RESPONSE TO OPERATING CONDITIONS OF THE SSC MAGNET USING NONLINEAR FINITE ELEMENT ANALYSIS*

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Introduction

Using a plane strain 2D finite element model to represent the dipole magnet, and material properties as a function of temperature, the operating conditions and environmental conditions were simulated to evaluate the adequacy of the design, investigate areas of nonconformance, evaluate modifications to the design, support analytically the measurement effort, and by performing a sensitivity analysis, determine what design parameters are critical. These objectives have been met by the current analysis.

Model Configuration

The cold mass assembly consists of the beam tube, trim coil, collared coils, stacked iron yoke lamination and outer helium containment shell (see Figs. 1 and 2). The cold mass is subjected to the following operational loads: assembly pressure, cool down, helium pressure, energization, and eddy current forces and pressure rise during quench, as illustrated in Fig. 3, cool down and Fig. 4 quench. The computer calculations permit the simultaneous treatment of all the loads and temperatures in the time regimes imposed by the actual system.

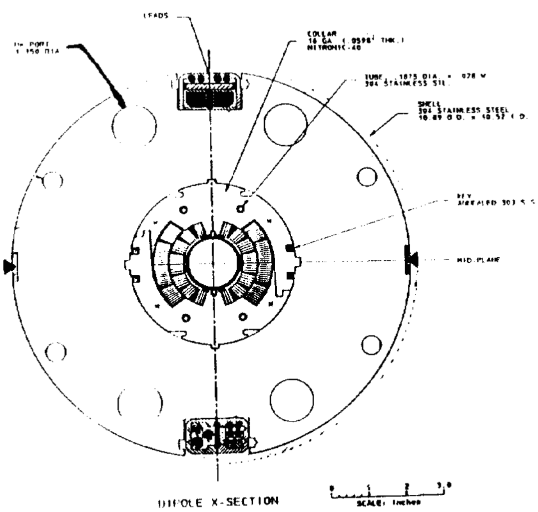

Fig. 1. Cross section of dipole.

The model (Fig. 5) was formulated by using a computer code called MAZE[1]; the temperature was obtained using a code called TACO[2] (see Fig. 6 for procedure). A structural analysis code called NIKE[3] was utilized using the same mesh (model) as TACO as well as the output from TACO which consisted of the temperature at every node as a function of time. The structural analysis provided the displacements and stresses for the nodes and elements respectively as a function of time. The post-processor was a code called ORION.[4]

Only one-fourth of the mesh was required as symmetry was employed. Eighteen different materials

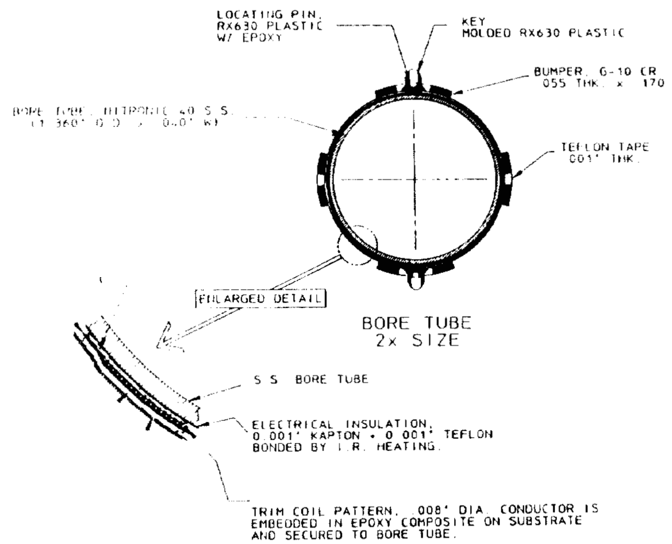

Fig. 2. Detail of beam tube, trim coil.

