testing company+ was able to certify that with a pressure of 1 mTorr the leakage was less than 1 x 10^{-9} std cc/s helium.

The vessel was then crated and shipped by sea to Japan where the cold mass will be installed# and the magnet tested.

CONCLUSIONS

The investigation of isogrid for the insulating vacuum vessel of the superconducting SDC solenoid led to the successful fabrication and testing of an isogrid outer shell for a 4.12 m OD x 2.34 m long prototype vessel. The manufacturing procedures and techniques developed for the prototype shell will be directly applicable to the full-length shell. The use of isogrid for the SDC application results in a shell that is 40%, or 0.182 X_0, thinner than a solid shell. Although an isogrid shell will not be as thin as a honeycomb shell, the simpler manufacturing process is an advantage and may result in a less expensive shell. The isogrid

+ Sierra Technologies, Lancaster, California

Toshiba Corporation, Keihim Product Operations, Yokohama, Japan

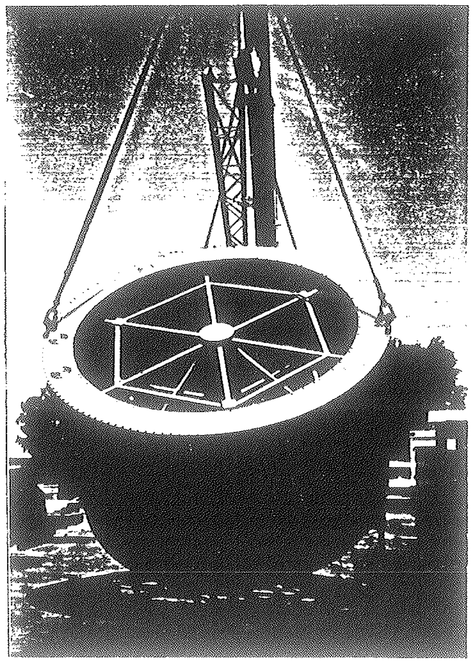

Figure 8. Completed prototype vacuum vessel.

shell will probably be more resistant to damage when shipping the magnet to the SSCL and during its installation into the detector, some 63 m (200 ft) below the surface.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of their colleagues at Fermilab: R. Kephart, D. Friend, and W. Cyko. P. Slysh and L. Swenson, of PS Associates, designed the isogrid pattern and performed the finite-element analysis. The technical and managerial contributions of S. Riley, the president of Amro Fabricating Corp., were invaluable to the success of the prototype vacuum vessel.

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AQ 36

FINITE ELEMENT STUDY OF THE QUENCH BEHAVIOR OF A SOLENOID FOR SSC DETECTOR*

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ABSTRACT

When a superconducting magnet starts to quench, the resistivity of the normal zone of the superconductor increases greatly and the current moves into the stabilizer. Ohmic heating results and the temperature of the quench initiation site begins to rise very quickly. Therefore, the magnet and quench protection system must be designed so that this "hot spot" does not reach a damaging temperature. The work described in this paper is part of the R&D effort leading toward the design of a thin solenoid for an experiment at the SSC. The 4 m diameter x 8 m x 2 T magnet has a single layer of aluminum-stabilized Cu/Nb-Ti superconductor cooled indirectly. Quench protection is through a room temperature dump resistor. The behavior of a quench has been extensively studied by a computer simulation using three methods. In the first, one dimensional model, it is assumed that the heat flows only in the circumferential direction along the conductor. In the second model turn to turn heat conduction is added with one thermal conductivity along conductor and another transverse to it. In the third model current diffusion is also included. The calculations are done with the commercial finite-element program ANSYS.

INTRODUCTION

Contact-cooled superconducting solenoids magnet are often used in high energy collider physics experiments requiring low radiation and absorption length to minimize multiple scattering. These magnets must survive the sudden onset and propagation of a zone of normal resistivity (a quench). Typically, quench detection circuitry will sense the change in coil voltage resulting from the normal zone, and trigger a discharge of the magnetic energy through an external resistor. The large inductance and the need to limit peak discharge voltages mean that the magnet current usually takes ten of seconds to decay. During this decay, the normal zone spreads, and maximum coil temperature increases. Due

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to the small volume of helium inherent in these designs, the joule heating of a quench will be absorbed primarily by the thermal mass of the superconductor and the outer support cylinder. The superconductors used in these magnets are typically Nb-Ti-Cu cable embedded in a high-purity aluminum stabilizer. The diffusion of current from the superconducting region to the stabilizer is not instantaneous, and the resistance in the diffusing region is high during the time it takes to spread the current throughout the stabilizer cross section. This leads to additional heating of the cold mass and may alter the final temperature of the coil.

