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Shear Tests of Injection Molded Composite Posts Simulating Hydrostatic End Loads on a Magnet Cold Mass

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Conclusions

1. A single center post for the RHIC dipole magnet, constructed of injection molded Ultem 2100, is capable of resisting a 12 500 pound hydrostatic end load in combination with a 3 000 pound dead weight of the cold mass without the assistance of diagonal straps. This conclusion is predicated upon the condition that the posts sections are bolted to saddles and cradles capable of transmitting 80 000 pound inches of bending moment through to the vacuum vessel and to the cold mass.

2. A good value for the horizontal stiffness of a center post of Ultem, so constructed and fixed, is 45 000 pounds/inch in the direction of the ion-beam and 21 000 pounds/inch in the lateral direction.

3. The Noryl post sections cast so far have not exhibited the quality needed for a resisting the hydrostatic end thrust. However, there is greater strength potential which may be realized through changes to the mold currently in work. Eliminating knit lines in the castings should produce the flaw-free posts needed.[1]

4. Stainless steel backup rings are required on the saddle and cradle flanges of the posts in order to carry the 12 500 pound load. Backup rings are not needed on the heat shield flange.

5. The end posts, which are weaker because they do not benefit from a moment transfer connection to their cold mass cradles, have the ability to add at least a 50% safety margin to the end load capacity of the RHIC dipole support system.

6. The horizontal stiffness of an end post of Ultem, so constructed and fixed, is 21 000 pounds/inch in both the ion-beam and in the lateral directions.

7. Changes to the mold now in work, to eliminate the knit lines, have the potential of increasing the post strength by at least 50%.

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[1] Wolf, L..J., *Tensile Tests for Quality Control of Injection Molded Composite Posts, Brookhaven National Laboratories*, Technote AD/RHIC 78, August, 1990.

Background

The injection molded composite (IMC) posts will replace not only the shrink-fitted fiberglass reentrant posts, but also the diagonal straps. The purpose of diagonal straps are to resist the end load due to pressure upset conditions. Since the IMC posts replace the diagonal fiberglass straps as well as the posts, the IMC posts are included in a structural system which must carry the end load. The structural concept upon which the design is based is one in which the lateral bending resistance of the post becomes paramount, and the cold mass cradle becomes a part of the bending moment transfer mechanism.[2]

The crystat design specification for the end load on the dipole magnet cold mass is 12 500 pounds. (The estimate of the actual end load due to a pressure upset is approximately 5 000 pounds.) In terms of the adverse effects upon the posts, the end load is a more severe condition than are the dead weight, seismic, or the dynamic transportation loads. Although, all the other loads continue to be investigated, the 12 500 pound end load governs the conceptual design of the structural system for supporting the cold mass.

The structural system conceived for resisting the end load without the use of diagonal straps is shown schematically in Figure 1. The support cradles at the top of the two end posts allow the cold mass to expand and contract axially. However, there are stops on these cradles which contact the side posts when the cold mass is fully cold and fully warm. The cradle atop the center post is fixed to both the cold mass and the post in all rotational and translational directions.

