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***Abstract*—NSTX-U uses an inertially cooled OH coil that is cooled with water between shots. Cooling is fed from the bottom of the coil and a cooling wave propagates up the height of the coil. The finite height of the cooling "wave" causes a thermal gradient in the coil that causes a bending stress in the coil build. The larger radial build of the new NSTX Upgrade OH coil produces a shorter "wave" than the previous coil, and larger bending stress. The OH insulation system uses CTD 425 epoxy with interleaved glass and Kapton. This insulation is intended to provide some accommodation of tensile strains and delamination. Localized tensile strains, and shear stresses beyond recommended allowables have been a characteristic of many coil winding packs. Mechanical and electrical array testing is often used to qualify these winding packs. Mitigation of tensile strains via preloads is also often employed. For NSTX-U, only a small preload is practical. Strain controlled array testing has been performed. This has demonstrated a robustly acceptable electrical behavior after cyclic loading. This allows some relief in the requirement to control the cooling water "thermal shock". To provide additional protection of the insulation, an active system that introduces cooling water with a more gradual thermal gradient and longer cooling wave height is being implemented to mitigate the tensile strains. This system employs an inline heater that supplies water at the post shot OH temperature that linearly decreases to the 12C supply chilled water temperature. Results of array testing, and design of the active system are presented. The final decisions regarding acceptance of the testing and implementation of the preheater are presented.**

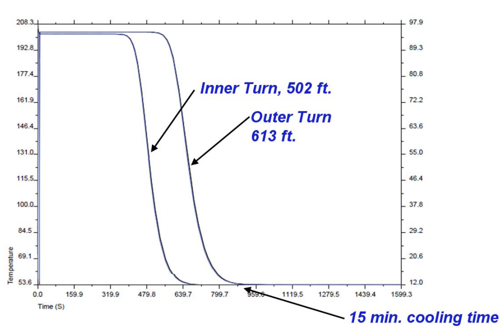

Figure 1 FCOOL Results from Ali Zolfaghari's OH cooling calculation [11]

Keywords—Mechanical strength of insulation, Ohmic heating coil

I. INTRODUCTION

The NSTX central solenoid or Ohmic Heating (OH) coil is an inertially cooled normal copper coil. It is cooled by constantly flowing water through the coil. The plasma pulse duration is much shorter than the coolant transit time, thus the initial condition of the cool down is a coil warmed by Joule heat with 12c water entering from the bottom, with cooling progressing in a wave from bottom to top. Figure 1 shows a simulation of the cooling. Various versions of in-house codes Fcool (by Fred Dahlgren) and ACOOL (by Art Brooks) are used for the simulation. Outlet temperature vs time is plotted. The outlet water temperature remains at the shot end temperature until a cooling "wave" exits the coil. Introducing cold cooling water into a coil can cause a "thermal shock" or stress due to a sharp initial temperature gradient. NSTX operated successfully without systems to mitigate this effect. Winding pack and build differences between the new coils used in the upgrade and the original coils in NSTX, have raised concerns over insulation tensile strains in both the new TF and the new OH coils. The TF coil thermal shock was improved by introducing the outer leg cooling exit water into the inlet of the inner legs. In the new NSTX-U TF, the cooling tube centered in the blade or Bitter plate conductor cross section, produced contractions and tensile stresses around the soldered coolant tube (shown in figure 5). TF cooling stresses and analyses of feeding the inner leg with outer leg coolant are included in [12] Cooling progresses differently in the TF and OH coils. Cooling progresses up the coil in a "wave" or transition zone from cold to hot, because of the very long path length in the OH coil conductors. Radial thermal growth varies from bottom to top of the transition zone and these displacements cause a bending strain in the winding pack. The behavior is strain controlled – determined by the geometry of the wave and the differential temperature. Tensile stress is a function of the modulus. NSTX has chosen both to live with some level of tensile strains and to mitigate them with an active system.

