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***Abstract*— The fastening of the National Compact Stellarator Experiment's (NCSX) modular coils presented a number of engineering and manufacturing challenges due to the high magnetic forces, need to control induced currents, tight tolerances and restrictive space envelope. A fastening method using high strength studs, jack nuts, insulating spacers, bushings and alumina coated shims was developed which met the requirements. A test program was conducted to verify the design. The tests included measurements of flatness of the spacers, determination of contact area, torque vs. tension of the studs and jack nuts, friction coefficient tests on the alumina and G-10 insulators, electrical tests, and tension relaxation tests due to temperature excursions from room temperature to liquid nitrogen temperatures. This paper will describe the design and the results of the test program.**

Keywords-Stellerator; Bolting; Testing; Cryogenic; Friction

I. INTRODUCTION

The NCSX mission was to investigate solutions to the problems of achieving high-β steady state operations and avoiding disruptions in a Magnetic Fusion Experiment (MFE) device. It was designed with a lower aspect ratio (R/<a>=4.4) than previous optimized stellarator designs, and a quasi-axisymetric (QA) magnetic field with low effective ripple (<1.5% at the plasma edge) [1].

The NCSX coil systems are comprised of 18 modular coils, 18 toroidal field coils, four pairs of poloidal field coils and a 48-coil set of trim coils. The stellarator core conceptual design, having a major radius of R=1.4 m, a magnetic field of B=1.2 to 2.0 T, and a pulse length of 0.3 to 2 seconds, was completed in 2003. The two largest component fabrication contracts began in 2004 and were completed with the delivery of the final vacuum vessel segment in 2006 and the final modular coil winding form in 2007. At the time the NCSX project was cancelled in 2008 due to cost and schedule over-runs, assembly of the first field period was underway, providing the opportunity to demonstrate the assembly techniques developed and which can be beneficial to future devices

The modular coils are assembled and bolted together into sets of three. Two 3-packs are then assembled over a 120° vacuum vessel segment to create a field period assembly. At final assembly the three field period assemblies are bolted together at the C-C joint to complete the modular coil set.

II. OVERVIEW

The NCSX modular coils are bolted together using 1-1/4" diameter studs at flanged connections. The design depends on a secure connection that can be adjusted at assembly to achieve tight dimensional tolerances [2]. Once bolted together the joints must resist high magnetic field loads during operation without slippage at cryogenic (77K) temperatures. The joints are also electrically isolated at the outer diameter to minimize field distorting conducting loops. Tight assembly clearances preclude the use of large hydraulic torque wrenches to tension the studs.

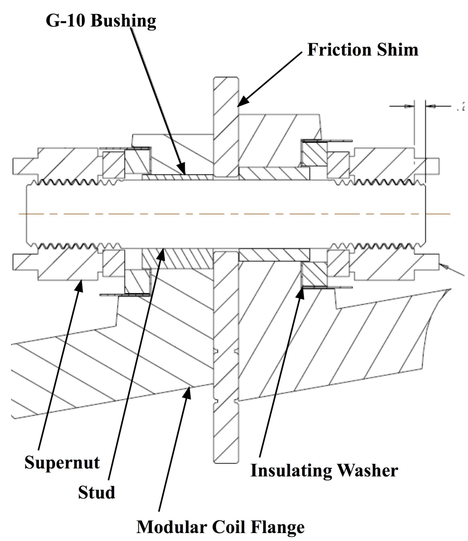

Figure 1. Modular Coil Flange Stud Kit Design

The design (Fig. 1) devised to achieve these requirements utilizes Inconel studs tensioned with, Supernuts™, which can be torqued using small hand tools to develop an 80 to 85 kip preload. Bushings fabricated from G-10 and match drilled at assembly insulate the studs from the coil castings. Adjacent coils are spaced apart a nominal 0.50" using insulated friction shims to carry the magnetic shear loads. The design originally called for alumina coated shims at each stud since they provided a high coefficient of friction. However the combination of coating thickness and flatness tolerances was difficult to achieve in large quantities, so an alternate material was sought for the 15 joints operating at lower loads. In the alternate design all of the coils in each field period assembly

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are spaced using G-10 insulated shims (coefficient of friction, μ =0.20). The three C-C joints between the field period assemblies are spaced using a high friction (μ =0.45) alumina coated shim set.

In order to validate the design a testing program was developed to test the friction coefficients of G-10 and alumina coated shims against stainless steel. Tests to verify the stud tensioning at room temperature, during cool-down and warm-up were also conducted.