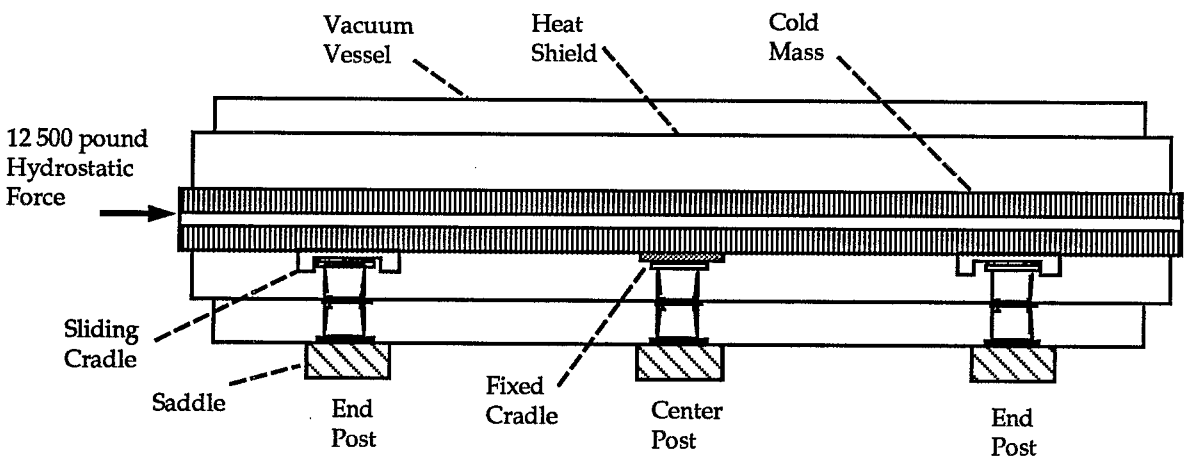

Figure 1. Foreshortened representation of the structural system supporting the cold mass of the RHIC dipole magnet.

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[2] Wolf, L.J.. *Structural Concept for Support of the RHIC Cold Mass Using Injection Molded Composite Posts*; Brookhaven National Laboratory; Technote AD/RHIC-65; February, 1990

A cold mass support post was designed of two sections (Sometimes called "hats.") to be injection molded from a composite material which exhibits high strength and low thermal conductivity. The design of the IMC post is shown in Figure 2. Each section consists essentially of a cylindrical shell, approximately 8-1/2 inches in diameter and 4-1/2 inches long, having a thickness of 3/16 of an inch. The shell has a 1/2 inch thick flange at each end for bolting. The flange is external at one end of the shell and internal at the other. The sections are connected with twelve-7/16 bolts on the external flange and twelve-3/8 bolts on the internal flange. The shell has a slight conical angle of 1-1/2° which is a draft angle to facilitate removal of the casting from the mold.

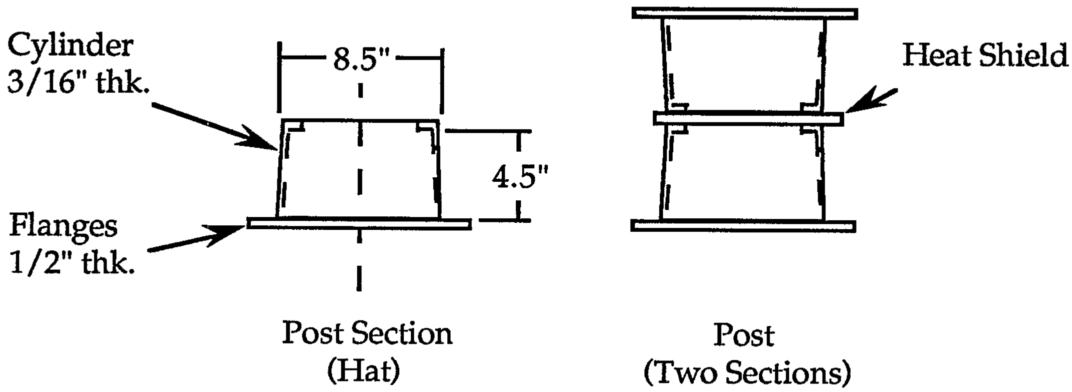

Figure 2
The basic dimensions of the injection molded test posts.

Two candidates, Ultem® 2100 and SE1-GFN3 Noryl®, have been investigated for the IMC material. Ultem is a polyetherimide resin. The 2100 grade is reinforced with glass fibers about 3mm in length to make up 10% of its weight. Noryl is an alloyed resin. The SE1-GFN3 grade has glass fibers making up 30% of its weight. Both Ultem and Noryl are thermoplastic rather than thermosetting plastic materials. Developed by General Electric Company, they are marketed in sacks of pellets for injection molding. With a deflection temperatures of 400°F, molders regard Ultem as a relatively high-melting structural plastic.

Test Fixture

A test fixture shown in Figure 3 was built to test the posts under the shearing force and bending moments likely to be encountered. Two identical posts are tested together in order to get the opposing bending moments at the opposite ends of the posts. Simultaneously, a force of 3 000 pounds was applied using a hand-pumped hydraulic cylinder to simulate the dead weight of the cold mass. The test fixture has been carefully designed and constructed to have about the same bending stiffness as the cold mass itself so as to give a truly representational test. Since there are two posts sharing the load in the test fixture, the testing force needs to be twice the 12 500 shear force for which the posts are designed.