II. HISTORY

A. *Original Design Calculations*

OH Thermal stresses and cooling wave height effect on OH stresses were identified early in the NSTX-U project by Ali Zolfaghari and MAST Peer reviewers. A. Zolfaghari's comments in his calculation follow :

"The temperature of the coil reaches close to 100 C in a few seconds but the water entering the coil (from the bottom of the coil) is at 12 degrees C. As the colder water moves through the coil, it creates a temperature gradient in the coil that causes stress in the coil. To study this effect we analyzed the results of cooling in the inner most layer of the OH coil. The highest temperature gradient (as calculated by FCOOL) over the first 4 turns (each turn is 1.378 m) of the coil happens at t=5.96 seconds after the start of the shot."

And in another section of the calculation [2]:

"If CTD-425 insulation system is used with primer, the shear stresses are below the static and fatigue limits. The vertical tensile stress limit in some areas exceed the 10 MPa allowable in the insulation. We recommend the use of a more gradual cooling scheme whereby the starting temperature of the coolant is higher than 12 C and gradually reduced as time progresses. This would reduce the temperature gradients at the beginning of the cooling process in the bottom of the coil and therefore reduce the stresses. "

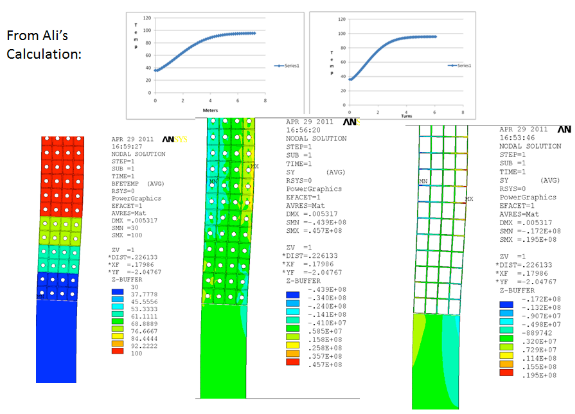

Fig. 2 Vertical Stress in the Coil Due to the Cooling Wave in the Bottom of the Coil, In the Iinsulation Adjacent to the bond.From Zolfaghari [2]

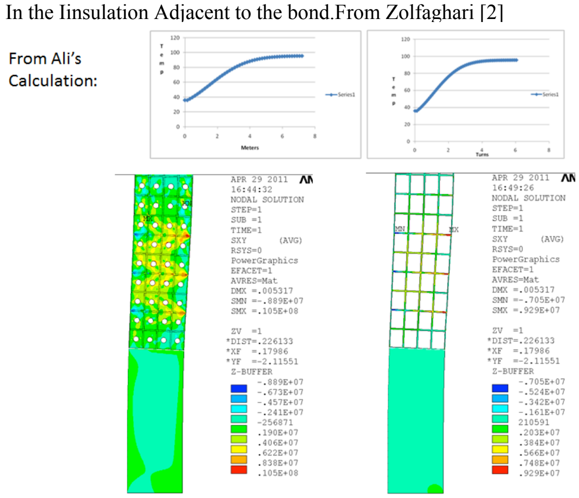

Fig. 3 Shear Stress in the Coil Due to the Cooling Wave in the Bottom of the Coil, In the Insulation Adjacent to the Bond. [2]

Two causes of tensile strains were identified. One from the cooling wave as it enters and progresses uniformly along the axial direction in the coil, and a second from the different progression of the wave in the inner, shorter cooling paths and the outer longer cooling paths.

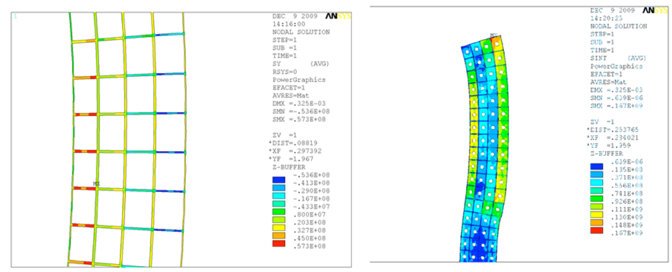

Fig. 4 Stresses in the OH Coil Due to the Cooling Wave Exiting the Coil at Different Times Due to the Layer Path Length Differences [2]

Figure 4 shows the stresses for the case where the cooling paths and equal flow rate produce layer to layer differences in temperature. This has been greatly improved, by metering valves at the entrance to the individual layer inlets. These are adjusted to produce equal transit time for all four layers.

