NOVEL USE OF WATER SOLUBLE "AQUAPOUR" AS A TEMPORARY SPACER DURING COIL WINDING FOR THE NSTX-U CENTERSTACK*

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***Abstract*— A major facility upgrade to the National Spherical Torus eXperiment (NSTX-U) is currently underway at Princeton Plasma Physics Laboratory (PPPL). A key component of NSTX-U is the fabrication of a new, higher field centerstack (CS). In order to simultaneously provide robust joints between the inner and outer legs of the Toroidal Field Coils (TF) and minimize radial build, the NSTX-U CS design requires that the Ohmic Heating solenoid (OH) be wound directly on the inner TF bundle. To protect the OH against thermal expansion stress during scenarios where the inner TF bundle is hot but the OH is relatively cool, the completed CS will have a 0.100 inch annular gap between the outer diameter of the TF bundle and the inner diameter of the OH solenoid. "Aquapour", a proprietary material produced by the Advanced Ceramics Manufacturing Company will be used during manufacture to produce this gap.**

After the TF bundle is vacuum pressure impregnated and cured, a cylindrical "clam shell" mold will be assembled around it, and a slurry of powdered Aquapour and water will be pumped into the annular space between the mold and TF bundle. Subsequent baking will turn the Aquapour solid, and a protective layer of wet lay-up fiberglass and resin will be added. The OH solenoid will be wound directly on this wet lay-up shell. After vacuum pressure impregnation of the OH, the water soluble Aquapour will be washed away, leaving the required radial clearance between the TF and OH.

This paper will describe prototyping and testing of this process, and plans for use on the actual CS fabrication.

Keywords—NSTX-U, Spherical Torus, Coil Manufacturing, Centerstack, Ohmic Heating Coil, Coil Winding, Aquapour

I. INTRODUCTION

The National Spherical Torus eXperiment (NSTX), a MA-class spherical torus at Princeton Plasma Physics Laboratory (PPPL) in the US, is currently undergoing a major facility upgrade (NSTX-U). NSTX-U will have twice the toroidal field, plasma current, and NBI heating power as NSTX, and will increase the pulse length from 1-1.5 s to 5-8 s [1]. A major component of this upgrade is the fabrication of a new Centerstack (CS), which consists of the Inner Legs of the Toroidal Field Coils (TF), the central solenoid or Ohmic Heating Coil (OH Coils), as well as inner Poloidal Field Coils (PF Coils), a structural casing, and plasma facing components. The CS components form an integral system, as shown in Fig. 1, which will be manufactured and assembled outside of NSTX-U and then lowered and installed into the center of the vacuum vessel as a single unit. The compact aspect ratio of the Spherical Torus requires minimizing the radius of the CS as much as possible while simultaneously meeting the mechanical, thermal, electrical, and magnetic performance

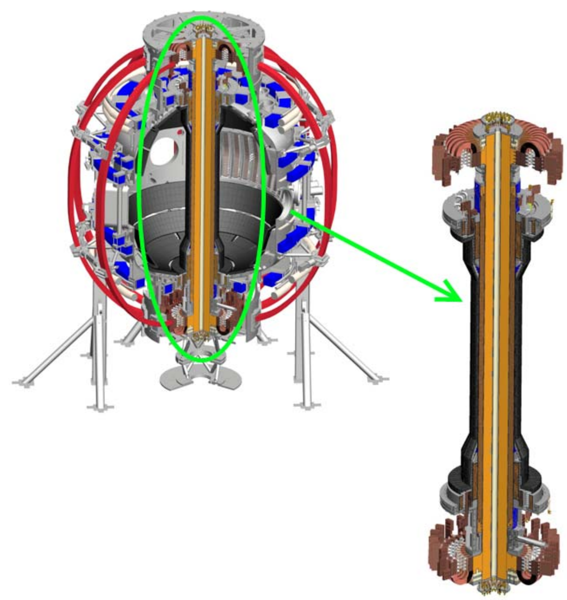

Fig. 1. NSTX-U and Detail of Centerstack

requirements, which results in unique engineering challenges. This paper will specifically detail an adaptation of a pre-existing industry technique to introduce a clearance gap between the outer diameter (OD) of the inner TF bundle and the inner diameter (ID) of the OH coil.