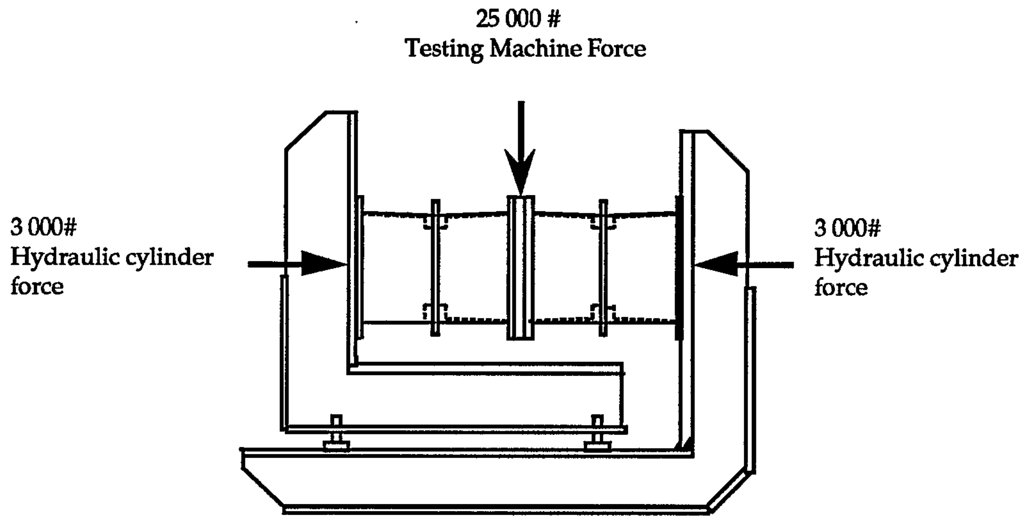

Figure 3. Test fixture simulating the worst conceivable loading upon the IMC posts.

Shear Tests on Center Post

Tests were conducted on Ultem and on Noryl Posts. The results are given in Table 1. In every case, a constant horizontal end load of 3 000 pounds was hydraulically applied to the test fixture, and held constant as the testing machine force was increased from zero.

The first Ultem posts tested in shear failed to reach the required 25 000 pounds. The post sections broke at the flanges indicating the need for backup rings. Also, other castings from that batch later failed to meet the quality control test.[3]

The test on Noryl, conducted on 7/3/90, also failed to produce the 25 000 pound load capacity. Backup rings on the external flanges were used during this and all future tests. Again, castings from this first batch of Noryl failed the quality control test.

The tests on Ultem on 7/9/90 and 8/3/90 did reach the 25 000 pound load capacity. The force-deformation curves for these tests are given in Figures 4 and 5. As can be seen from the graph, the test on 8/3/90 was a cyclic one in which the test load was increased by 5 000 pounds each cycle. The castings were selected from a batch which had been properly pretreated before injection molding. Castings from this batch did exceed the quality control

[3] Wolf, L. J., Op..Cit., *Tensile Tests for Quality Control.......*

standard. The castings for the test on 8/3/90 had been subjected to a 20 000 pound tension test before being installed it the fixture for this test. Backup rings were used for both tests.

Table 1
Proof Tests of IMC Posts

Date of Test	Material	Serial Numbers of Sections Installed	Ultimate Force Pounds
6/21/90	Ultem	U1, U2, U3, &U4[1]	12 400
7/3/90	Noryl	N11, N12, N19, &N20[1,2]	17 720
7/9/90	Ultem	U11, U12, U13, &U12[2]	25 020
8/3/90	Ultem	U16, U17, U22, &U23[2]	26 740

[1] Castings from this batch failed the quality control test.
[2] Backup rings installed on flanges.

Failure Modes

The first test, without backup rings, was obviously a flange failure.The last three tests conducted were shell wall failures. In these tests, at least two of the four post sections under test failed. Both tension failures and compression failures occurred. They happened where one would predict their presence from simple beam theory. Tension failures tended to propagate from knit-line regions. Compression failures took the form of brittle buckling and were explosive. Plexiglass shields were used to protect the operators from the shards.

