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SUMMARY OF CONSTRUCTION DETAILS AND TEST PERFORMANCE OF RECENT SERIES OF 1.8 METER SSC DIPOLES AT BNL*

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ABSTRACT

Certain design features of the SSC dipole magnets are evaluated with 1.8-meter models built and tested at BNL. We report the results of recent tests of such magnets relating quench performance and field quality measurements to mechanical design and assembly features such as collar material, collared coil dimensions and fit with the yoke and coil prestress level.

DISCUSSION

Description of Magnets Tested

The five magnets that are described in this report represent the SSC Baseline Design for the 40mm aperture dipoles. The coil cross-section is known as C358D and has been described in detail in other publications[1]. The cross-section of the cold mass is shown in Figure 1. The five magnets all have several common features which include the following:

a. Nitronic 40 stainless steel collars (90 Kpsi minimum yield strength).
b. Collars spot welded in pairs, alternating L/R to produce a twist free collared coil assembly.
c. Zero clearance nominal fit between collars and yoke, at room temperature.
d. One piece, 1½-inch thick end plates.
e. Ends of coil loaded by means of set screws mounted in end plates.
f. Epoxy bonded stainless steel yoke blocks on ends for axial rigidity and lowering field at end.
g. A beam type strain gauge transducer mounted at the minimum coil size section to measure inner and outer coil polar stress.
h. Forty one voltage taps to locate the origin of quenches.

* This work supported by the U.S. Department of Energy

[1] BNL -43775, "Status Report on SSC Dipole R&D"

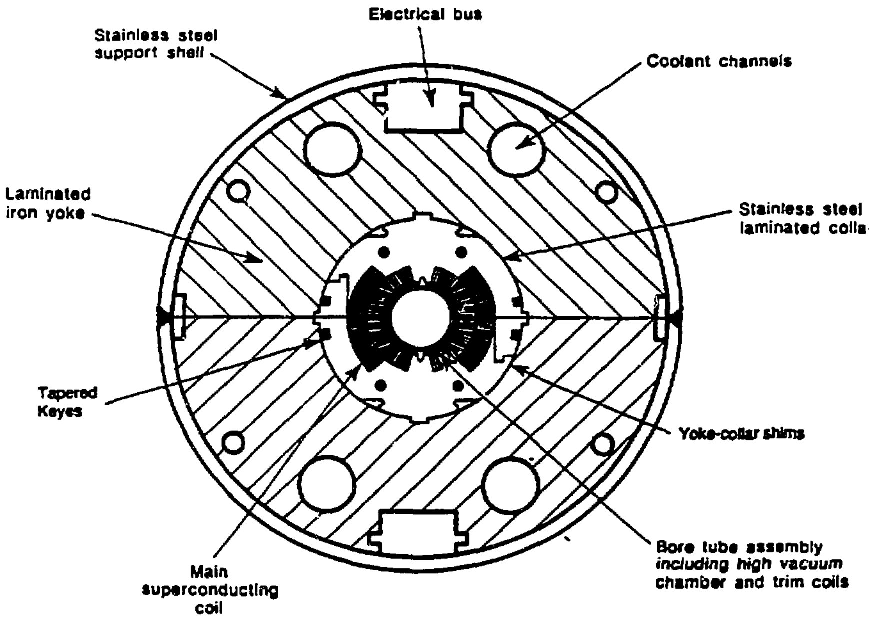

Figure 1.

In addition to these common features, two of the tests were with magnets that had a design variation of the collar to reduce the vertical ovality of the collared coil assembly (DSV016 and DSS019). This type of collar has been called "anti-ovalizing". The reduction in vertical ovality has been achieved by relocating the slot for the tapered key by .010 inches closer to the midplane. This results in an unloaded collar assembly that is slightly flat (nominally .010) but stretches to a round shape (still with some vertical ovality) when containing the assembled coils.

The superconducting cables used in the inner and outer coils were of two slightly different types whose characteristics are shown in Table I. This table includes the measured value of the current density in the superconductor and the critical current carrying capacities for the inner and outer cables.