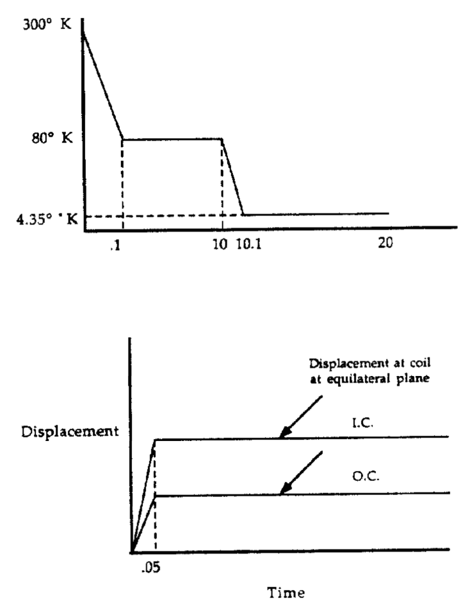

Fig. 3. Cool down.

were used, and the model consisted at 753 nodes, 497 elements, 25 slide line consisting of 205 slave nodes, and 227 master nodes. Slide lines are line which distinguish two adjacent parts. Nodes, which are a numbering system based on coordinates, must be identified as to which side of the slide line or which part they represent. Slide lines can then allow parts to separate, come together, slide, and slide with friction. Extensive verification of the code was performed.

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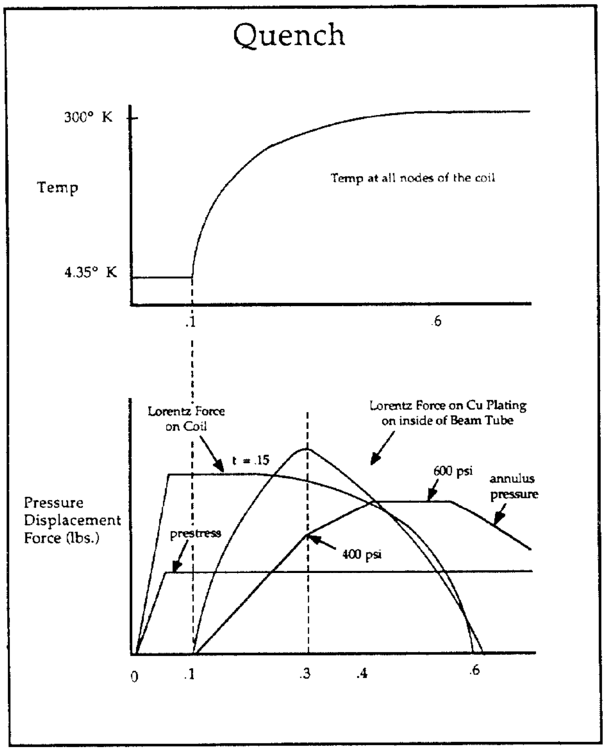

Fig. 4. Quench.

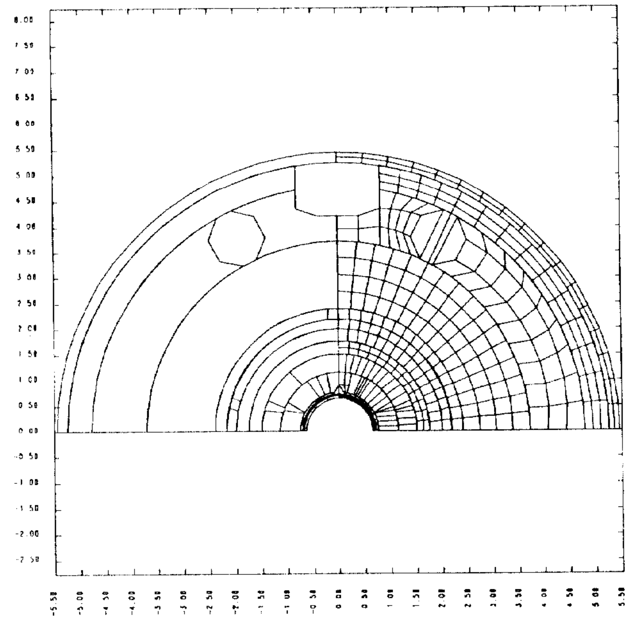

Fig. 5. Two-dimensional finite-element model.