Deflection Measurement

Deflection was measured at three points on the loading fixture; at the testing machine force application point, and at both heat-shield flanges. Dial gages were used at first to measure the heat-shield flange deflection, while the central deflection was measured electronically and recorded. It the last test, linear potentiometers were used to give a plot of the heat-shield deflections as well. The two heat-shield deflections were equally half the central deflection, which was as it should have been. Thus the stiffness and symmetry of the test fixture was confirmed, assuring that either one of the two posts was not getting more than its share of the load.

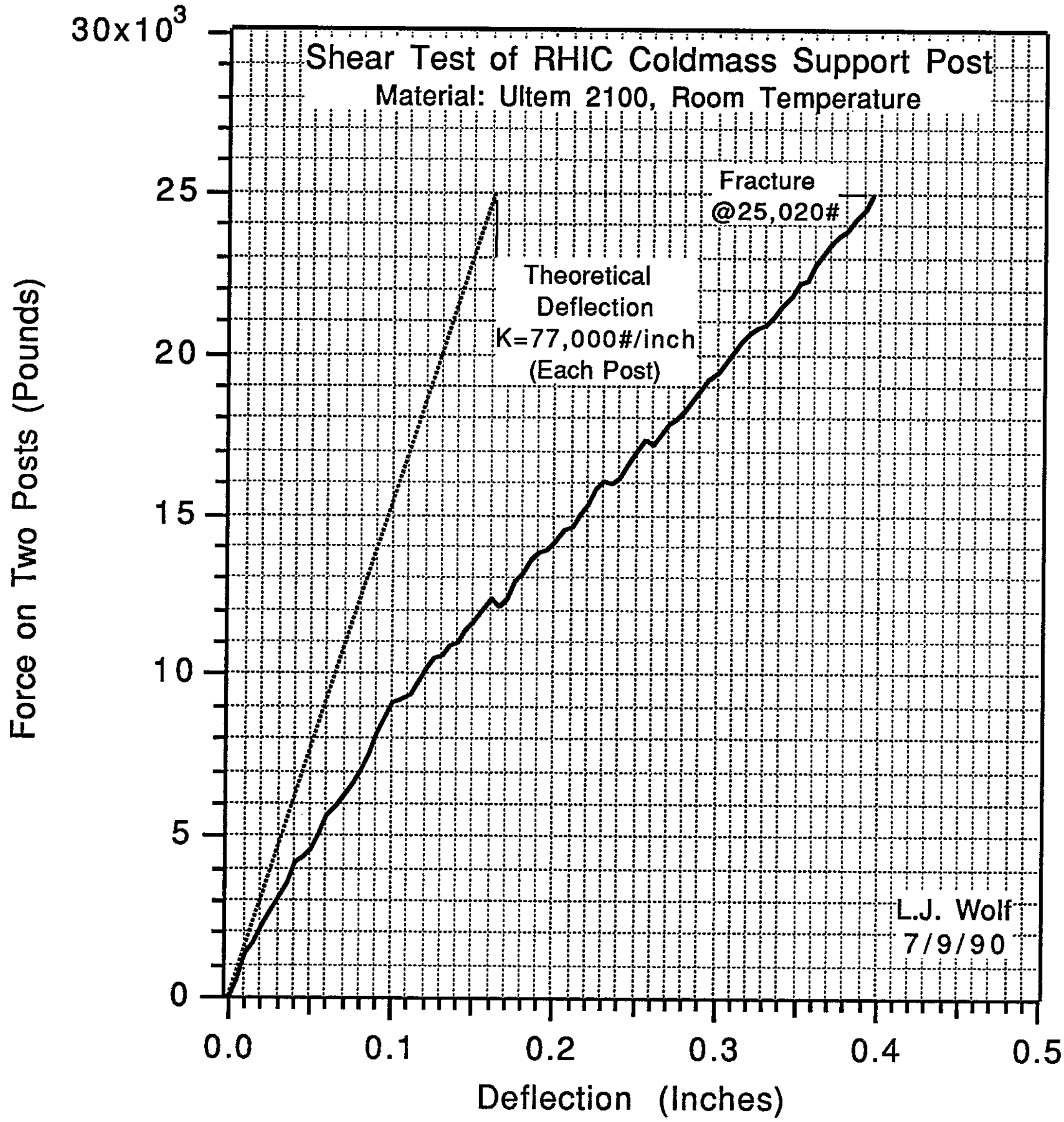

Figure 4
The force-deflection curve for the test conducted on post sections U11, U12, U13, &U12.