II. INTENT AND MOTIVATION

During pulsed power operation, the temperature of the CS and inner TF increases nearly uniformly from ~ 12 C to ~ 100+ C, in less than 10 seconds, due to resistive heating. However, during the subsequent cool down, they have very different transient temperature distributions and cooling rates. This normal cooling behavior, as well as potential fault conditions could result in all or part of the TF bundle being "hot" while the OH is relatively "cool". If the ID of the OH coil was in direct contact with the OD of the TF bundle, the resulting differential thermal expansion from the TF (~ 0.0272") would apply both a radial normal contact pressure and a vertical shearing force which would result in unacceptable shearing stresses in the insulation of the OH coil. In order to protect the CS from this situation, a clearance gap must be incorporated between the OD of the ITF bundle and the ID of the OH. For more detailed information on the thermal and stress response of the CS coil systems, see [2].

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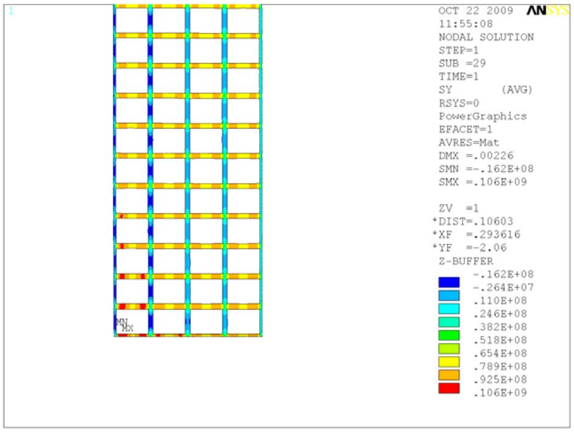

Fig. 2. Tensile Stress (Mpa) in OH Insulation due to TF Vertical Expansion if Clearance Gap did not exist

In the original NSTX design, this clearance gap was created by manufacturing the inner TF and OH as separate units. The OH coil was wound and impregnated onto a hollow mandrel, or "tension tube", which had a sufficiently large ID that it could then be slipped over the TF bundle. This was possible because the TF had no protrusions extending radially beyond the diameter of the OH; the lead flags blocks, part of the electrical path between the inner and outer TF coils, were bolted onto the TF coil after it was married to the OH.

In NSTX-U, structural considerations require that the bolted joints be moved further radically outboard. The lead flag blocks have been permanently joined to the TF conductors with friction stir welding before vacuum pressure impregnation (VPI) of the TF bundle. This geometry prevents the OH and TF bundles from being fabricated separately and then joined.

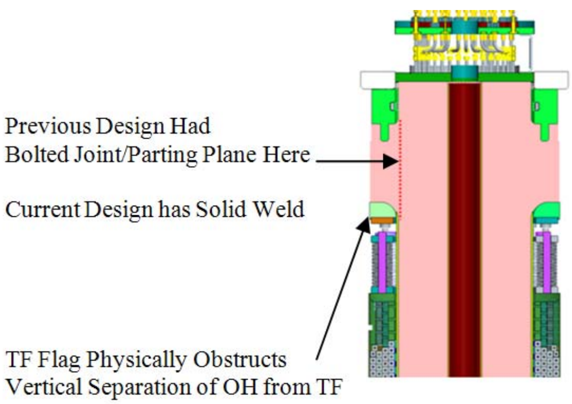

Fig. 3. Geometry of TF Lead Flags Obstructs Seperation of OH and TF

The combination of these two requirements introduces a new manufacturing challenge: winding and impregnating the OH coil onto the ID of the ITF bundle while simultaneously maintaining a clearance gap to accommodate thermal expansion. The relative scales of the clearance gap are impressive: an annulus of 0.100" thickness, ID of 15.788", and a height of ~15'. The chosen technique is to use Aquapour – a water soluble material which can be used as a temporary spacer during winding, and then dissolved away after the OH VPI is finished.