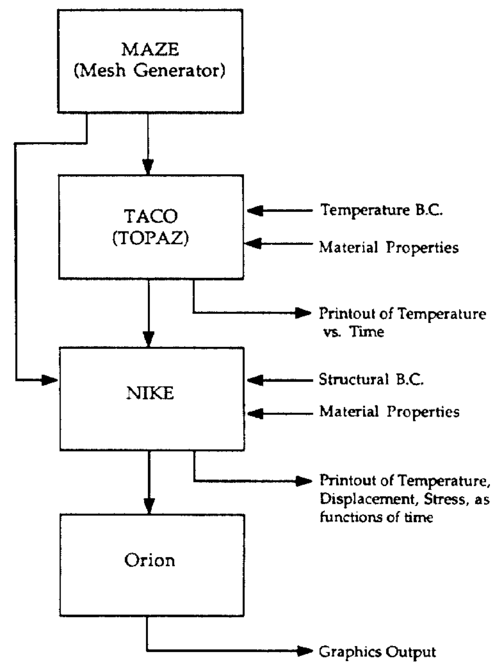

Fig. 6. Procedure.

<u>Input and Results</u>

Prestress is that stress necessary to counteract the Lorentz stress on the coil adjacent to the collar to prevent the coil and collar separating in the circumferential direction. As a consequence of cool down, approximately 50% of the initial stress is lost. It is the stress subsequent to cool down in the coil elements adjacent to the collar that is referred to as prestress. This stress is 4000 psi for inner coil and 3500 psi for the outer coil. The Lorentz forces are based on 6.6 Tesla. There is an additional Lorentz force, due to eddy currents in the plating on the inside surface of the beam tube, which starts to buildup as the coil quenches. When the coil quenches there is a rapid rise in conductor temperature which results in a rise of helium pressure in the annulus between the coil and beam tube. This in turn, results in a rise in temperature in the other cold mass components.

As shown in Fig. 4, as the temperature in the coil rises, the Lorentz forces in the coil decrease as the current decreases, the Lorentz force due to eddy currents increases, and the pressure in the annulus increases to 600 psi or 40 atm. The Lorentz force due to eddy currents can vary by a factor of two based on the amount of heat transfer permitted; it varies from 100 psi without any heat transfer to 200 psi for 100% heat transfer and is a cosθ distribution (max. at equatorial plane). The Lorentz force in the coil can also vary due to input, 6.6 Tesla vs. 8.5 Tesla. The 600 psi helium pressure is a upper limit.

Figure 3 represents the input to TACO for the nodes surrounding the coolant channel and the annulus. The prestress loss from 300 K to 4.35 K is approximately 58% with steel collars. The loss with an Al collar is somewhat less, and therefore, the preassembly pressure can be less with Al. The calculations that have been performed are transient i.e., time dependent. The material properties, specifically, α coefficient of thermal contraction, are functions of temperature and indirectly, time. At room temperature, the value of α for steel and Al are greater than the coil, so that the collar is contracting at a faster rate than the coil. At 4.35 K, the converse is true in that α for the coil is greater. In addition, the interface between the coil and the collar is <u>not</u> radial, so that the two components will not slide but will interact producing stress especially if there is a bumper at the pole with insufficient clearance.

The maximum stress in the beam tube is at the end of cool down and is 90,000 psi for an Al collar and 76,000 psi for a steel collar. The clearance between the bumpers and the beam tube has been used up as a consequence of cool down. The maximum collar stress (occurs at the end of cool down) and is 100 ksi for steel and 62,500 psi for Al. As the yield strength increases by a factor of 3 at 4.35 K over that at 300 K for steel, the design requirements (σ_0 = 180 ksi) are satisfied. Al yield strength goes from 73.8 ksi to 94.8 ksi over this temperature range so that it also meets design requirements. The properties of Al and steel are well known over this temperature range. The coil is a composite and its properties are not as well established. Figures 3 and 4 summarize the two sets of calculations.

When Al collars were investigated, no clearance was permitted at room temperature between the yoke and the collar; when steel collars were investigated, a clearance of 3 mils was included in the model. Therefore, the stress in Al collars would be higher due to thermal stress, during a quench when collar temperature exceeds that of the yoke. This is offset by the fact that the modulus of Al is one-third that of steel. The model was also adjusted to determine the effect of clearances under the bumper, elimination of the bumper, thickness of the beam tube, variation in magnitude of Lorentz forces, helium pressure variation, and variation in assembly pressure. In addition, sensitivity analysis was performed on some of the material properties. The material properties were input as functions of temperature. The material model was thermo-elastic plastic; however, as the plastic portion constituted failure, those properties were not required.

