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EPOXY IMPREGNATED SOLENOID COIL TRAINING DEPENDENCE ON BOUNDARY FORCES AND PEAK FIELD

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EPOXY IMPREGNATED SOLENOID COIL TRAINING DEPENDENCE ON BOUNDARY FORCES AND PEAK FIELD*

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ABSTRACT

Five solenoid coils are required for the axial component of a Minimum B magnetic field of a confined plasma ion source under construction at NSCL. The design requires an initial radius of 0.15 m and a coil current density of 12 kA/cm^2 at a B_{max} of 3.5 T. The initial fabrication scheme was envisaged to be wet wound coils in pockets on the outside of a stainless steel bobbin, (the inner surface being reserved for a six coil superconducting hexapole magnet that completes the magnetic structure). Finite element analysis indicated the possibility of large internal and boundary stresses on the epoxy/coil composite, and we have completed several empirical studies of this geometry. We have measured bobbin to epoxy bond strengths, and have found that the best, most consistent results are obtained by acid etching the stainless steel for good epoxy adhesion. A test arrangement of three coils with differing boundary conditions (potted in pocket, potted in lined pocket and a free coil) reached, respectively, 40, 48 and 58 kA/cm^2 after training. Finite element analysis indicate the probable failure mode of the fixed coil to be boundary stress and for the free coils, internal shear is the indicated failure mode.

SOLENOID COIL DESIGN REQUIREMENTS

The focus of this paper is the testing of prototype solenoid coils for the[1] SCECR superconducting electron cyclotron resonance ion source under construction at National Superconducting Cyclotron Laboratory. The cryostat of this device is shown in Fig. 1. Five circular coils, divided into a group of three and a group of two, will produce two axial magnetic mirrors with on-axis peak fields of 2.2 and 1.5 Tesla respectively. These two mirrors, with individual coils spaced approximateBly 5 cm apart, are thus split to allow fine adjustment of the mirror ratioBs, but result in large axial forces between adjacent coils.

In addition, the (inner bore) hexapole magnet coil ends have alternately attractive or repulsive interaction with the solenoid coils, and contribute approximately 1 Tesla to the peak field at the solenoid conductor. The design parameters for the circular coils are summarized in the first column of Table 1. The B_{max} entry for the design column includes the contribution from the hexapole coils.

The solenoid coils are random wound, epoxy impregnated using Stycast 2850 FT epoxy, based on the design of the high energy beam transport magnets also under construction at NSCL,^{2,3} where we have built superconducting quadrupole and dipole coils with current densities of up to 18 kA/cm^2 but at lower peak fields. The SCECR geometry requires that the coils be axially compact, to allow access for radial cryostat penetrations, and to sharpen coil axial field profiles for source tuning. The additional requirement of low helium consumption dictates the use of potted high current density coils with a large number of turns instead of the intrinsically reliable cryostable coils.

The total stored energy in circular coils is 65 kJ, and the mutual inductance is only about 30 percent of the total. Quench calculations covering a number of different quench senarios predict the coils to be self-protecting under all circumstances.

COMPOSITE COIL BOND STRENGTH TESTING

Bobbin To Coil Bond Tension

A layer of superconducting wire was epoxied between 2.5 cm diam. 304 stainless steel cylinders. The cylinders were then pulled apart with the strength monitored by a calibrated strain stud. Average fracture strengths of 31 MPa +/- 15% were obtained for acid etched cylinders. The samples generally failed by epoxy debonding from the wire and not from the cylinders.

Composite Coil and Coil-to-Bobbin Shear Strengths

Strength testing was done on sections cut from an actual coil previously operated in LHe. Sections were clamped halfway across inner and outer surfaces, with a load applied perpendicular to the surface. Two samples were tested with the shearing occuring at approximately 17 MPa. Testing of the coil to bobbin shear strength was performed in the same way, and a strength of 8.8 MPa was obtained.

Table 1. SCECR solenoid coils - main parameters.