III. What is Aquapour

Aquapour™ is a commercial available, propriety material developed by Advanced Ceramics Research, Inc of Tucson, Arizona used to facilitate composite manufacturing. It is a ceramic based material, available as a dry powder, which can be mixed with water to form a liquid slurry. This liquid slurry can be poured in to molds, allowed to dry, and then heated to drive away the remaining moisture and cure. This results in a solid form which visually and texturally resembles plaster, is robust enough for handling and use in manufacture, can sustain elevated temperatures, and is relatively inert. However, after use, it breaks apart and can be washed away by cold tap water, and disposed without special precautions.

Typically this process is used to create winding forms for fiber reinforced composite lay ups. For example, fiberglass cloth can be wrapped around the mandrel, which is either pre-impregnated with uncured resin, or "painted" with an uncured epoxy. After conventional oven curing, this results in composite part, and the Aquapour mandrel can be dissolved away from the inside. This technique is especially useful for creating annular parts with internal hollows, or concave surfaces where a mandrel could not be easily slid out.

The requirements for the NSTX-U CS manufacture is similar in concept to the conventional intended use of Aquapour; however, it required testing and prototyping to extend the use to a new situation and geometries which introduced new challenges:

1) Extreme Aspect Ratios
   a) Thinness of Aquapour with respect to hieght of OH makes washing and pouring difficult.
   b) High Surface Area to Volume causes a tendency for Aquapour to stick to the molds
   c) High Accuracy requirements hard to achieve on Large Components
2) Adaptation to Coil Winding and VPI Process

IV. Testing and Prototyping

Multiple stages of testing and prototyping were performed in order to develop acceptable procedures for NSTX-U coil manufacturing. Initially, small samples, several inches across and approximately 1/8" thick were mixed, poured into open pans, dried, and cured to investigate the suitability of the material for intended purposes and to experiment with different water/powder ratios and curing times and temperature.

Next, a mold was fabricated from plastic sheets riveted 0.100 inches apart and sealed on five sides. The internal hollow space was filled with Aquapour, which was subsequently dried, cured and washed out with water from a pressure washer to verify that the material could be washed away from a confined space using only the force of water. Figure 4, on the following page, shows still images from a video taken during this test.

Fig. 4. Time Lapse of Small Scale Wash Test

The third test illustrated that cured Aquapour had sufficient strength to resist the forces caused by winding the copper conductor. A small winding mandrel was fabricated by welding a ring of aluminum, approximately 16" in diameter and 6" high to a flat plate and applying a ~ 0.1" layer of Aquapour, which was dried and cured in an oven. A thin film (~ 0.003") of polyvinyl flouride was wrapped around the cured Aquapour, and then a single layer (~ 0.007)" of fiberglass tape was wrapped as a half lap and painted with a room temperature curing epoxy. After this protective shell was cured, copper bar, approximately 5/8" square was wound around the Aquapour, to demonstrate that in an enclosed volume, there was sufficient strength to resist the force of coil winding.

Fig. 5. Copper Winding Test

The last medium scale test was used to prove the feasibility of forming the Aquapour into a layer of the required 0.100" thickness around a relatively tall cylinder, and subsequently wash it out. A pipe, ~ 8" in diameter, was used to represent the TF bundle, and a two piece rolled cylindrical clam shell mold was fabricated, which bolted around the pipe, creating the required clearance gap. After several iterations, the appropriate filling method, release agent, mix ratio were determined which could form the required thickness of Aquapour and still wash away.

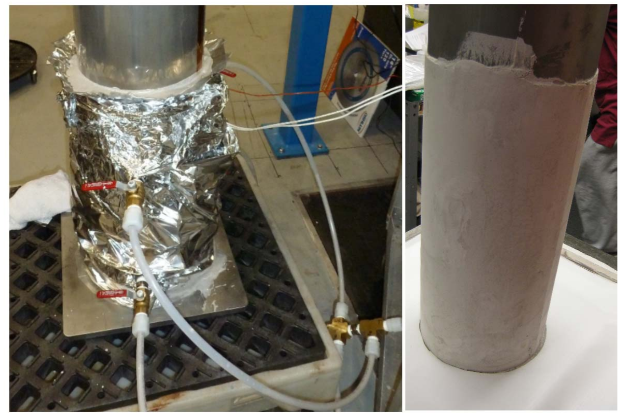

Fig. 6. Medium Scale Test,
Left: During Baking with Heater Tape, Pumping Tubes Still Attached
Right: After Curing