III. Cryogenic Tension Tests

A. Test Methods

Two stud kits were assembled using production parts according to the design drawings. The two surrogate flange surfaces were fabricated using 1.5" thick Stellalloy material taken from one of the NCSX Prototype castings. The first two assemblies were tested using alumina coated shims (by White Engineering). One of the assemblies used a threaded surrogate flange (stud #1) and the other assembly was through bolted using a hexnut on one end and a Supernut on the other (stud #2). All of the washers and shims were production articles. Each stud was fitted with a resistance strain gage to measure the strain directly.

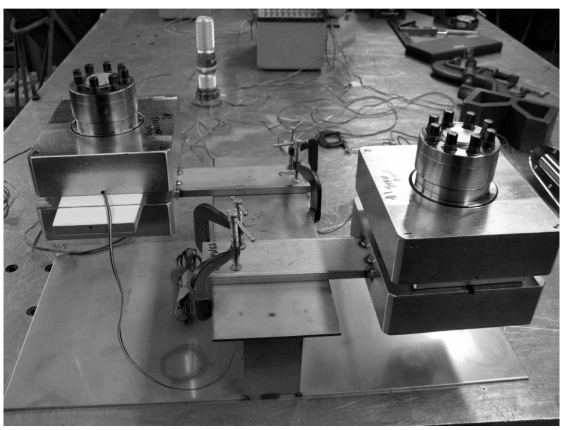

Figure 2. Cryogenic Tension Test Setup

The cryogenic tests were conducted in a foam insulated dewar fabricated especially for these tests. Temperature compensation was accomplished using a thermocouple mounted to a dummy stud inside the dewar cavity. The test articles were mounted about 1-2" above the floor of the dewar.

The long stud was tensioned in the 100 kip MTS machine to 80-85 kips to derive the calibration curve for load vs. strain indication on the strain gages. A compensating gage was used on the short stud. The test was conducted by running the load up to 85 kips and back down to zero (0) kips while reading the strain gage values using a bridge.

The stud kits and surrogate flanges were then assembled using the assembly sequence shown on the drawing. The Supernuts™ were torqued to achieve 80-85 kips and were verified using the calibrated strain gages attached to each stud. Torques were applied using a "click" type torque wrench set to the indicated values. The torquing method used was that specified in the Supernut™ assembly instructions. Measurements on the outside corners of the surrogate flanges were taken as the parts were tensioned to get an indication of how much the joint compressed under load.

Once the parts were properly torqued they were mounted inside the LN2 dewar as shown in Fig. 2 and cooled to 77 K using liquid nitrogen. The first run was cooled by flooding the volume around the test specimens with LN2 to quickly bring the parts down to temperature and subsequent runs were cooled slowly over a 2 hour period.

B. Cryogenic Test Results

During the initial cool down the tension in the studs varied considerably as expected. Tensions increased from the nominal 82 kips up to 112 kips until the temperatures in the individual components equalized. Once at 77K the tension in the studs dropped slightly as was predicted in the analysis (Fig. 3).

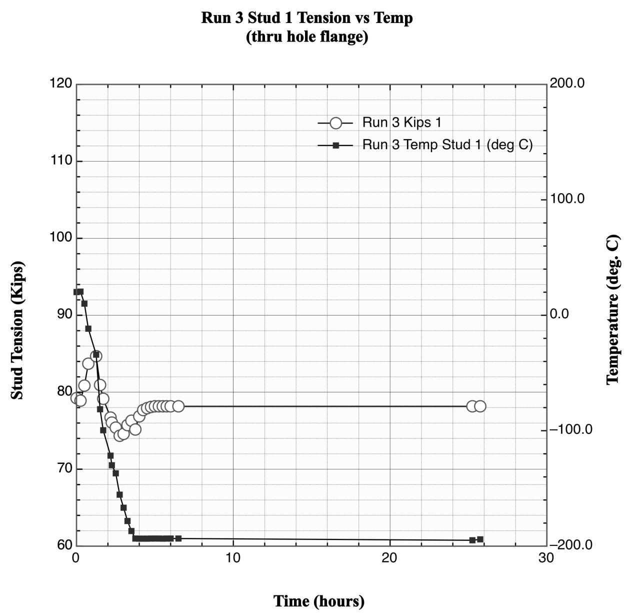

Figure 3. Tension vs Temperature

IV. Friction Tests

A. Test Methods

The object of these tests was to quantitatively measure the friction coefficients of G-10 shim material against stainless steel and alumina coated stainless steel against stainless steel. The G10 measurements were taken while varying the G-10 thickness, stainless steel surface finish and the orientation of the G-10 fiber relative to the friction force. The alumina friction tests were conducted using plasma sprayed parts which were kept in their "as-sprayed" condition.