The necessity of estimating maximum temperatures and the difficulty of determining these temperatures experimentally has led to the use of numerical methods as a practical way of studying the quench problem. The simplest approach assumes that the entire energy of a quench is dumped into a volume of conductor adiabatically - that is, the heat generated by the quench is not allowed to transfer away from the normal region. A simple energy balance and numerical integration will give a worst case estimate of the maximum temperature.

This approach can be further refined by finite-difference techniques which include heat transfer, an example of which is the QUENCH[1] program. QUENCH smears the properties of the conductor, insulation, and support material, assumes an ellipsoidal normal zone shape advancing at a known initial velocity, and solves for successive layers of normal temperature.

More recently, investigators have used the finite element method to study quench behavior. Bottura[2] used FEM to solve a pure heat diffusion equation in two dimensions. Zienkiewicz[3] developed a one dimensional cable model to simulate the quench propagation for force flow cooled conductor. The present work is an attempt to use the commercially available finite element package ANSYS[4] to simulate the quench behavior of the Solenoid Detector Collaboration (SDC) 4 m x 8 m x 2 T thin solenoid. The post-processing of intermediate results allowed the inclusion of coil resistance in the current decay expression, as well as an approximation of the diffusion heating effect.

SOLENOID GEOMETRY AND DUMP CIRCUITRY

The SDC solenoid consists of about 2000 turns of superconductor wound inside a 31 mm thick support cylinder. Insulation between the turns is 0.1 mm Kapton, and insulation between the coil and the support cylinder is 0.2 mm G-10. A cross section of the coil/support cylinder and a detail of the conductor are shown in Figure 1. The solenoid produces a central field of 2 T at a current of 8000 A. The dump circuitry design is not finalized, but for this analysis a dump resistance of 0.1 ohms was assumed.

THE FINITE ELEMENT MODELS

Three finite element models were created. The first was one-dimensional, and consisted of only a length of superconductor conducting heat in the helical direction. This model was used to investigate methods of starting the quench, and study the minimum propagation zone. The next model was two dimensional, allowing conduction axially (through the turn-to-turn insulation) as well as helically. The third model was two dimensional with the current diffusion effect added. All three models were based on the same element and material characterizations.

The conductors were modeled as thermal-electric bars[4], capable of carrying current generating and conducting joule heat with temperature dependent resistivity and conductivity. The material properties were input at 24 temperature, ranging from 4 to 293

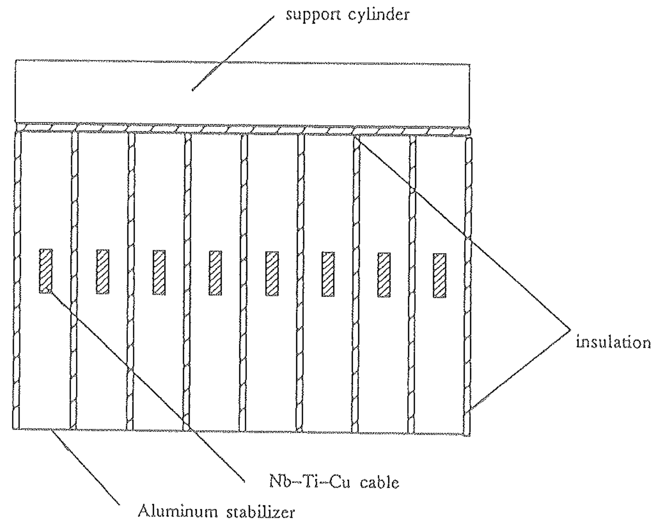

Figure 1. Geometry of the conductor.

K. A step change in resistivity was applied at 8 K to simulate the transition from superconducting to normal state. Due to the large area ratio of aluminum stabilizer to Nb-Ti-Cu cable, the properties input were those of the stabilizer only. The calculations presented here used an RRR value of 600 for the aluminum.

The insulation between turns and between the coil and the support cylinder was modeled with conducting bar elements. These elements were given the temperature-dependent specific heat and thermal conductivity necessary for a transient thermal analysis, but carry no current.

The helical conduction path of the conductor requires that a full 360 degree sector be modeled; the correct length to model axially is more problematic. For short times it is sufficient to have available only enough solenoid to ensure that some region is still at it's initial state. The 2-D model in this work used 500 turns of the solenoid; it is shown in Figure 2.

LOADING OF THE FINITE ELEMENT MODEL

The primary driver of the transient problem was the current. In a dump scenario, this current will decay with a time constant of

$$\tau = \frac{L}{(R_d + R_c)} \quad (1)$$

where L = inductance of coil, R_d = dump resistance and R_c = resistance of coil.