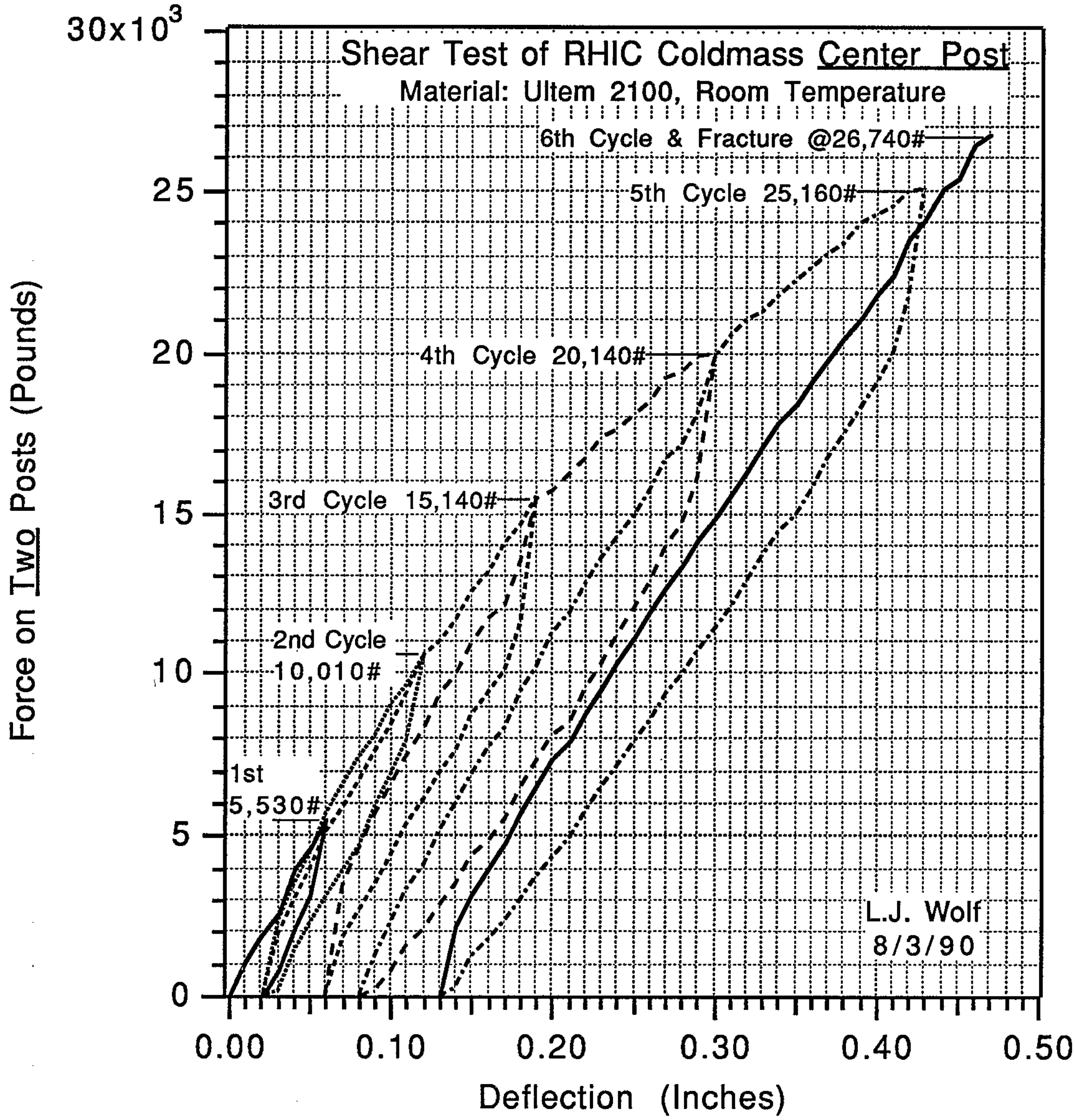

Figure 5
The force-deflection for the cyclic test conducted on post sections U16, U17, U22, &U23.