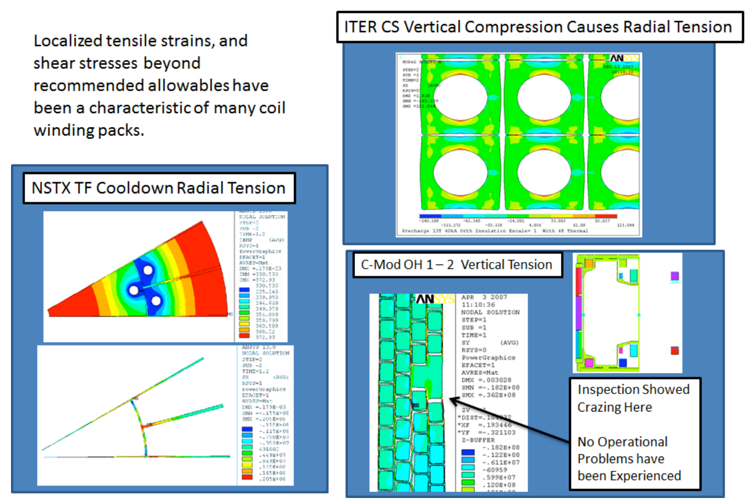

Fig. 5 Other Examples of Coil Tensile Strains

The tensile strains in the NSTX Upgrade OH coil are not unique. Other coils have experienced or will experience tensile strains due to thermal gradients and Lorentz forces. Figure 5 shows some examples from the original NSTX, ITER central solenoid, and the C-Mod OH coil. In the examples cited, no failures during operation, or test resulted from the tensile strains.

III. Criteria

Stress Criteria are found in the NSTX Structural Criteria Document[1].

2.5.2.1 (of [1]) Mechanical Limits for Insulation Materials

The stress criteria defined herein may be locally exceeded by secondary stresses in an area whose characteristic length along the insulation plane is not more than the insulation thickness and where it can be demonstrated that cracking or surface de-bonding parallel to the insulation layer and limited to the local length will relieve the stresses without violating the integrity of the structure. In this situation, final verification must be obtained by mechanical/electrical testing of a representative winding pack section.

2.5.1.1.2 (of[1])Tensile Strain Allowable Normal to Plane

In the direction normal to the adhesive bonds between metal and composite, no primary tensile strain is allowed. Secondary strain will be limited to 1/5 of the ultimate tensile strain. In the absence of specific data, the allowable working tensile strain is 0.02%

IV. RECENT ANALYSES

A. Final OH Cooling Calculation

Work on cooling water connections, bus bar connections and diagnostic fit up was deferred until late in the project as emphasis was placed on winding and impregnating the new centerstack coils and constructing the new vessel structural components needed to resist the higher Upgrade loads. In the Fall of 2014 More technical issues arose from the failure to remove material that was intended to form a gap between the TF and OH and this reinitiated the consideration of the way the OH is cooled and a determination had to be made as to whether the possible frictional interaction of the two coils would alter the cooldown behavior. This was investigated and found not to be a problem, but the initial concern over the cold water entering the OH with a sharp change in temperature needed to be considered. Because details of the water system were deferred until most of the construction was in process, the wave height stress was not addressed until the summer of 2014. Also the need for the water system upgrade to solve the wave height issue was not fully understood because it had not been an issue for NSTX.