Assembly Characteristics

Starting with the collaring operation, the inner and outer coil stresses are measured with the beam type strain gauge collar pack[2]. A typical stress history for the collaring and subsequent operations is show in Figure 2 for DSS017. Some significant stress values are as follows for the inner coils:

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[2] C. L. Goodzeit, et al., "Measurement of Internal Forces In Superconducting Accelerator Magnets with Strain Gauge Transducers", IEEE Trans. Magn. 25, No. 2 (1989):1451

Table I

Cable Characteristics of Magnets

A. Inner Coils

Magnet	Wire Mfg.	Cable Jc (5T) A/sq mm	Cable Ic (7T)	JCu @ Ic	Cu:SC	Filament Dia. (μ)
DSS016	IGC	2775	7741	1104	1.47	6.0
DSS017	IGC	2775	7741	1104	1.47	6.0
DSS018	OST	2682	7020	985	1.53	6.0
DSV016	IGC	2775	7741	1104	1.47	6.0
DSS019	OST	2682	7020	985	1.53	6.0

B. Inner Coils

Magnet	Wire Mfg.	Cable Jc (5T)	Cable Ic (5.6T)	JCu @ Ic	Cu:SC	Filament Dia. (μ)
DSS016	IGC	2549	8130	1300	1.72	4.8
DSS017	IGC	2549	8130	1300	1.72	4.8
DSS018	IGC	2549	8130	1300	1.72	4.8
DSV016	IGC	2549	8130	1300	1.72	4.8
DSS019	SCN	2715	8586	1365	1.75	6.0

Manufacturers: ICG - Intermagnetics General
OST - Oxford Superconducting Technology
SCN - Supercon

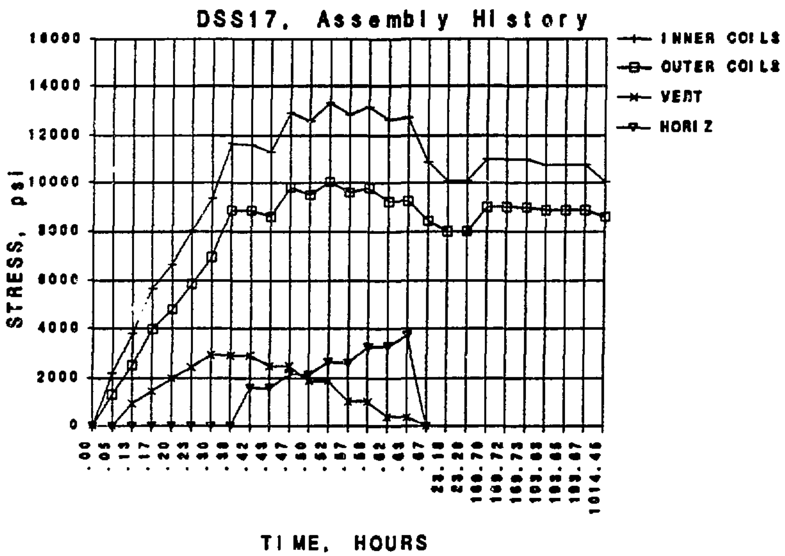


Figure 2

The maximum stress during the collaring operation occurs usually when the tapered keys are just starting to be inserted and in this case reaches a value of about 13,000 psi. After the keys are inserted (.67 hours), the hydraulic pressure is relieved and the stress immediately drops to ~11,000 psi. Note that there is a loss of stress due to creep in the first day after collaring of about 1000 psi (~10%). After about a week the shell has been welded around the yoke and the weld shrinkage causes an increase in the coil stress by about 1000 psi as the ovality of the collared coil is reduced by compression in the yoke.(Note that this is a line to line fit collar-yoke assembly). The coil continues to creep, but at a slower rate now and after about 33 days has relaxed another 700 psi. A summary of these significant stress values for the five magnets is shown in Table II.

Collared Coil Ovality Measurements

The structural response of the collars to the load applied by the prestressed coils is to produce a vertical deflection or ovality with little or no horizontal deflection. This action can be understood by referring to the force diagram of the collars as shown in Figure 3. The reaction of the keys on the collars produces a moment which tends to bend the collars inward at the midplane while the tensile hoop stress tends to stretch the collar vertically. The measured vertical and horizontal deflections along the length of a collared coil are shown in Figure 4 for DSS017. Since the ends of the coils are rather compressible compared with the straight section, the reduced loads on the collars produce a smaller distortion in those sections. In order to partially compensate for the ~.012 inch vertical deflection, the location of the key slots in the standard collars has been moved .010 inch closer to the midplane for