	DESIGN	LOOSE (A)	FIXED (B)	FREE (C)
r (cm)	14.6	14.6	14.6	11.5
z (cm)	5	6.1	6.1	4
A (cm2)	19	9.3	9.3	6.1
max I (amperes)	40	147	123	181
max j (kA/cm2)	12	47.4	40.0	57.0
Bmax (Tesla)	3.5	4.7	3.9	5.2
Turns/cm2	315	323	323	315

PROTOTYPE SOLENOID COIL TRAINING TESTS

Three coils with differing boundary conditions were tested. A schematic diagram for this test is shown in Fig. 2. Coil A was wet wound in a mylar pocket against a teflon lined stainless steel pocket on the test bobbin O.D. Care was taken to avoid epoxy leakage between the two layers. Coil B was wet wound directly in an acid-etched pocket on the bobbin O.D. Coil C was wound on a seperate form, then removed from the form and installed with approximately 0.1 mm clearance on the bobbin I.D., with G10 bumpers for axial restraint. A photograph of the test bobbin is shown in Fig. 3. The bobbin is the same dimensions as the source design, but the test coils have approximately half the area and turn number of the source design, as indicated in Table 1.

All three test coils trained to operating levels below the short sample current limit. These operating levels seem to scale nicely with the level of boundary constraints, as Fig. 4 shows. The jaggedness of the Coil C training curve was due to a sensitivity to the test dewar helium level. Coils were installed in the dewar with the orientation show in Fig. 3. The dewar was filled to cover the coils, but the level dropped with successive quenches until the coils were partially exposed, resulting in a degradation in performance at higher currents. This was particularly evident for Coil C. The results are summarized in Table 1.

Given the current densities obtained in the tests, one type-B coil would be sufficient to obtain the required on-axis peak field of 2.2 T. This makes the final coil design, as indicated in the first column of Table 1, somewhat conservative in terms of single coil characteristics, but provides a comfortable margin for the ensemble.

TEST COIL STRESS ANALYSIS

Representative stress calculations for the tree test coils are presented in Figs. 5-8. The calculations were made using a code developed at NSCL for this purpose.[4] Figures 5 and 6 show the maximum shear stress for the A and B coils respectively, while Figures 6 and 7 show the maximum principle stress for coils B and C. The results for coils A and C are essentially identical except for the absolute magnitude of the forces, thus only one coil is shown for each plot case. In all cases the ordinate is coil radius in inches (1 inch = 25.4 mm) and the absissa is the axial dimension.

Coil A is treated as a free coil with a frictional coefficient of 0.3 for teflon. The magnetic force causes the coil to expand away from the bobbin both radially and axially, and the coil cross section is entirely under compression. The largest problem appears to be the shear stress, that exceeds 9.5 MPa within the coil middle along the I.D. This stress is probably high enough to induce coil cracking. This stress is not a shear along the bobbin boundary but actually through the wire epoxy composite at an angle to the bobbin ID.

Coil B is essentially fixed at the bobbin ID, top and bottom plates. The axial stress goes fom tension at the bobbin boundary to compression in the core, while the radial stress is in tension through half the radial cross section. The maximum pricipal stress follows the axial stress contours in regions of high stress. Coil failure most likely occurs from tension on the epoxy along the boundary, since the measured composite coil bonding strength was only 8.8 MPa.

SUMMARY

From the training behavior of the test coils we believe that any of the cases tested could be adopted for use in the SCECR, since the current densities achieved exceeded the required density of 12 kA/cm^2 at 3.5 T. The inner coil, the one achieving the highest level, presents mechanical difficulties when considered with the rest of the magnetic structure. Therefore we have adopted the loose coil since it achieved the next highest current density and because vis' a vis the fixed coil it requires fewer qunches to achieve the required current.