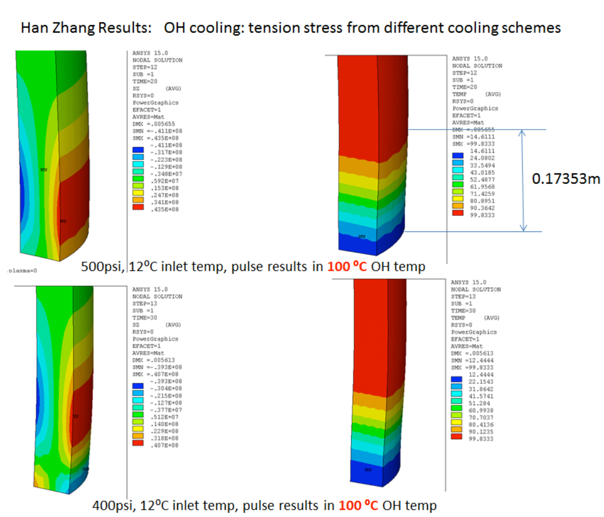

Fig. 6 Axial (Vertical) Tension Stress in the Coil Due to the Cooling Wave in the Bottom of the Coil

Han Zhang simulated the cooling wave thermal strains, and found results similar to the earlier calculations. These are shown in figure 6. Han Zhang took FCOOL temperature results and applied them to her coil model. She got ~40 MPa, very similar to Ali's results. These are larger than the stresses (26MPa) from estimated wave heights in figure 8. Han, Ali, and Art Brooks have found the wave height is shortest near the lower base of the coil. The differences in reported stresses are due to the position along the height of the coil that is being analyzed.

Table 1 Cooldown Axial Tension Results for NSTX-U with 12C inlet water

Analyst	Waveheight	Axial Tension Stress
H. Zhang , Figure 4.0-5	.173 m	43 MPa (Smeared)
Ali Zolfaghari	.4m	25 MPa in the insulation
P. Titus, Figure 8	.28	25 MPa (Smeared)

The stress results in table 1 vary. They were calculated independently, but they all point to a stress problem in the OH if the insulation system has a minimal tensile capacity. At the time A. Zolfaghari prepared his calculation, the tensile stress allowable with Kapton was guessed to be ~10 MPa by Dick Reed. Later bond strengths without Kapton were measured by CTD to be ~14 MPa, but with Kapton, the bond strength measured at MIT was nearly zero[6]. Without specific allowables from early CTD tests, the stress limit for the preheater design was taken to be the stress that the original NSTX experienced successfully – see figure 8. The need for a strain based allowable led to the most recent round of CTD tests discussed in section VI.

December 4 2014 The project had a conference call with MAST regarding this issue. MAST protects their coil against the layer to layer delamination, even though they feel that the delamination would be benign. They have Kapton wrap in their layer to layer interface, not turn to turn. They meter the flow to protect against excessive motion between layers, and expect that the turn to turn to be able to sustain the tensile stresses due to the cooling wave. With the layers poorly bonded, the tensile stresses due to bending of the coil build will be less.

The risks to the NSTX-Upgrade OH coil were considered significant enough to investigate ways of mitigating the tensile strains. Han Zhang had suggested stepped temperature increases, Zolfaghari had suggested gradual increases. A. Brooks added temperature gradient calculations to his ACOOL simulation.

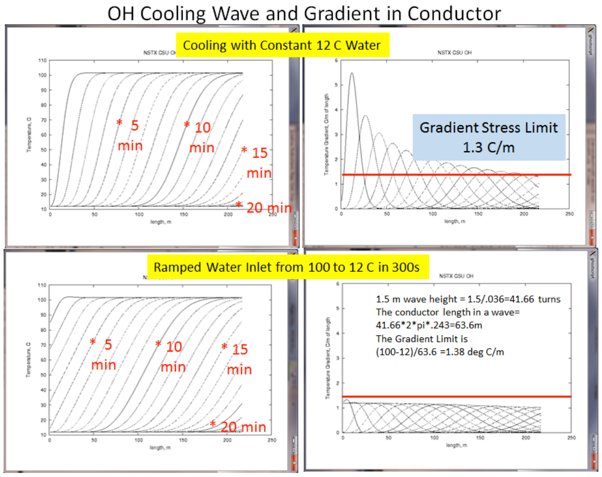

Fig.7 Comparison of the Temperature Gradient for the 12C inlet and Ramped Inlet Temperature

A 1.5 meter wave height for the 100C to 12C transition was used as a target for the simulation based on stress calculations in which the wave height was imposed on the model of the coil. This corresponded to an “unwrapped” transition along the conductor length of 1.3 degrees C per meter.