The Central Design Group (CDG) has prepared a set of structural and other requirements[5] which the design must meet. The bending stress $\leq$ 90% yield, the ultimate stress $\leq$ 1/2 tensile ultimate, buckling analysis $\geq$ 4 x operating load, membrane stress $\leq$ 2/3 yield, and membrane + bending $\leq$ 2/3 yield. The computer results provide the stresses and displacements, not the failure criteria. The output from the computation is to be compared with CDG requirements for compliance including stability. While a 600 psi external pressure on the beam tube meets the stability requirement, 600 psi on a elliptical shaped tube due to the Lorentz force emmanating from eddy currents on the inside surface, does not. Timoshenko and Gere[6] have treated this problem. Considering the variability of the cosΘ Lorentz force, either the beam tube thickness of 40 mils needs to be revised to 50 mils, or supports (G-10 bumpers) retained in the system, or some combination of the two. The supports prevent the beam tube from collapsing due to external pressure while in an elliptical shape, thus permitting higher external pressure before collapse. Since, the G-10 bumpers are also vehicles for transmission of forces to the beam tube and can alter the distribution of the prestress, it is recommended that the thickness be increased to 50 mils with an outside diameter of the beam tube retained at 1.36 inches and the bumpers eliminated.

With either adequate clearance between the bumpers and the beam tube (>5 mils) or elimination of bumpers (thickness of beam tube increased to 50 mils), the stress in the beam tube and copper plating meet the CDG requirements. The advantage to aluminum collars compared steel collars is the reduction in maximum stress since the modulus of Al is one-third that of steel. The conductivity of Al is higher than that of steel, meaning that equilibrium is reached faster in Al. When a heat transfer calculation (TACO) was performed on the basis of energy deposited in the coil, the temperature distribution in coil and collar were as calculated by other methods, except at very early times when the calculation does not account for the vaporization of the helium and after 0.4 seconds when the temperature begins to drop from 285 K to 200 K at 1 second, since all the energy has been deposited into the system by 0.5 second. Stress calculations need to be extended to longer times with the new temperature profile.

The coil stesses are generally under 10 ksi and poses no difficultly since the Lorentz stress alone on the coil is 6830 psi for 6.6 Tesla at equilatorial plane inner coil (5490 psi outer coil at equilatorial plane). The stresses developed in yoke and shell meet design requirements.

Comparison with Experimental Measurements

In order to measure the prestress, a section of the collar was removed and replaced with a strain gauge insert. Additional measurements have been made of the deflections of the collars. The experimental results are very dependent on the model type and assembly prestress. Analytically, this analysis was performed by inserting a slide line with separation and friction between the insert and the collar. Slide lines of this type were already in the model on two sides of the insert (adjacent to coil and between the G-10 bumper). The MAZE model did not replicate the collar with all its nuances to capture the effect of these variations as it was not a priority objective. LBL's most current measured value of cold prestress in the inner coil is 4 ksi and 4.3 ksi for outer coil. This compares with 3.9 ksi and 3.75 ksi calculated, respectfully. LBL measured collar deflections at 4 K energized state of 1.1 - 2.1 mils vertical and 1.6 mils horizontal. Evaluating NIKE results for a similar condition, we have 2.1 mils, for vertical and 1.54 mil, for horizontal. Considering the variability in measurements, this is in excellent agreement.

If the clearance is not adequate when bumpers are being used, additional problems can arise such as loss of prestress. When the coil is constrained along its azimuthal length, i.e. along the bumper and along the coil collar "radial" interface, the region where it is not constrained is free to deflect and as a consequence, a circumferential stress cannot be transmitted. On the other hand, if the clearance is too large, it will not provide a support for the beam tube when pressurized in an elliptical mode.

The two material properties for which the design is most sensitive are coefficient of thermal expansion/contraction, α, and modulus of elasticity.

References

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