Table II

Summary of Significant Coil Stresses During Assembly
(stress in psi)

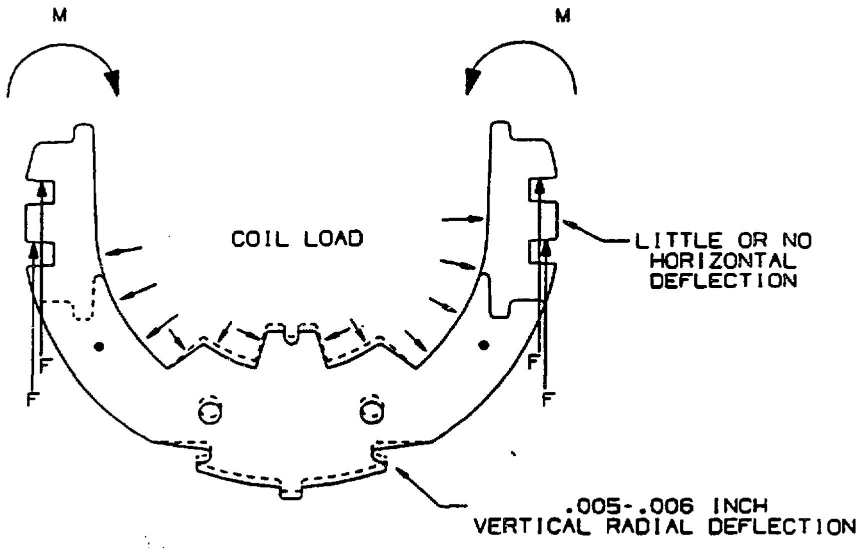
A: Inner Coils

Magnet	Maximum Collaring	After Collaring	Delta	Before Welding	After Welding	Delta	Comment
DSS016	11315	8876	-2439	8165	7772	-393	Note 1
DSS017	13300	10888	-2412	10102	11015	913	
DSS018	11839	9316	-2523	7875	8879	1004	
DSV016	12034	11964	-70	11280	13350	2070	Note 2
DSS019	11356	9532	-1824	8200	8520	320	Note 2

B: Outer Coils

Magnet	Maximum Collaring	After Collaring	Delta	Before Welding	After Welding	Delta	Comment
DSS016	7660	5984	-1676	5587	6091	504	
DSS017	10047	8422	-1625	8007	8868	861	
DSS018	8010	6158	-1852	5292	6221	929	
DSV016	8259	8049	-210	7717	9826	2109	Note 2
DSS019	6653	5510	-1143	5070	5316	246	Note 2

Notes:
1. Stress loss caused by overheating of magnet due to abnormal shell welding condition.
2. Anti-ovalizing collars used in this assembly.



REACTION FORCES (F) OF KEYS AND
MOMENTS (M) ON COLLAR PAIRS

Figure 3

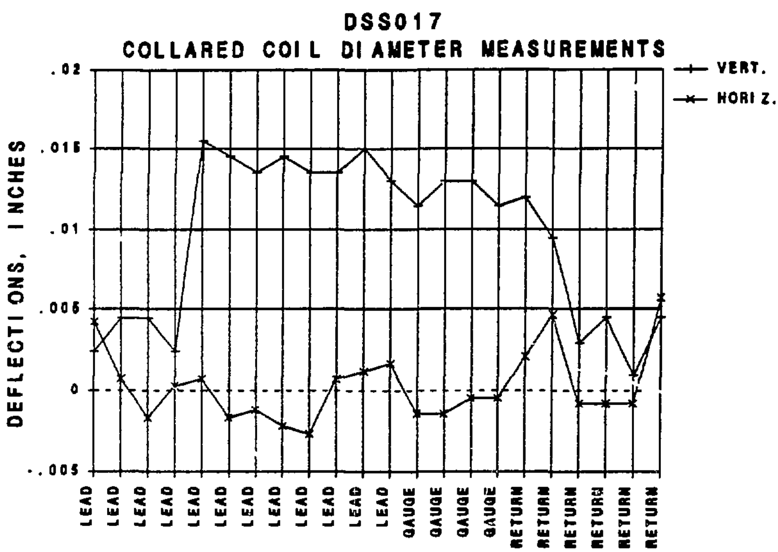


Figure 4

the anti-ovalizing effect. In the case of the five magnets that are reported, three of them had regular collars and two (DSV016 and DSS019) were assembled with anti-ovalizing collars. The vertical deflections of the collars (at the strain gauge transducer location) for these cases is shown in Figure 5 along with the calculated value of the ovality based on the structural model of the collar. According to these measurements, the sensitivity to coil stress level tracks well with the calculation. It is also seen that for the anti-ovalizing collars, the vertical deflection has been reduced from typically .012 inch to the .004-.007 inch range.