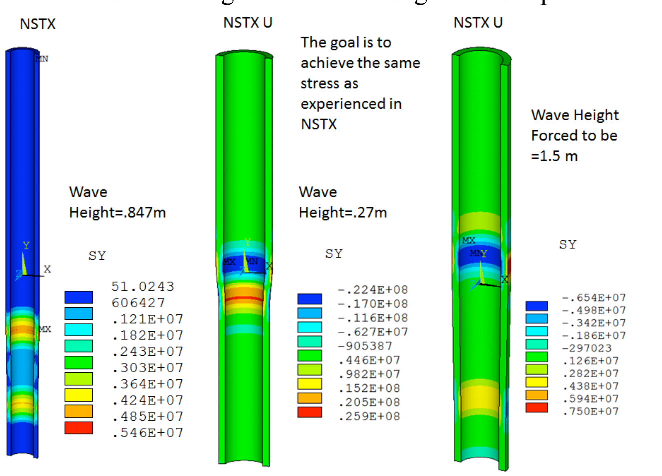

Figure 8 Axial or Vertical Tension Stress in the OH Coil Due to the Cooling Wave for NSTX, NSTX Upgrade, and NSTX Upgrade with a chosen 1.5m wave height.

The axial heights of the cooling wave in the two solenoids were estimated to to be .27 m in the upgrade and .81m in NSTX - the main reason for this is that the cooling wave along the conductor is comparable for both, but in NSTX it is wrapped around a smaller diameter and thus goes a longer axial distance. For a given displacement the longer wave absorbs the radial strain with less bending stress. Based on a beam analogy the effect goes as L^2. This makes NSTXU about 3.6 times worse.

The thermal radial growth of the coil is larger for the NSTX U than for NSTX, just because it is larger. The analogous beam stress is linear in displacement. - This is about a factor of 1.7 worse

The thickness of the coil is greater for NSTXU than NSTX - For a given bending displacement a thicker shell will have a bigger bending stress. This makes NSTXU about 1.5 times worse.

The total effect is 3.6*1.7*1.5 = 9.2 times worse for NSTXU than for NSTX. NSTX has lower stresses than NSTXU because of geometry. The finite element solution produced a less pronounced effect, but the Upgrade stresses are significantly larger than the stresses in NSTX.

The cooldown stresses in the upgrade will be much higher than in NSTX. Survival of the NSTX OH coil is not a good basis for accepting the tensile strains in the Upgrade.

The tensile strength of the OH winding pack is uncertain but it is expected to be minimal because of the inclusion of interleaved Kapton. Even without Kapton, tensile strength of the epoxy bond to copper is only ~14 MPa with an allowable of about half of this Ref [8]. Kapton forms parting planes and is intended to provide electrical integrity even if there are “small” amounts of cracks and delaminations that impose strains on the Kapton. The definition of “small” in this instance requires judgement and testing. Testing was attempted for ITER insulation and substantial static load damage could be accepted while retaining electrical function. Fatigue loading was not evaluated in this test [6]. For really small potential delamination and cracking in the W7X trim coils, a judgmental argument was developed [7]. As of December 2014, the trim coils have been successfully commissioned.

To develop an allowed cyclic tensile strain, tests have been performed by CTD to test strain controlled cyclic electrical degradation. Final test results were available Feb 19 2015 [25]. The misaligned sample is shown in Figure 12 and 14. The aligned sample is shown in figure 16. The outcome of the tests demonstrates acceptable electrical performance for all of tested cyclic strain.. The CTD samples (aligned and misaligned samples were tested) survived well electrically. It has been concluded that the preheater is not needed during early operations. The preheater will be retained to improve the life and reliability of the OH coil because there was some indication of progressive mechanical degradation,. It is also useful for operations to mitigate the effects of the aquapour TF-OH interaction.