Finally, after the various sub steps of the process were developed on small scale testing, a larger test was performed as final verification. A full diameter, ~ half height prototype was made by turning an ~8" aluminum pipe to the 15.788" diameter expected of the finished TF bundle. Flanges were welded at the top and bottom, leaving the appropriate clearance spaces between the top and bottom of the mold, to represent the obstruction of the TF flags. A single half lap layer of 0.008" wet lay up epoxy was added to the cylinder to more closely represent the surface properties of the TF bundle. The actual mold segments intended for use during manufacture were used for this test, including the electrical heating system for curing. The Aquapour was successfully applied and cured, a protective epoxy/fiberglass shell was laid up on part of the Aquapour, and the Aquapour was washed out over a height of 72".

Fig. 7. Full Diameter Test
Left: After Baking, Right: During Washing
Note use of preplaced wire to faciliate removal

The details of the procedure which was determined from this series of sequential testing will be described in the following section.

V. Process Procedures

The outcome of the previously described testing was to develop and build confidence in the following procedures and key points, which will be used during the Aquapour operation of coil manufacturing for the NSX-U CS. All Aquapour operations will be performed with the centerstack standing vertically.

1. Prepare Half Clam Shell Molds
    a. Line inside of molds with Mylar sheet
    b. Spray with industrial Lecithin based release agent. Allow release agent to dry overnight before use.
2. Assemble and Seal Mold Segments
    a. Assemble a single pair of mold segments
    b. Use set screws and shims to set gap
    c. Pre-place steel wire between mold and TF bundle surface to use during washing out
    d. Seal mold gaps with Apiezon Q sealing compound and aluminum tape
3. Mix and Pump Liquid Slurry
    a. Mix 9 parts Aquapour to 10 parts water (by mass)
    b. Pump through pipes nipples welded on molds using disposable tubing of equal length with back pressure of nitrogen gas
    c. Seven minutes of working time before viscosity increase prevents pumping
4. Vibrate mold using palm sander to remove air bubbles
5. Repeat Steps 2 through 4 for all mold segment pairs.
6. Allow Aquapour to Set
    a. After approximately two to four hours, remove mold segments to prevent Aquapour from sticking to inside of mold
    b. Let Aquapour sit, exposed to air overnight
7. Heat to Cure
    a. Reassemble mold segments "loosely", leaving ~ 0.25" gap between ID of mold and OD of Aquapour, to create oven effect
    b. Use electrical heating blankets on exterior of molds, fiberglass thermal insulation and thermocouple instrumentation to slowly ramp to 130 C over the course of several hours
    c. Hold at 130 C for at least one hour
8. Add Protective Shell
    a. Wrap cured Aquapour with thin sheet of Teflon
    b. Wet lay-up single layer of fiberglass tape and room temperature curing epoxy to form protective shell
9. Wind and Impregnate OH Coil
    a. Reposition to centerstack to horizontal, and perform normal coil winding operations directly on top of protective shell. For more details refer to [3].
10. Remove Aquapour
    a. Use flexible, thin-walled stainless steel tubes and pressurized water to wash away Aquapour using "water pick" effect.
    b. Use vacuum suction to remove water and dissolved Aquapour; protect centerstack with waterproof plastic sheeting
    c. Steel wires pre-placed during step 2c may be used "floss" and break apart Aquapour.
    d. Washing is done when steel wires, ~ 0.093" in diameter, can be brought 360° around TF bundle unobstructed

VI. Conclusions

The design of the NSTX-U centerstack requires a clearance gap between the TF and OH coils to allow thermal expansion. The new geometry of the TF flag joint requires that the TF and OH are fabricated as a single concentric unit and cannot be separated from each other.

A commercially available material, "Aquapour", can be used to create a temporary spacing layer during manufacture and can be washed away before installation of the coil. A comprehensive testing program has taken place to develop and validate appropriate procedures for use during center stack manufacture.

The initial pouring and curing of this layer is expected to occur during August of 2013.

Acknowledgment

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