ACKNOWLEDGEMENTS

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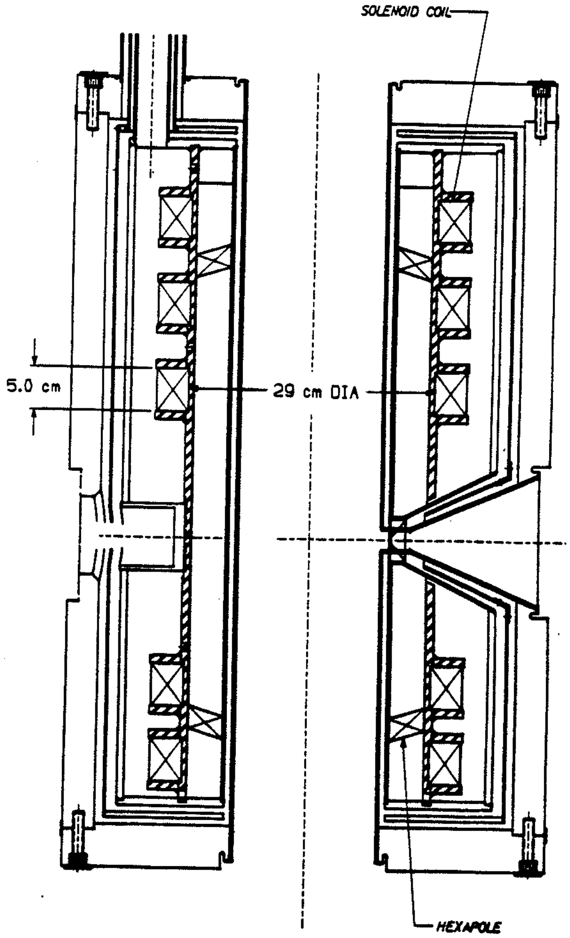

Figure 1. A sectional view of the SCECR magnet cryostat.

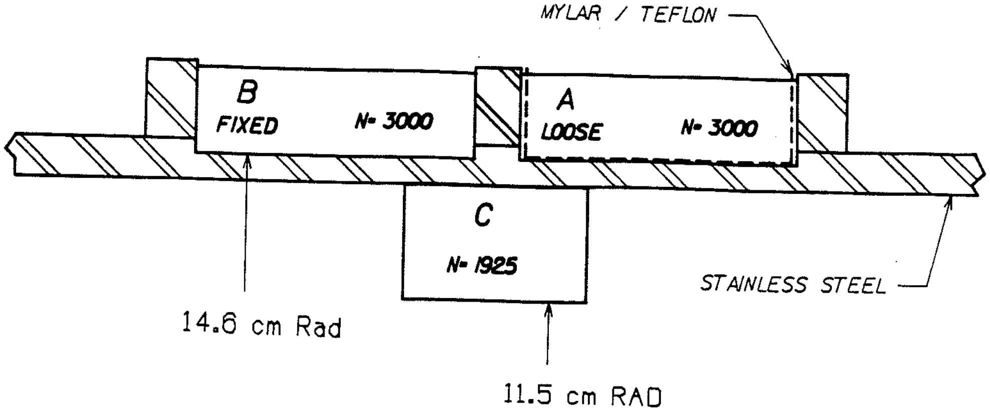

Figure 2. A schematic diagram for the solenoid test coils is shown. Coils A & B are potted in machined pockets on the outer bobbin surface; Coil C was wound seperately and installed in the bobbin bore, with G-10 axial bumpers.