Quench Performance The complete quench-test history of one of the magnets, DSS018, is shown in Fig. 6. The test sequence is typical of all the magnets discussed in this paper. After initial studies at the SSC design operating temperature, 4.35 K, the mechanical reserve of the magnet is tested as the temperature is reduced in 0.5 K steps. Following further testing at 4.35 K the magnet is taken to room temperature and then recooled to 4.35 K (thermal cycle) to determine whether it retains its initial training. At each temperature, most of the quenches occur during a ramp at 16 A/sec., but during the last run to quench the current is increased stepwise so that the strain gauge readings can be taken at constant current. Also at each temperature, the magnet's performance at the limit of the conductor is compared to an estimate based on the current-carrying capacity of a short (1 m) sample of cable taken from the same spools used to wind the magnet. In the case of DSS018, the estimate is very close at SSC conditions. (The temperature dependence of the estimate is an average over a number of cables.)

The quench histories of the five magnets reported here are given in summary form in Fig. 7. The initial training is limited to one or two quenches, the magnets reach the limit of the conductor at 3.35 K at central fields of approximately 8 T with little additional training, and retraining is negligible. (For DSS017, after the thermal cycle, the magnet was initially tested at 3.35 K, as indicated.)

Multipole Measurements. The 1.8 m models are not "field quality" magnets (made as identically as possible) since they are still being used as test beds for refinements in production. Thus, the focus is on understanding the relation between the measured field uniformity and magnet construction rather than on detailed comparison with SSC tolerances. For this discussion, it is most interesting to ask whether there are differences between the three magnets made with standard collars (DSS016, DSS017, DSS018) and the two with anti-ovalized collars (DSV016, DSS019).

The standard expression for the multipole representation of the fields is:

$$B_y + iB_x = B_o \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

The multipole coefficients are evaluated at a radius of 1 cm, in dimensionless units of 10^{-4} of the dipole field.

The measured allowed and unallowed geometric coefficients at 4.35 K are given in Tables III and IV, respectively. Apart from differences in collars, two factors are known to significantly affect the multipoles. First is magnet-to-magnet differences in the sizes of the shim placed between the pole turn of the coil and the collar. The shim size is changed to make the prestress as uniform as possible while the development of coil curing procedures is underway. Second is out-of-tolerance

Table III. Allowed Multipoles (10^{-4} units)

Multipole	DSS016	DSV016	DSS017	DSS018	DSS019
b_2	-3.21	1.33	0.44	-1.39	-2.45
b_4	-0.53	-0.62	-0.72	-0.79	-0.58
b_6	0.03	0.13	0.06	0.08	0.04
b_8	0.04	0.03	0.04	0.03	0.04
b_{10}	0.06	0.07	0.07	0.07	0.07
b_{12}	-0.01	-0.01	-0.01	-0.01	-0.01

Table IV. Unallowed Multipoles (10^{-4} units)

Multipole	DSS016	DSV016	DSS017	DSS018	DSS019
b_1	-0.73	-0.36	-1.06	-0.19	0.41
b_3	-0.22	-0.11	-0.13	-0.03	-0.15
b_5	-0.02	-0.01	-0.01	-0.02	0.01
b_7	0.00	0.00	-0.01	0.00	0.00
b_9	0.00	0.00	0.00	0.00	0.00
b_{11}	0.00	0.00	0.00	0.00	0.00
a_1	0.09	-0.30	-2.62	-1.34	-1.79
a_2	-0.57	-0.63	-0.39	-0.16	-0.20
a_3	0.01	0.46	0.44	-0.02	0.42
a_4	-0.11	-0.12	-0.09	-0.02	-0.07
a_5	0.00	0.03	-0.03	-0.04	-0.02
a_6	-0.02	-0.01	-0.03	0.00	0.00
a_7	0.00	0.02	0.01	0.00	0.00
a_8	0.00	0.00	0.00	0.00	0.00
a_9	0.00	-0.01	0.00	0.00	0.00
a_{10}	0.01	0.01	0.00	0.01	0.01
a_{11}	0.00	0.00	0.00	0.00	0.00
a_{12}	0.00	0.00	0.00	0.00	0.00