V. PREHEATER SYSTEM

The preheater system consists of an in-line heater with controls that produce a water cooling flow that ramps down from the final OH shot temperature to the 12 degrees C chilled water temperature in 300 seconds.

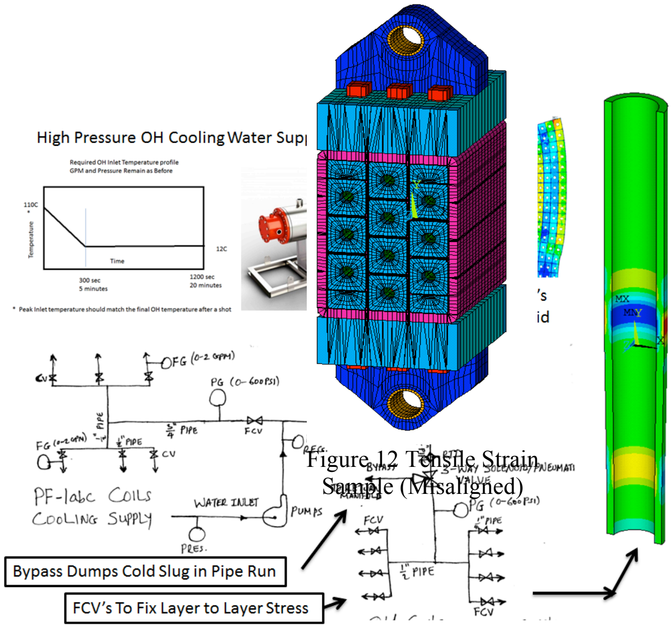

Figure 12 Tensile Strain Sample (Misaligned)

Fig. 9 Early Diagram of the OH Preheater Cooling System

Inlet water in the lines feeding the coil is "dumped" by a bypass valve and temperature sensor until the water is at the desired start inlet temperature.

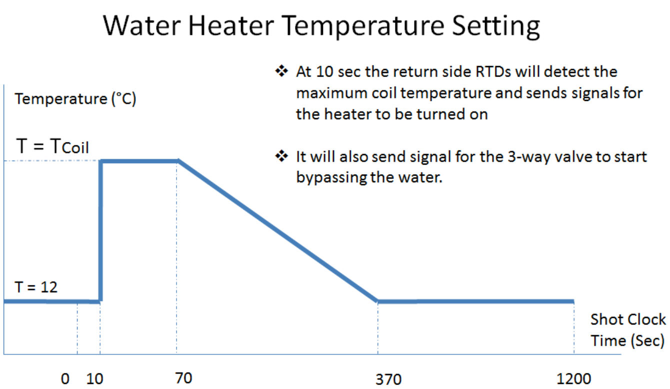

Fig.-10 Target Temperature for the water heater.

The proposed ramped inlet temperature shown in figure 10, produces a cooldown time of just 20 minutes. The Upgrade Project has expressed an interest in keeping the cooldown time below 20 minutes. The OH cooldown is the longest component that establishes the rep rate, and ideally after the system is configured and run, cooldown times can be improved, at least for OH temperatures less than 100C. The stress in the coil is a function of the temperature gradient, so if the coil starts at , 50 C, the ramp time of 5 minutes could be halved.

An important consideration in the configuration and design of the preheater system is the transit times of the water flowing in the hoses. Temperature control of the coolant is not possible for some of the hose runs that are between sensors, bypass valves and the OH coil inlet. Time delays are imposed by the lengths of the hose connections from the OH outlet to the RTD's at the top of the machine that provide the target temperature of the OH coil for the preheat system.