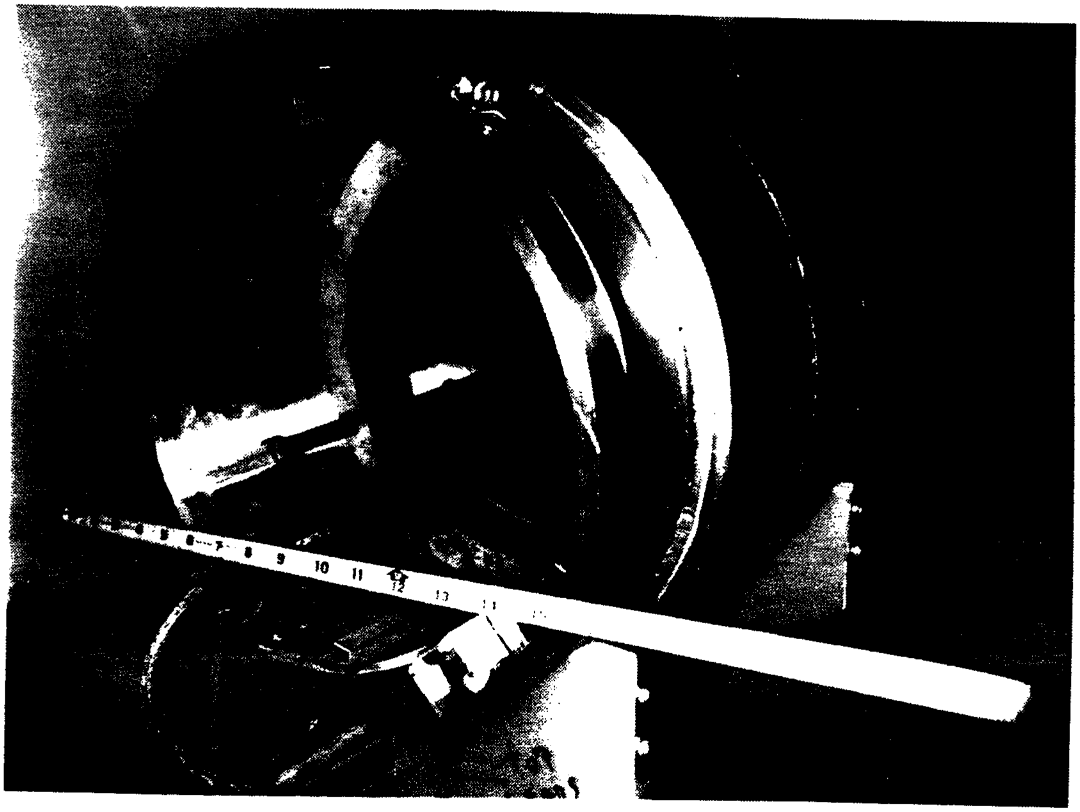

Figure 3. A photograph of the SCECR solenoid test coil set-up. All three test coils and part of the lead bus (under bobbin) are visible.