distortions in the stainless steel shell which is welded around the yoke. These magnets have used such shells, while a satisfactory vendor was being identified. Both of these factors are expected to improve in production. For these magnets, no differences in either the allowed or unallowed multipoes can be traced to the type of collar.

Magnet Testing Measurements

The coil stress measurements made by the beam type strain gauge transducers are compensated for thermal and magnetic effects and therefore can accurately measure the coil stress of the magnet under operating conditions. However, stress measurements during cooldown from ambient to operating temperature are not regarded as reliable because of the large variation in strain gauge grid resistance between 15K and 100K. Thus, we can only obtain reliable measurements near ambient temperature or at operating temperature in the range 3.5K to 4.5K. The changes in coil stress due to cooldown and magnet excitation are discussed below:

Thermal Stress Loss

A summary of the stress changes of the five magnets tested for the inner and outer coils are listed in Table V. Except for the case of DSS019, the stress loss is significantly larger than what would have been calculated from the intrinsic thermal contraction properties of the yoke, coilar and coil materials. This effect has been

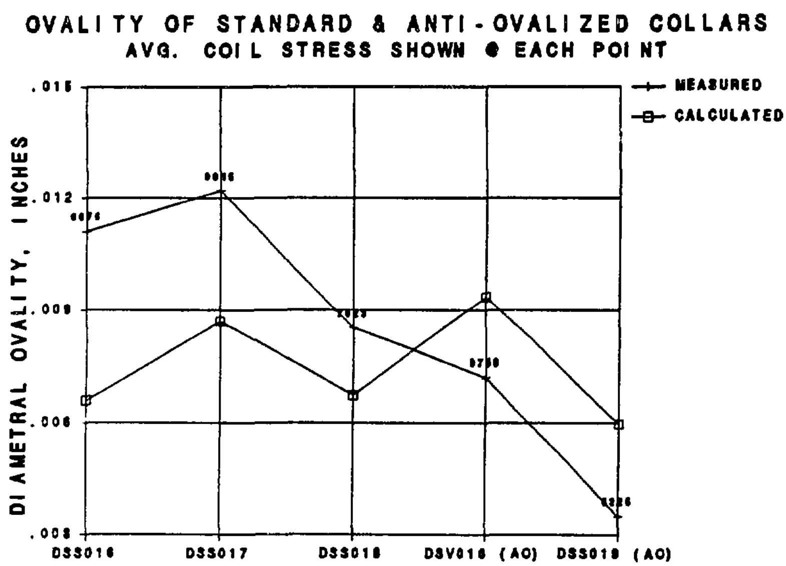


Figure 5

Table V

Coil Stress Changes During Testing
(σ is stress in psi)

A: Inner Coils

Magnet	σ Start Warm	σ Start Cold	Delta σ	σ End Warm	Global Delta σ	Comment
DSS016	7651	3143	-4508	7669	18	
DSS017	10039	5540	-4499	9393	-646	
DSS018	6914	3218	-3696	6043	-871	
DSV016	12282	8594	-3688	10607	-1675	Note 1
DSS019	7364	4991	-2373			Note 1

B: Outer Coils

Magnet	σ Start Warm	σ Start Cold	Delta σ	σ End Warm	Global Delta σ	Comment
DSS016	6063	3027	-3036	5570	-493	
DSS017	8586	6642	-1944	8119	-467	
DSS018	5223	3213	-2010	4787	-436	
DSV016	9418	6946	-2472	8674	-744	Note 1
DSS019	4349	3408	-941			Note 1

Notes:
1. Anti-ovalizing collars used in this assembly.

attributed to the effect of coil ovality on the fit between the collared coil and the yoke and has been analyzed by Chapman, et. al.[3] This analysis and measurements, as well, show that the coil ovality produces an extra force between the collars and yoke which appears as compressive stress in the coils. When the magnet is cooled, the extra force decreases as the fit between the collars and yoke changes. Collars with the greatest amount of ovality show the largest thermal stress loss. In the magnets that are reported here, the least oval collared coil assembly was that from magnet DSS019. Figure 5 shows the diametral ovality to be about .0035 inches compared to .010-.012 for the other magnets. Note that the thermal stress loss for this case was also the lowest as shown in Table V.