Coefficients of friction (COF) were measured for G-10 samples with fiber strands orientated at 90, 0 and 45° relative to the friction force. The COF was also measured for each thickness of G-10 expected to be used on the outboard shims between the NCSX modular coils. Tests were also conducted for, mill finish, ground stainless steel surfaces and sand blasted surfaces. Since there are two (2) G-10 shims acting in parallel in the test setup the friction force at the shim interface can be described by the equation,

$$\mu = F / 2N. \tag{1}$$

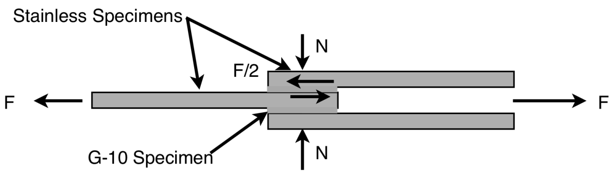

Figure 4. Friction Test Setup

N= normal force applied to the friction elements under test

F= force at which the joint begins to slide when loaded with normal force N

μ = coefficient of friction (COF)

Friction tests where the strand orientations were noted used the conventions shown in Fig. 5. All tests were conducted at ambient temperature with the cloth weave in different orientations from normal. All specimens were tested with a transverse (Normal) load of 8000# applied using a hydraulic cylinder unless noted otherwise.

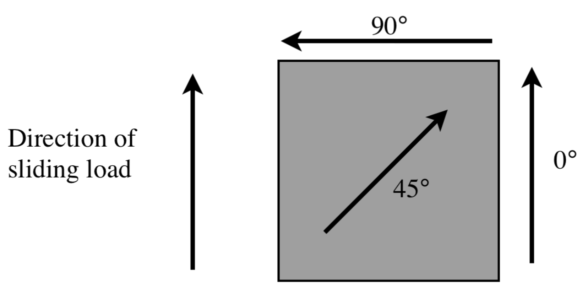

Figure 5. Strand Orientation Convention

These tests were run on the PPPL's 100 ton MTS Systems tensile test machine. The specimens were oriented on the test machine with the "normal" force applied by the hydraulic cylinders in the horizontal direction. The MTS test machine rams generated the force which opposed the frictional force (in the vertical direction).

The G-10 samples were prepared by roughening up the surface with abrasive cloth. The stainless steel samples used either a standard mill finish, a Blanchard ground surface to simulate the NCSX coil shims (as purchased) or a lightly sandblasted surface. The sandblasting was implemented after the first tests using the ground surface indicated a low friction coefficient. Materials used in the test were cleaned using acetone and allowed to air dry to remove any oils from the surfaces.

Each run consisted of loading up unused and prepared stainless steel and test samples into the machine as shown in Fig. 6. The hydraulic system was used to apply the normal force of 8,000 lbs. The tension on the joint was then slowly increased until slippage of the joint was detected. The load at which slippage was detected was recorded as the pullout force. Each test run used fresh samples as the material and stainless steel was by the slippage of the joint under load. The damage was caused by the loaded side plates slipping off the center bar and pinching the bar edges and G-10 together as the hydraulic ram closed.

B. *Friction Test Results*

Results of the alumina friction tests are shown in Fig. 7. In all cases but one the friction coefficient exceeded the requirement of 0.45. The test results from the G-10 tests are shown in Table 1. The results indicated that G-10 COF was insensitive to thickness and weave orientation but was significantly improved when the SS surface was rougher either by mill finish or by sandblasting a smooth machined surface.