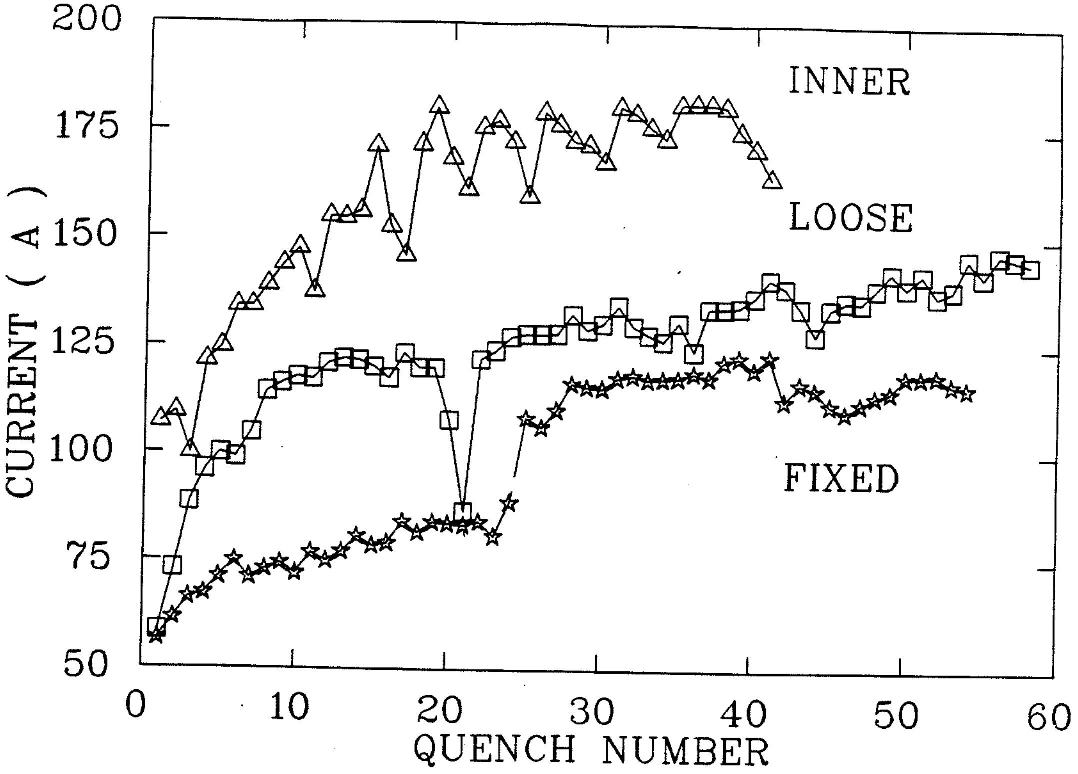

Figure 4. Training characteristics of the three test solenoid coils are shown. During all tests, the dewar was filled to 50-70% of capasity and then several quenches were made, with the helium level dropping to 20% before refill. The INNER Coil C was most sensitive to the dewar level, as the irregular training pattern shows.

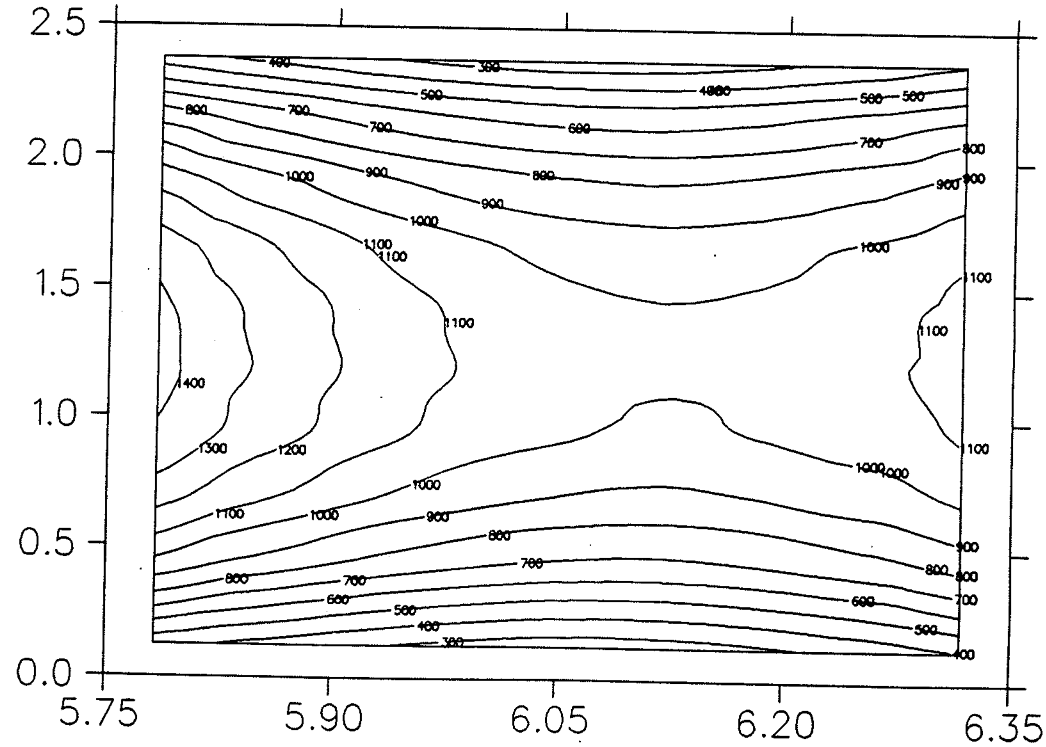

Figure 5. Coil A-- maximum shear stress. The numbers on the contours are stresses in psi (14.7 psi = 0.1 MPa).