Stiffness of the Center Post

The stiffness of a post compares favorably with calculated values. However, I hasten to add that this is only at the very low initial loads. Beyond that it is a matter of definition. If defined as the slope of the load deflection curve, the stiffness falls to less than a third of its original value as it reaches its full load capacity. For example, the force-deflection curve for Figure 4 is tangent to a theoretical deflection line, computed from a finite element analysis of both the posts and the fixture, having a slope of 154 000 pounds/inch. But from a deflection of .1 up to the fracture point, the slope of the force-deflection curve is a fairly constant 54 000 pounds/inch, for the two posts.

However, it is not sensible to use either the initial or final slope as the model of reality. The initial slope will be buried in the plastic readjustments which all complex structures exhibit as load is applied. And, the final slope includes the effects of creep as well as of plasticity. In the case of bolted flanges, inelasticities include bolt slippage and local yielding around contact points.

A better method of determining a realistic stiffness value, is to cycle the load and then take the average slope of the loading and unloading lines as the structure shakes-down to elastic action at progressively higher loads. Deflections on these shake-down lines are at least repeatable, whereas those on a single load-deformation curve are not.

Figure 5 shows the effects of cycling on stiffness. At each level of load, the structure takes a permanent set and then conforms to an elastic line on which loading and unloading takes place. The set is not recoverable, unless the load is fully reversed to a negative value. At 15 kips, the unloading and subsequent loading lines show an average slope of 90 000 pounds per inch. At a load of 25 kips, an average stiffness of about 73 000 pounds/inch is observed. The higher load produces more hysteresis which is due to creep. Since more creep occurs at higher loads, the creep has the effect of lowering the apparent stiffness. Lower loads, shorter cycling times, and lower temperatures can be expected to show stiffer posts.

At a load level of 15 kips at room temperature the measured stiffness of a post is 45 000 pounds per inch, half of the 90 000 pound/inch of the two posts.

Calculated Stiffness

The deflection of a single fixed-ended cylindrical shell post like the center post can be calculated by simple beam theory from the relationship:

(1) $$\delta = \frac{FL^3}{192EI} + \frac{2L}{GA}$$

where δ is the deflection,
L is the overall length of the post (11.2 inches),
F is the force,
E is the elastic modulus,
I is the moment of inertia of area (44.3 inches^4),
G is the shear modulus ($E/2(1+\mu)$),
μ is Poisson's ratio (assumed to be .3),
and A is the cross sectional area of 5 square inches.

The first term in Relationship (1) is the deflection due to bending and the second is due to shear. In slender beams shear usually contributes little to the deflection. The shear flexibility is 98.5% of the total flexibility according to Relationship (1). This is due to the fact that the post is a short stocky beam. The stiffness, K, of a post is given by the relationship:

(2) $$K=F/\delta$$

Tensile tests of Ultem coupons cut from the castings give a value of .64E6 Psi.[4] for the modulus of elasticity at room temperature. The value at helium temperature, obtained from tests on vibrating beams, was found to be .94E6 Psi.[5] No value of μ has been obtained experimentally. Being that shear predominates in the deflection of the post, Poisson's ratio should be measured rather than assumed as was done here.

From Relationships (1) and (2), K for the Ultem post calculates to be 55 000 Psi. This compares to the measured stiffness of 45 000 cycling between zero and a load level of 15 kips. This is fairly good agreement for such a broadly defined parameter, considering the simplicity of the analysis. Presumably, the post stiffness at helium temperature can be estimated using Relationships (1) and (2) with similar accuracy.

Shear Tests on End Post

A side post can be simulated using one half of the test fixture as shown in Figure 6. A single post, consisting of Ultem sections U17 and U22, was tested as a cantilever beam. The 3 000 pound force, simulating the weight of the cold mass, was again applied with a hand-pumped hydraulic cylinder and was held constant throughout the test.