A time step of half-second was chosen for current adjustment. For the first two seconds, the full current was applied to simulate the time necessary to detect the normal zone and initiate the current discharge. At subsequent times, as the normal zone grows, the coil resistance changed. This resistance was available from the element output at the end of each time step, and was used to re-calculate the current which will be flowing during the

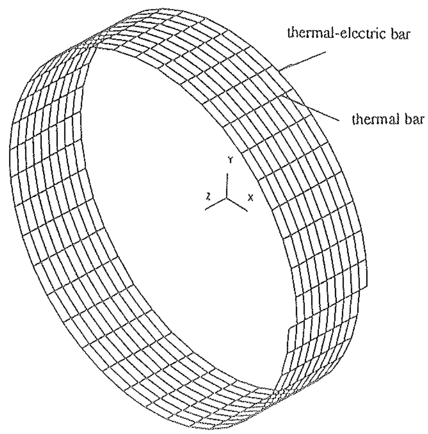

Figure 2. Schematic of the 2-D finite element model.

next half-second time step.

Current diffusion was approximated with a method described earlier[5]. Calculations for the SDC conductor geometry showed that the diffusion time was about 3 seconds, and that the net heat input was about 50% greater than the joule heating calculated if the entire cross-section were instantaneously active. The finite element model approximated this closely by extracting the joule heating in each element just after it became normal, multiplied it by 0.5 and issued a volumetric heat generation command to the model at the beginning of the next time step. Three seconds later, the heat generation was turned off. Figure 3 shows a schematic of finite element approach.

RESULT AND DISCUSSION

The quenching of the conductor in the finite element model can be initiated in several ways:

1. One or more elements can be assigned material properties which give finite resistance even at the starting temperature of 4.2 K.
2. A heat pulse can be applied to one node or element for a brief time step, causing the element temperature to rise into the resistive region. The heat pulse is then turned off in the subsequent time step, and the solution continues with a self-propagating quench.
3. A temperature at the resistive threshold can be applied at a node for a brief time, causing resistance as in 2). The temperature is then deleted in the subsequent time step and the solution continues with a self-propagating quench.

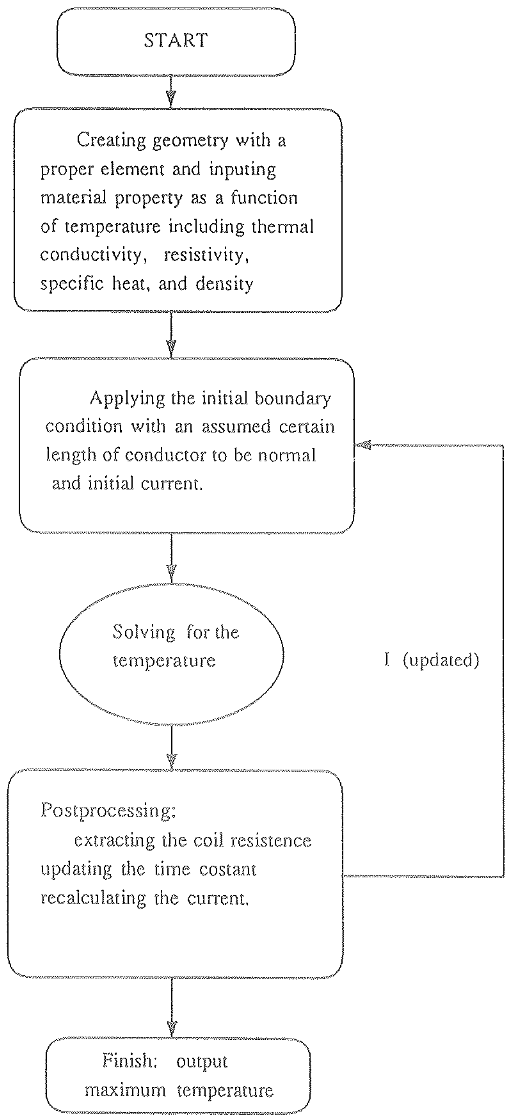

Figure 3. Schematic of finite element approach.

Method 1 is equivalent to assuming an initial zone of resistive material. It does not require any load deletion during solution, and there are approximations available from the literature for estimating a minimum propagating zone (MPZ) size. For these reasons, this method was chosen for initiating the quench.

An estimate of the minimum propagating zone (MPZ) was modeled using

$$l = \sqrt{\frac{2k(T_c - T_o)}{J^2 \rho}} \qquad (2)$$

where k is a thermal conductivity, T_c is normal state temperature, T_o is a background temperature of the rest of the magnet, J is the initial current density and R is the resistivity of the aluminum[1]. If k=4600 W/m-K, T_c=8 K, T_o = 4.5 K , J = 4.2×10^7 A/m^2 and R = 4.2×10^{-11} ohm-m , then Equation 2 gives L = 0.33 m. The one dimensional model was used to look at the sensitivity of the maximum temperature as a function of the initial normal zone size. Figure 4 shows the maximum temperature for L = 0.16, 0.33, and 0.66 m after 90 seconds. The difference in temperature was less than 3 K. Also included on the figure is the plot for the adiabatic solution. The finite element models produce lower temperatures, as expected from the inclusion of heat transfer down the superconductor.