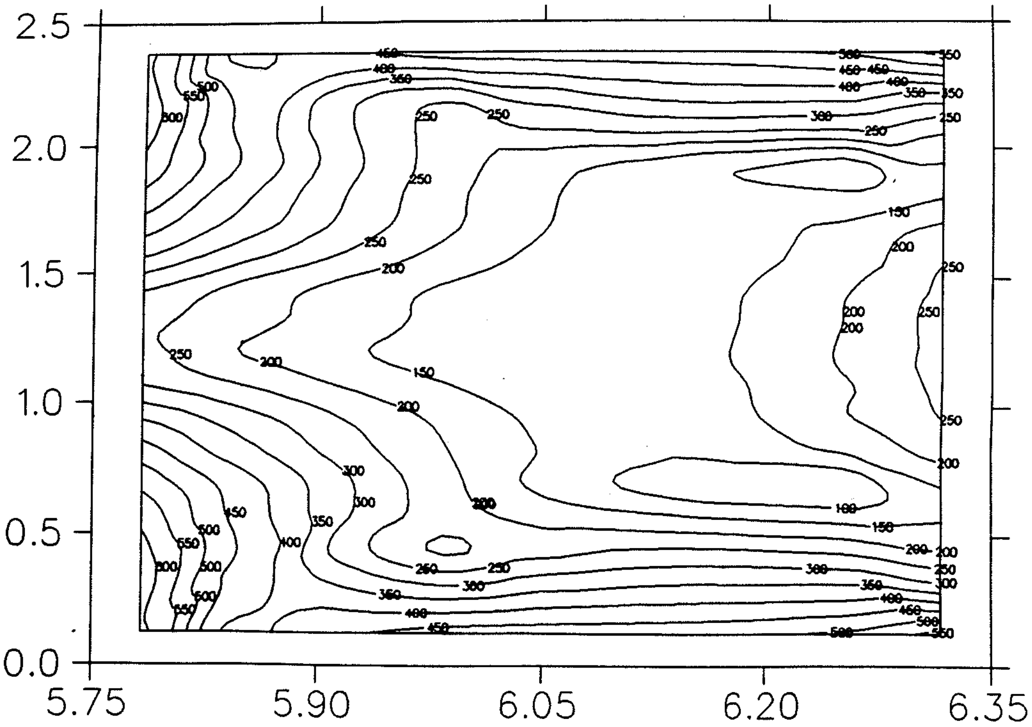

Figure 6. Coil B-- maximum shear stress.