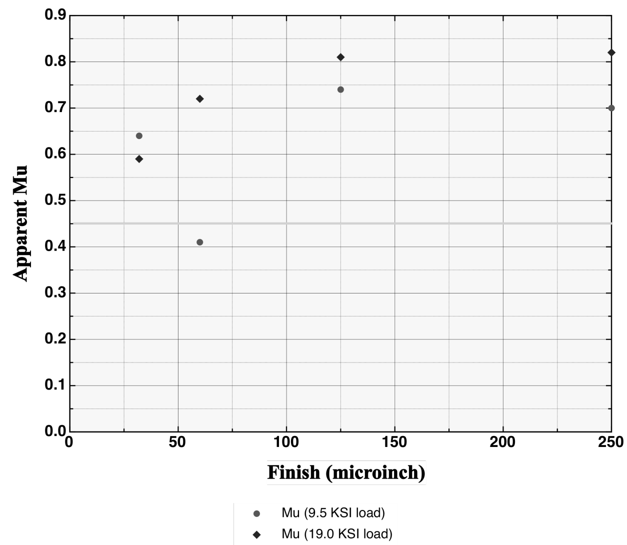

Figure 6. Alumina Friction Test Data

V. Other Tests

In addition to the cryogenic and friction tests the flatness, contact area and electrical leakage were tested. A special contact pressure paper was employed to measure the contact area on the shims before assembly. The paper was inserted between the shims and the modular coils flanges before assembly and then torqued to the design values. The paper changes from white to red proportional to the contact pressure as shown in Fig. 8.

Flatness of the shims was measured while under pressure. A special tool was developed which could apply the same pressure that is applied by a properly torqued stud and then measure the flatness of the shim. Four dial indicators in the pressure plates measured the shims thickness at each corner. The same tool was also used to measure the actual thickness of the G-10 shims so they could be sorted into various thicknesses for use during assembly.

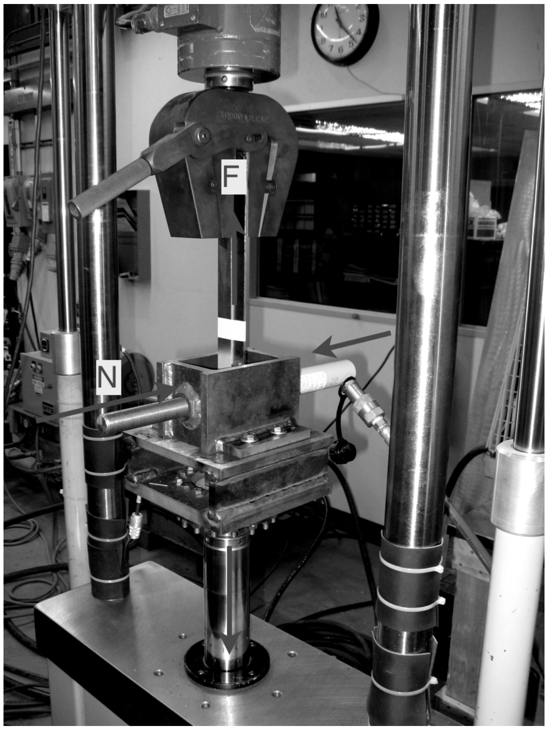

Figure 7. Friction Test Apparatus

TABLE I. FRICTION TEST RESULTS

Sample	G-10 Thickness (in.)	Calculated mu	Comments
Sample #1 Specimen #1 Supplier A	0.035	0.42	Center Bar Mill Finish, Weave angle 45
Sample #2 Specimen #2 Supplier A	0.035	0.46	Center Bar Mill Finish, Weave angle 0
Sample #3 Specimen #3 Supplier A	0.035	0.48	Center Bar Mill Finish, Weave angle 90
Sample #1, Specimen #2 Supplier B	0.032	0.36	Retest using Blanchard ground center bar and side plates
Vary Thickness Supplier B	0.015	0.29	Blanchard Ground Center and Side Bars
Vary Thickness Supplier B	0.032	0.32	Blanchard Ground Center and Side Bars
Sandblast Finish Supplier B	0.032	0.46	Sand Blasted Center and Side Bars (Finish 150, 80 Grit)
Sandblast Finish Supplier B	0.015	0.46	Sand Blasted Center and Side Bars (Finish 150, 80 Grit)
Sandblast Finish Supplier A	0.032	0.48	Sand Blasted Center and Side Bars (Finish 150, 80 Grit)

The electrical leakage to ground on the alumina shim coating was also tested at 150V while the shim was compressed under the 80 kip load. Leakage readings of 10-50 microamps for 10 mill coating thickness were typical.

Figure 8. Contact Pressure Paper showing color change

VI. CONCLUSION

Friction tests and cryogenic tension tests were performed on the shim materials and stud hardware for the NCSX Modular Coil joints which demonstrated the acceptability of the materials and application details.

VII. ACKNOWLEDGEMENT

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VIII. REFERENCES

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