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[4] Wolf, L.J., *Compression and Creep Tests on Injection Molded Composite Posts*, Brookhaven National Laboratories, Technote AD/RHIC 77, August, 1990, p4.

[5] Wolf, Sondericker, and DeVito, *Elastic Moduli of Ultem and Noryl at Cryogenic Temperatures Using Vibrating Beam Specimens*, Brookhaven National Laboratories, Technote AD/RHIC /RD-21, June, 1990, p2.

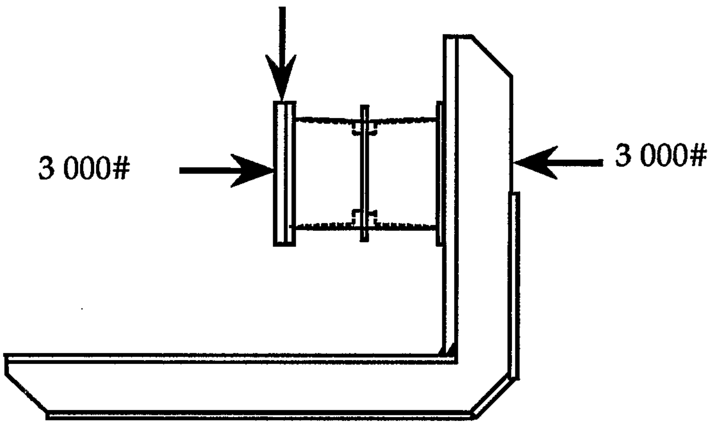

Figure 6.
Cantilever tests on an end post.

The results of a test, where the load was cycled as it was applied, are given in Figure 7. The deflection was measured directly under the testing machine force. The load was cycled five times to increasing levels until failure occurred. The first cycle is not included on the plot.

From beam theory, the end post should have about half the strength of the center post because the end post lacks the added rotational restraint at the free end. Here the full load of the testing machine bore upon the single post. Therefore, one would predict that the fracture load for this test would be one fourth that of the earlier test, or approximately 6 125 pounds. In fact it failed a 8 870 pounds, confirming that simple beam theory is quite adequate for these IMC posts. The fracture was a tensile one which took place in the shell near the flange which was bolted to the support fixture. The internal flange did not fail, even though it did not have back-up rings as did the external flanges. All of these were expected results.

Stiffness of the End Post

In the case of the simple fixed-free cantilever which is the end post, the shake-down to elastic action occurs more rapidly. Less permanent set takes place. The slope, taking the average of the unloading curve at the 8 kip level and the subsequent reloading curve, is about 21 000 pounds per inch. (The 8 kip level on the end post corresponds to the 16 kip level on the center post.)

The deflection of an end post could be calculated from simple beam theory using the following relationship:

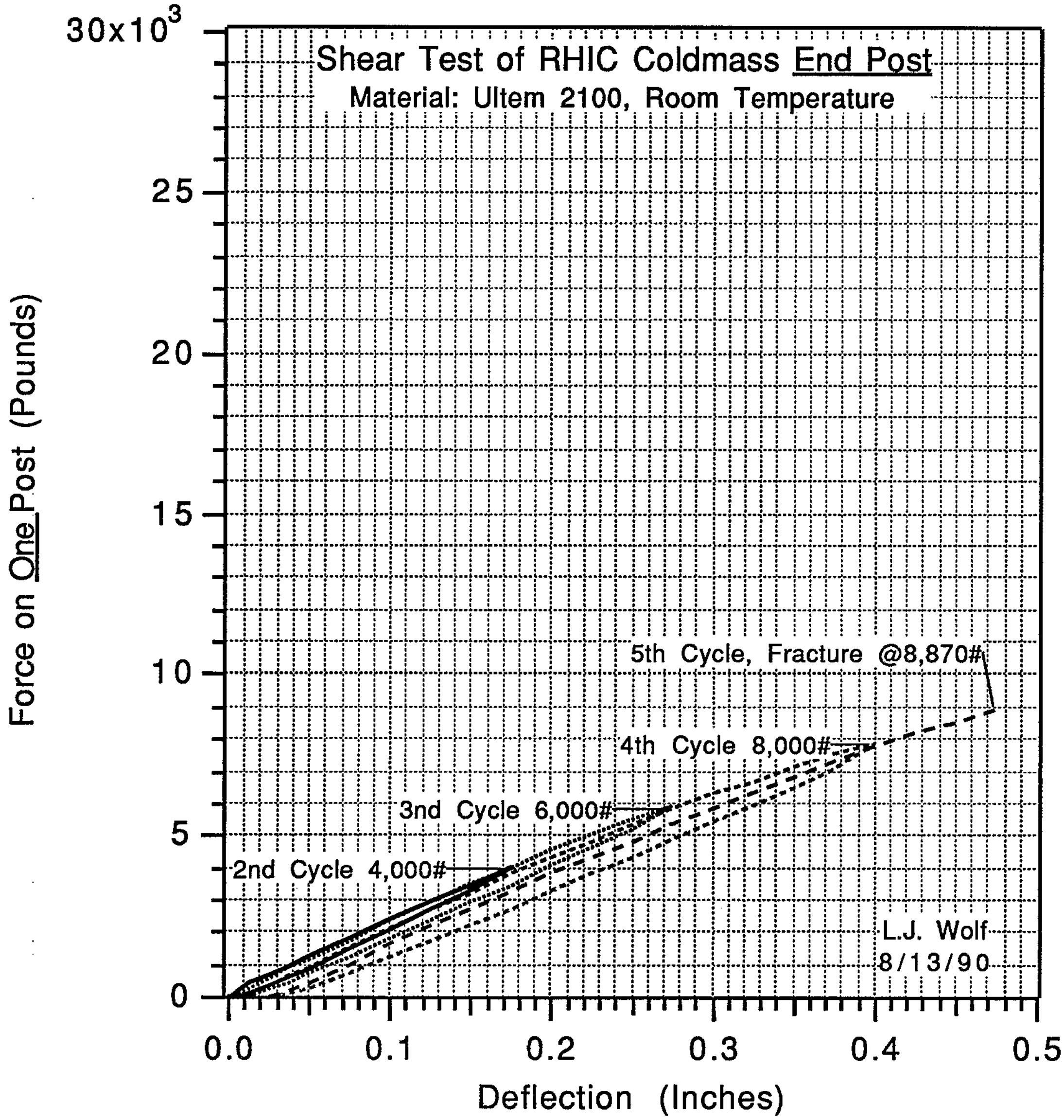
30x10^3
25
20
15
10
5
0
Force on One Post (Pounds)
Shear Test of RHIC Coldmass End Post
Material: Ultem 2100, Room Temperature
5th Cycle, Fracture @8,870#
4th Cycle 8,000#
3nd Cycle 6,000#
2nd Cycle 4,000#
L.J. Wolf
8/13/90
0.0
0.1
0.2
0.3
0.4
0.5
Deflection (Inches)

Figure 7

(3) $$\delta = \frac{Fl^3}{48EI} + \frac{2L}{GA}$$

The stiffness can then be calculated from Relationship (2). Here again, the shear deflection predominates, causing 94% of the deflection. But, it is a slightly lower contributor than in the center post. The value of K is 53 000 pounds per inch, which does not compare as nicely with the measured value as was the case with the center post. Apparently, bending has a larger effect upon the stiffness than was indicated by Relationship (3). That was actually quite obvious by observing the tests. Since the deflections of about 1/2-inch are in fact large and visible to the eye, it was easy to see the rotation of the loading plate in the case of the cantilever. Perhaps "large deflection theory" is more representative of the end post.

The end post stiffness is identical to the horizontal stiffness of the center post in the direction perpendicular to the beam tube. In that direction, the center post is also a fixed-free cantilever.

Expected Interaction Between the Center Post and End Posts

Since the total deflection at failure was .475 inches for the end post and .460 for the center post, it appears that the two are actually very compatible. Both could be expected to reach full load capacity in the event of a pressure upset causing an end thrust upon the cold mass. One of the end posts would be up against its stop, in a position to resist with an additional eight or nine kips for a safety margin. The center post would shake down to a stiffness of about twice that of the assisting end post, which is perfect for the end post which has only half the strength. The result would be a 50% margin of safety which is adequate for an unlikely occurrence, such as a pressure upset from only one end of the the dipole magnet.