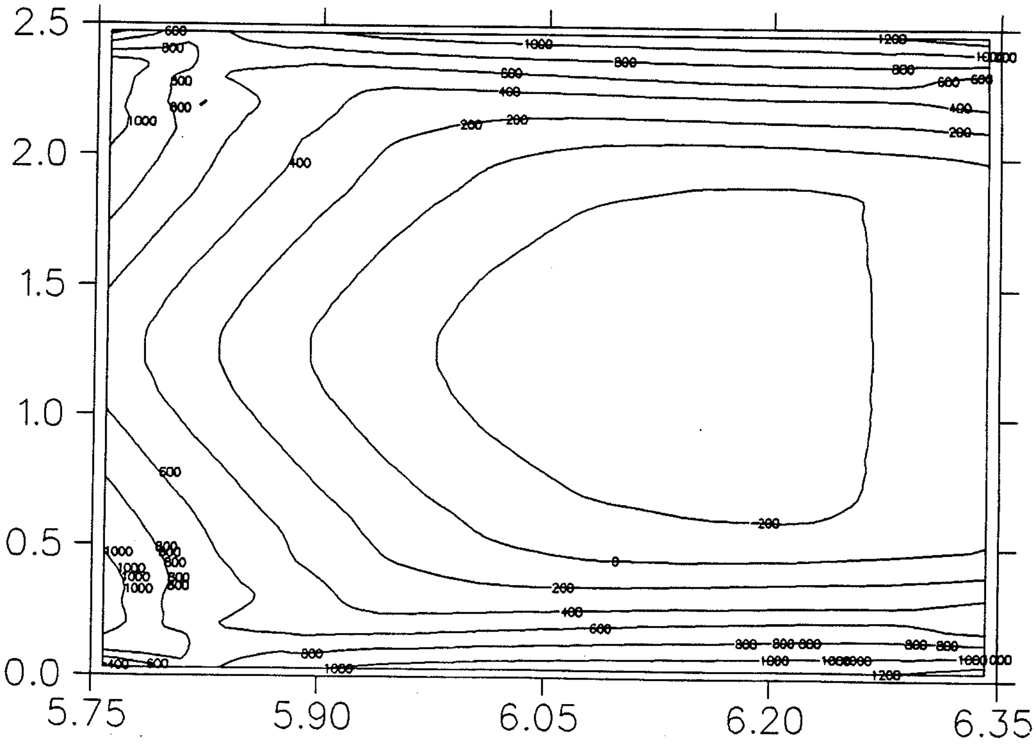

Figure 7. Coil B-- maximum principal stress. Positive values are tension and negative values are compression pressures.

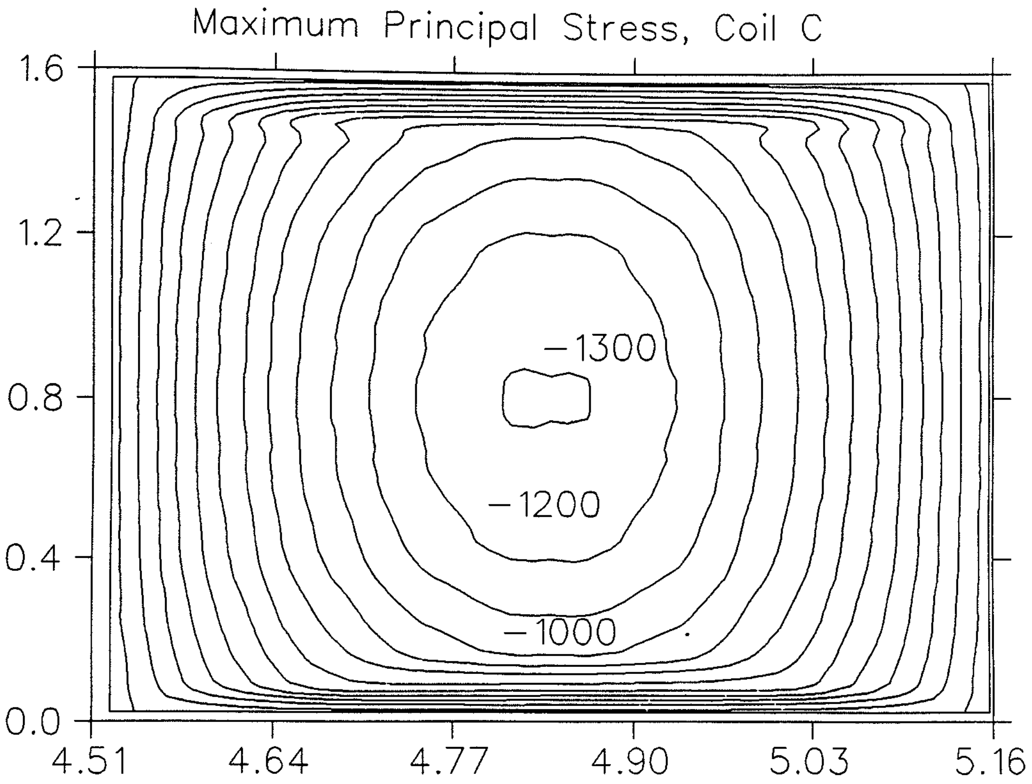

Figure 8. Coil C-- maximum principal stress.