Stress Change During Magnet Excitation

When the magnet is energized, the Lorentz forces tend to pull the coils away from the poles and compress it more at the midplane. Since the coil stress transducers measure the polar stress, one can see this effect from the measurements of the coil stress as a function of magnet current. Figure 8 shows the measurements of the polar coil stress for DSS017 up to the ~8000A. At the operating current of 6500A (for 6.6T), the inner coil stress has dropped from about 4200 psi to 1200 psi for a 3000 psi change which is about 90% of the value predicted by analysis without

[3] M. Chapman, et. al. "Mechanical Analysis of Different Yoke Configurations for the SSC Dipole", From the SSC Central Design Group (No report number)

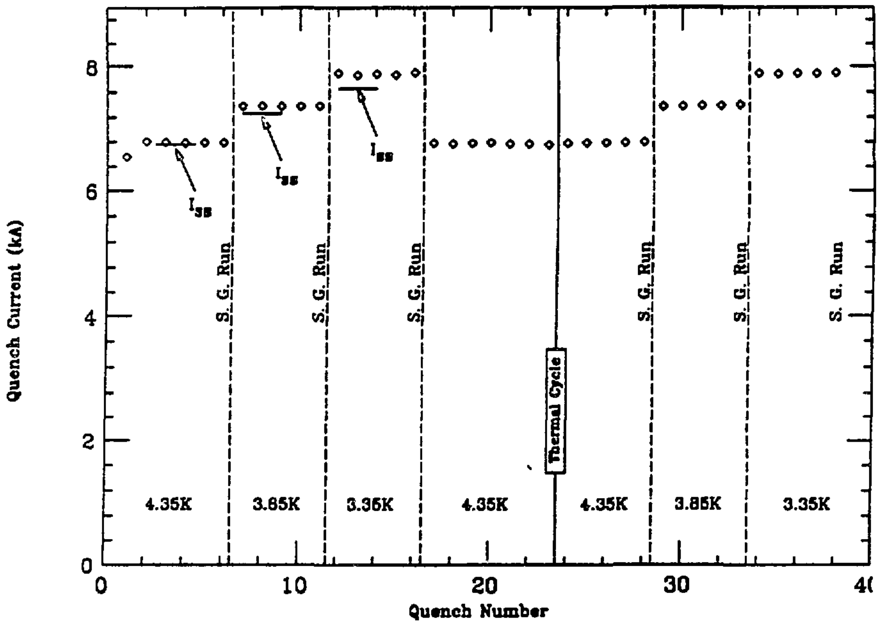


Figure 6. Quench performance of DSS018.

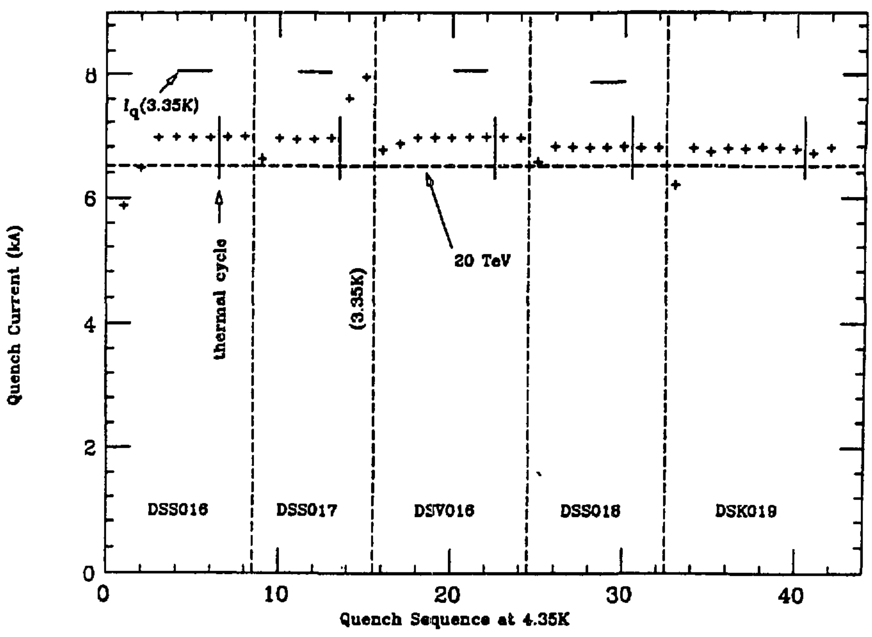


Figure 7. Initial and 3.35 K quench performance of five magnets tested.

