Appendix L

Aquapour Independent Peer Review Findings

Princeton Plasma Physics Laboratory

To: Distribution
From: P. Heitzenroeder
Date: October 14, 2014
Subject: Peer Review of September 8, 2014: Impact of CTD 425 Resin-Contaminated Aquapour on NSTX-U Operations
Reviewers: T. Todd, I. Katradomos (MAST); A. Kellman (GA); J. Irby, W. Beck, D. Terry, J. Minervini, R. Viera, E. Marmar, W. Burke (MIT-PSFC); B. Nelson (ORNL)
Attendees & Participants: J. Makiel, T. Indelicato, B. Sullivan (DOE); M. Williams, M. Ono, J. Menard, S. Gerhardt, R. Strykowsky, P. Titus, H. Zhang, S. Smith, S. Raftopoulos (PPPL).

The motivation for this peer review was described in the Introduction (Ref. 1). To summarize: A plaster-like compound called Aquapour was used to form what was to be a temporary surface 0.100” above the TF center stack surface on which to wind the OH coil. Aquapour is normally easily dissolved by water, and the intent was to remove it after the OH winding was completed to create a thermal expansion gap between the OH and TF windings so that the mechanical and thermal behavior of the two windings would be decoupled. Unfortunately the Aquapour became contaminated with the CTD 425 resin during the vacuum pressure impregnation (VPI) process. The resin-contaminated Aquapour is impervious to water, and is moderately hard. Attempts to remove it with picks, a variety of saws, and pressurized water were unsuccessful. After detailed discussions, the project decided that, rather than risk damage to the TF and OH coils, which were very good electrically, a mitigation strategy based on assuring that the OH coil is always hotter than the TF coil (and thus expanded away from it, permitting the two coils to expand and contract independently) seemed feasible and could be developed. The mitigation strategy was presented in the following two presentations (ref. 3 and 4).

It is worth noting that this risk was evaluated and listed in the risk registry around the time of the preliminary design review in June, 2010. Risk: “unable to completely remove temporary space material between OH and TF.” Mitigation Plan: “Administrative controls during operation requiring OH and TF to be powered together."

The mitigation plan that PPPL proposes is outlined below. (The alternative option discussed during the review, which is to build mockups of the OH coil and perform testing to qualify the coil for the expected strain rates, can be revisited in the future.)

- Preheat the OH to create a gap between the TF and OH so that each can thermally expand independently. The gap required is ~0.012”. There are two options for maintaining $T_{TF}<T_{OH:}$
    1. ***Pre-heat the OH coil*** using currents before the TF turns on.
    2. Control the shape of the OH S-curve by ***adjusting the amount of pre-charge***.

- **Year 1 and 2 physics program can proceed basically unaffected** since the OH and TF coils are only needed to operate at ~70-80% full operating parameters, even allowing for the proposed OH coil pre-heating. This provides “room” for the temperature rise due to preheating or recharging of the coil.

- Year 3+ requires 2 MA, 1T, 5s operation. To make room for the OH preheating while still permitting the full thermal excursion required, we propose extending the maximum OH operating temperature from 100 ^{0}C to 110-120 ^{0}C after tests to verify this change.

Depending on the maximum temperature, there may be a small (0.2-0.3 s) loss of pulse duration. Operation at τdischarge>3τ_{CR} (plasma current redistribution time constant) will not be affected. **With these changes in operation, the full NSTX-U Physics Program can still be achieved.**

Increasing the maximum OH operating temperature:

- The resin used to Vacuum Pressure Impregnate (VPI) the TF and OH coils is CTD-425, which is a cyanate ester / epoxy blend.
- The primary reason this resin was chosen was to assure maintenance of adequate strength properties at the projected 100 ^{0}C maximum operating temperature.
- DMA test data shows that this resin has a virtually flat storage modulus up to ~120C. The storage modulus behavior indicates that there will be minimal loss of the elastic modulus up to that temperature. *Consequently, we believe that it will be possible to safely extend the maximum operating temperature from 100 ^{0}C to 110-120 ^{0}C.*
    - We plan to verify creep properties. Creep (permanent deformation), can occur when a material is stressed for prolonged periods of time at elevated temperature.
        - Tests are planned to measure the creep behavior of a CTD-425 VPI impregnated mockup of a coil section, but this is not expected to be an issue.
        - The time that the coil will be at temperatures >100 ^{0}C will be limited - allowing for cool-down, it is in the range of 12 minutes per pulse.
        - It will only be a maximum of 10-20 ^{0}C above the design basis 100 ^{0}C.
        - If creep does occur, the preload mechanism (compressed Belleville spring washers) can absorb a modest amount. If more must be accommodated, the mechanism can be re-adjusted or, in the extreme, shims could be added.
        - The preload mechanism contains two sensors to measure solenoid thermal growth or, if creep occurs, decrease in height.

Reviewer Inputs:

Below are answers to the Charge questions and comments from the MIT reviewers and the responses from the Project:

Charge questions:

A. Does our approach with temperature controls appropriately control risk?

You are not making direct measurements of temperature or strain. The I^2t measurements must be good enough and the thermal coefficients known well enough to ensure you know the temperatures are within safe limits, with appropriate margin. Good measurements of inlet and outlet water temperatures and flow rates should be used to add confidence to the measurements. Assuming adequate testing of your new Digital Coil Protection System ensures you can maintain the entire OH coil at least 10 ^{0}C above the TF everywhere, your plans for 2015 and 2016 operation could be carried out with acceptable levels of risk. You should continue to refine your measurement and control capability, your analysis results, and your testing program over the next few months. These issues should be discussed before the readiness review in December.

Answer: RTDs measure the inlet and outlet temperatures for all 4 layers of the OH coil and all turns of the TF coils. RTDs are type A PT100 with accuracy of 0.1C. RTD temperature measurements will be used to periodically calibrate the accuracy of the algorithms used in the DCPS. These sensors will also be used to provide the permissive for the next shot.

10^0C is not proposed as the temperature difference between the OH and TF; rather we propose to keep the TF always colder than the OH, or at worst have their temperatures match. In the future we may assess scenarios with the TF slightly warmer than the OH. See S. Gerhardt's presentation for details of the OH preheat or precharge temperatures proposed.

B. Is the need for qualification tests urgent or can they wait for operating experience and/or physics need?

The characterization of Aquament mechanical properties should be completed before you begin operation. Creep tests on an OH mockup should be part of an ongoing program to prepare for full parameter operation in 2017.

Answer: By ensuring that the OH temperature is above or equal to the TF temperature there will be no mechanical interaction between the two systems. We do plan to cut samples from a VPI'd sample of Aquapour to measure its compressive and tensile strength and modulus. However, since our plan going forward does not require this data, it is just for information for possible future use. Based on the effectiveness of the VPI process and our suspicion that thermal expansion of the OH coil preceded thermal expansion of the TF coil which was interior to it and "insulated" by a layer of Aquapour, it is likely that resin flowed down the entire length of the Aquapour and impregnated the entire cylinder of Aquapour. The VPI'd Aquapour was found to be very tough (though not as tough as the resin) and hard to break up; we feel that it will not break up into pieces small enough to fall into the thermal expansion gap (~0.012") . Regardless, we will periodically monitor the bottom of the solenoid for any evidence of particles falling out.

C. Is the present and future work that is planned comprehensive enough to support our research goals?

If you continue to refine your models and do tests consistent with those mentioned in Pete's presentation, you will be able to make very good progress on your research goals. We still have questions and comments you should consider as you plan the engineering work ahead:

1. We strongly recommend tests to evaluate the Aquapour properties, including mechanical and thermal. This test should also measure the rate of penetration of the resin as a function of time during the VPI process.

   Answer: We do plan to evaluate the mechanical properties of Aquacement (see B above). The thermal conductivity, although not measured, was observed to be low during heating of the assembly during the relative motion tests (below). It will not have any appreciable effect on the dT between the two coils or cool-down during operation.

2. How was the relative movement of the OH relative to the TF core measured? Was it symmetrical top/bottom or with one end of the OH coil fixed? Symmetrical growth top and bottom does not ensure that the OH is free to move relative to the TF.