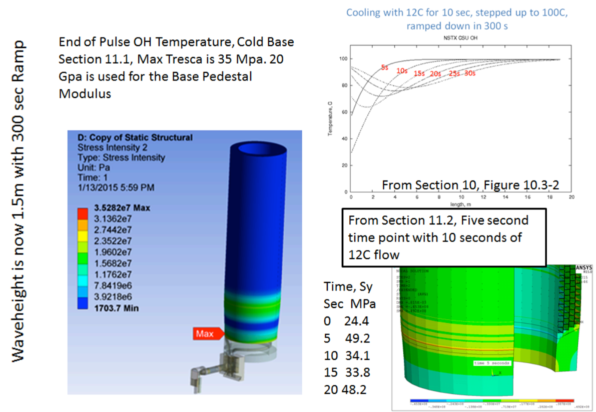

Figure 11 Initial "Slug" of 12C chilled Water Before Pre-Heater Water Enters

An inventory of cold water set by the flow velocity and an effective time delay must be accommodated by the coil inlets. This area was the subject of detailed analysis for a worst case situation of a fully hot coil, and 12C inlet temperature. The qualification [14] was challenging and there were a few locations thought to be challenged electrically that had extra Kapton wraps or efforts made to improve bonding. These simulations were revisited in light of the expected best effort temperature delays .

Even with the new system, there are local tensile strains that cannot be mitigated by the ramped temperature. The consequences of a 10 second flow of 12C water was simulated by A. Brooks and was evaluated using the [14] model, and another model that treats discrete conductors and layers of insulation and Kapton. The results for the lower base area are small regions which are above the NSTX 6.5 MPa target allowable . The rest of the coil for a 1.5 wave height is near the NSTX target value.

VI. Strain Controlled Tests

This paper is on the tensile strains that result from the cooldown behavior of the OH coil, but there are other sources of tensile strains that are as significant, or more significant than cooldown. The OH is tightly wound on the TF and there is a potential for a frictional interaction between a warm TF and a cool OH. In this instance, as the TF expands vertically, the OH will be "stretched" The tensile strains that potentially can develop from the interaction between the OH and TF would develop across the build of the OH. These tensile strains are being controlled by controlling the coil temperatures. The possibility of frictional interaction and the cooldown behavior provided ample justification for testing the effects of tensile strains. CTD was contracted to cyclically load misaligned (see figure 12) and aligned samples in displacement or strain controlled tests.

TABLE -2 TENSILE STRAINS FROM ANALYSES, AND THE PRESCRIBED TEST VALUE

Location	No Preheater Figure or Section	No Preheater	With Preheater	With Preheater
CTD Test SOW	Reference [23]	4.0e-4		
CTD Actual Test	4.0-14	~6.0e-4		
NSTXU Cooling Wave	Figure 8.0-3	2.56e-4	8.0-3	7.5e-5
NSTXU Cooling Wave	9.0-1	4.07e-4	9.0-4	1.3e-4
NSTXU Base	11.8, 11.9			3.37 to 4.1e-4

The tests are displacement or strain controlled, performed at 110 C at a strain rate of 0.4 x 10^-3 and a rate of ~10 hz. Table 2 shows the tensile strains from the simulation in this report along with the CTD test requirement.

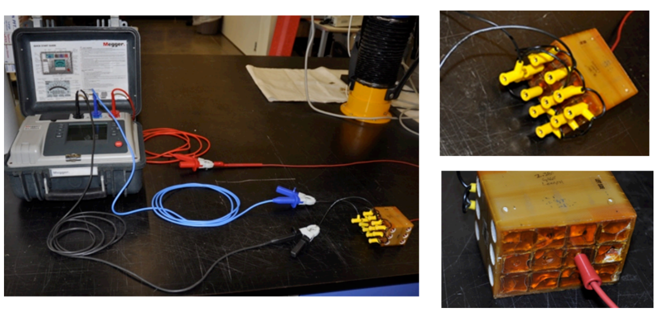

Figure 13 Elecrical Test Setup at CTD Showing the Aligned Array, From [25]