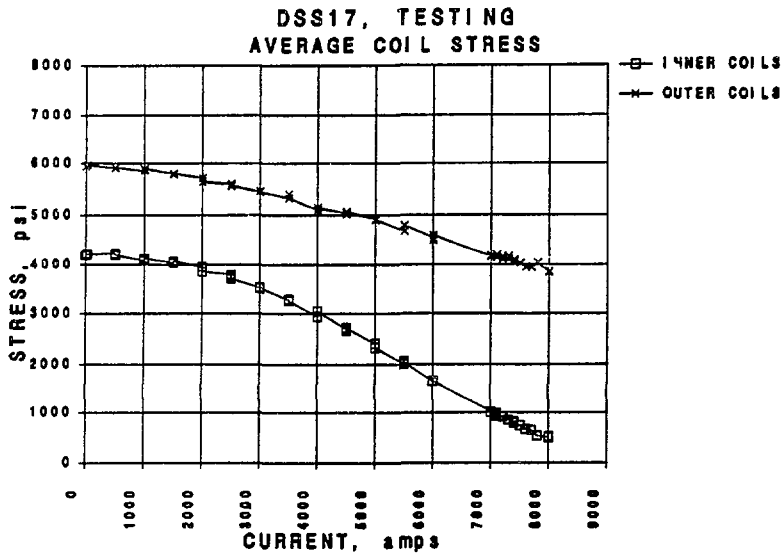


Figure 8

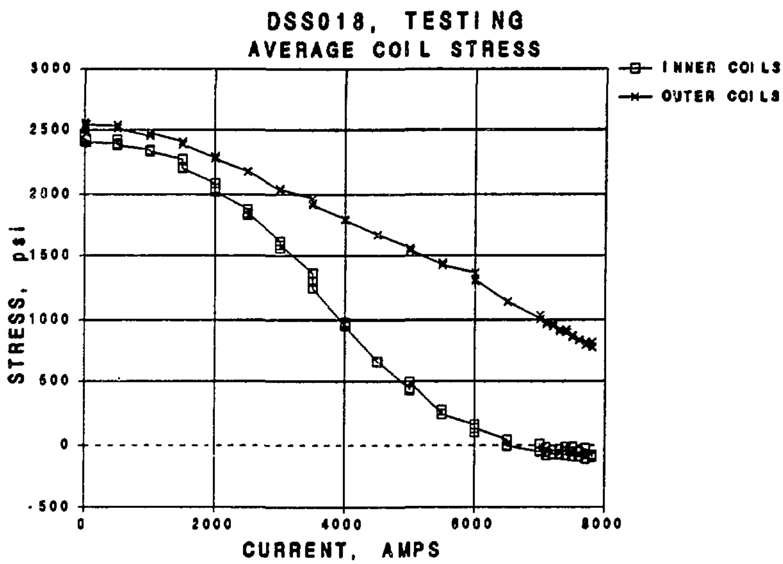


Figure 9

friction. The Lorentz forces on the outer coil are less than those on the inner coil and this effect is also seen by the drop of about 1500 psi for the outer coil stress at operating current.

A specified operating condition for the magnet is to maintain positive contact between the coil and the pole at operating current. This requires that the initial prestress of the collared coil be high enough to ensure that this condition is met. The coil stress measurements indicate that a minimum cold coil stress (for the inner coil) is sufficient to keep the coil in contact with the pole. However, during the R&D phase of the program this condition was not always met. In this case the polar turn of the inner coil would show no compressive stress and such a case is seen for DSS018 in Figure 9. In this case it is seen that the stress does not appear to decrease quadratically with current but shows an inflection and drops to zero at about 6000 A.