Figure 5 shows the results from the two-dimensional model without current diffusion. The maximum temperature was 52 K after 90 seconds. The current decay curve shows an initial two second period at the operating current, and followed by the discharge through the discharge resistor. Figure 6 shows the results for the same model with current diffusion included. Diffusion increased both the hot spot temperature and normal zone propagation velocity. However, the rate of current decay was also increased because of the increased coil resistance. These effects may offset each other somewhat, producing an overall increase in temperature due to diffusion of only 4 K.

The work presented here was our first attempt to use an commercially available finite element program to study quench behavior. Future work will include the heat transfer to the support cylinder, and eddy current heating in it. Experimental verification is also required.

All of the calculations presented here were performed with ANSYS Rev. 5.0 running on an SGI R4000 Indigo and an HP9000/730 Unix workstation.

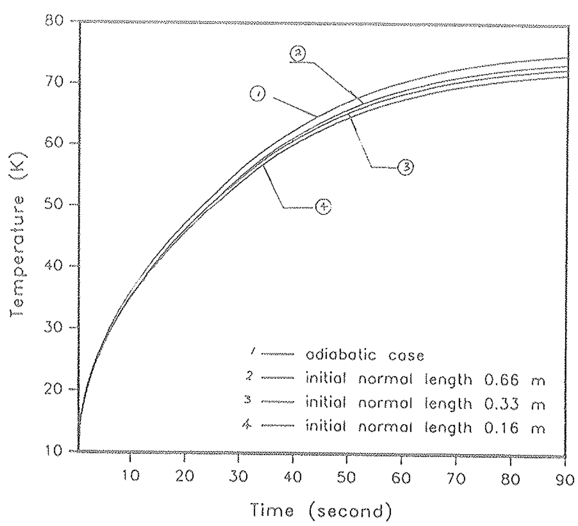

Figure 4. Calculation result from one-dimensional model.

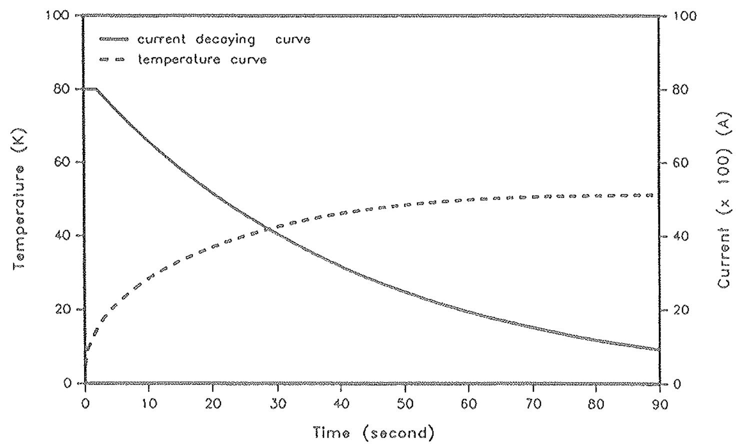

Figure 5. Calculation result from 2-D model without current diffusion effect.

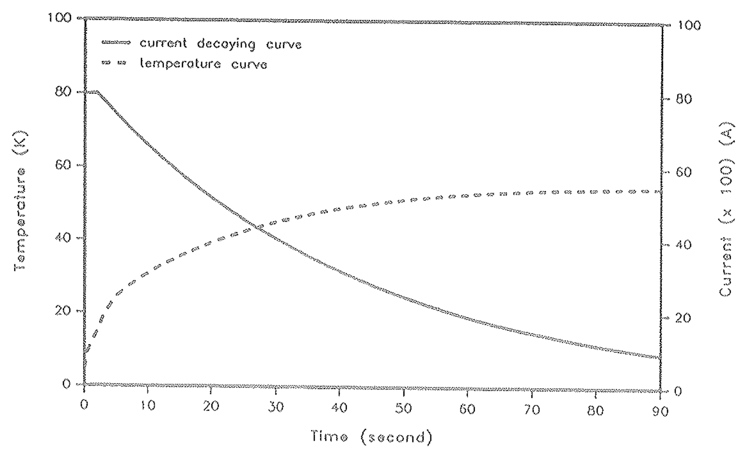

Figure 6. Calculation result from 2-D model with current diffusion effect.

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