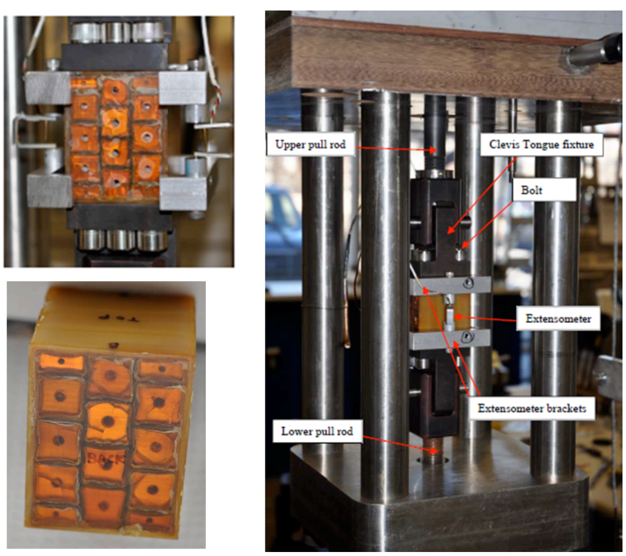

Fig. 14 Array Test Samples and Fixtures from [25]

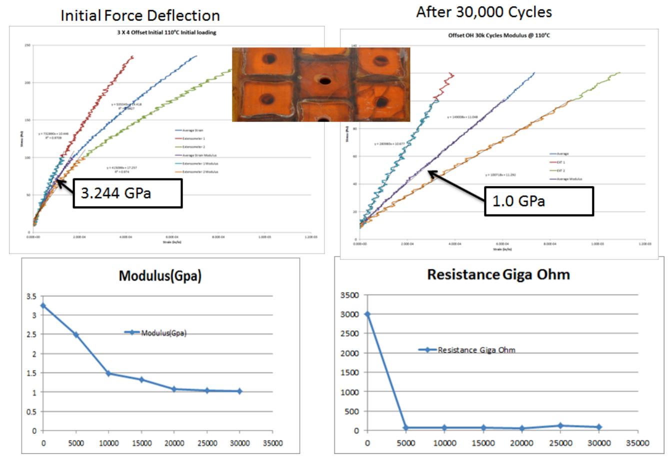

Fig. 15 CTD Tensile Strain Controlled Tests

In the misaligned turn test results provided by CTD, there is evidence of cyclic mechanical degradation. Photos of the samples, Figure 16, do not show any indication of cracking or delamination, although the photos are of the outer faces of the impregnated samples. These are resin rich areas that often crack just from the cooldown from the cure temperature. There is little difference between the two photos of the same sample before and after cyclic testing. The aligned conductor array looks like whatever mechanical change occurs, and this includes the appearance of cracks in the neat resisn, occurs essentially in the first load cycle.

Fig. 16 CTD Tensile Strain Controlled Test, Aligned Sample

Work continues on the OH cooling water preheater system. Results of the CTD insulation array tests have been received and are favorable. The CTD conductor tests show a significant accommodation of tensile strains. Both misaligned and aligned samples have been tested, and no electrical failures have been reported after 30,000 controlled strain cycles. Aligned tests show an initial large drop in the modulus, and the misaligned array shows a more progressive degradation. Either perfectly aligned and maximally misaligned conductor configurations are rare in the coil build. Some average misalignment would characterize the winding pack. Thus some progressive cyclic change in modulus and degree of Kapton adhesion is expected. Based on these results, the preheater system does not have to be fully operational for CD-4. Mechanical behavior of the samples shows some progressive reduction in the moduli of the samples indicating damage to the interlaminar bonds. The conductors are wrapped with Kapton interleaved with glass with the expectation that some mechanical strains would have to be accommodated. Completion and operation of the preheater system is still planned to reduce mechanical strains in the insulation system over time, and to support OH coil temperature adjustments to minimize the OH interaction with the TF due to the Aquapour remaining in the interface gap.

VII. PREHEATER STATUS

The preheater and its controls have been purchased and are undergoing tests. It is planned that the preheater system will be installed after the first plasma but before major operations begin.

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Fig. 17 WATTCO Pre heater, As Received

ACKNOWLEDGMENT

The authors would like to acknowledge the contributions of Ali Zolfaghari, the author of the original qualification of the OH coil for the early recognition of the strain issues in the OH coil. Many PPPL reviewers contributed to the final configuration of the preheater system.

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