   Answer: Normally the OH coil is fixed on the bottom and expands towards the top. It was measured by dial indicators. For this test, the bottom support was removed and the coil expanded both ways (not quite symmetric, ~0.040" bottom; 0.060" top).

3. OH coil cool-down analysis which includes the Aquacement thermal properties should be performed.

   Answer: The heating time-temperature behavior during the relative motion tests demonstrated that the Aquacement has relatively poor thermal conductivity and will not appreciably affect cool down during operation (See B above). .

4. What is the degree of accuracy of the temperature measurements and is the error within the allowable delta T for safe operation of the coils?

   Answer: Thermal calculations will be done within DCPS. These calculations will be calibrated by the RTD's which measure the water inlet and outlet temperatures. The accuracy of the RTDs is 0.1 degrees; the calculation accuracy and calibration accuracy together will be better than ~1-2% , which is safe for assuring adequate dTs between the coils.

5. What type of electrical testing will be performed on the coil once it is installed in the tokamak, and at what temperatures will the tests be performed?

   Answer: After installation, impulse tests will be repeated at 5 kV and hi-pot tested at 9 kV and compared to the previous measurements. The tests will be performed at room temperature. A subsequent Integrated System Test Procedure (ISTP) will qualify the coil for operation.

6. Cool-down fault analysis should include failure of any or all of the coil cooling systems. Are the implications of such events benign? As one example, if the TF cooling system failed at the end of a high performance pulse, what will happen to the TF and OH temperatures (and gradients) as the coils cool passively through conduction and convection to the rest of the structure?

   Answer: The coils do not require active cooling during a pulse for safe operation. In a passively cooled condition, analyses show that the TF cools faster than the OH due to the TF flags which extend from the coil in the umbrella structures and acting like cooling fins; this is a desirable condition. If the TF cooling water trips or has a flow problem, the programmable logic controller (PLC) can be programmed to stop the flow of the OH cooling water. As a result of this review, we do plan to program the PLC to stop the flow of water to the OH if the TF cooling water trips or has a flow problem.

7. Do the 4 wires (intended to help remove the Aquapour, but now trapped in the coils) pose any electrical or mechanical risks? Issues could include stress concentration and peaking of electric fields. Is there modeling that could/should be done?

Answer: The electrical insulation has large factors of safety (see Att. 3). An ANSYS 2-D electrostatic model indicated no risk electrically since the calculated electric field is 1.8 MV/m compared to a dielectric strength of 30 MV/m for G-10 (which has comparable electrical properties to VPI impregnated fiberglass) and 3 MV/m for air. They pose no mechanical risk.

8. Is the time between pulses using the new cool-down scenario adversely affected?

   Answer: The cool down scenario will not be affected due to Aquacement issues.

9 Slide 31 in Titus's presentation shows one preliminary simulation of post-shot cool-down, but in the case shown it appears the stresses might be as high as 16 MPa, which seems too large (based on slide 4 from the same presentation). Pete says "more analysis required". When will that be complete, and will it be reviewed?

   Answer: Although not related to the Aquacement issue, the cooling wave phenomena was recognized and is being further analyzed. The analyses are expected to be completed in early November, and a Peer Review will be held shortly after that.

10. What about a TF crowbar at end of TF flattop, when OH current is back to 0. Slide 4 from Gerhardt's presentation shows a case where the OH temperature gets very close to the TF (within perhaps 3 degrees C). [a]. Are there simulations of cases like this, with a TF crowbar at the end of flat-top? [b]. During the review it was mentioned that a TF crowbar at full current would cause something like an additional 4 ^{0}C temperature rise. A simulation that shows this for 130 kA TF cases with the TF starting at 100 C should be run. [c]. Slide 20 discusses the DCPS algorithm to be implemented for protection, but without more information, it is not clear if this will prevent access to some of the desired (required) operating space. Also, what is the maximum temperature the TF can take, independent of the OH stress considerations?

    Answers: [a] and [b] The DCPS algorithms factor in the temperature rise due to crowbarring. [c]. It may slightly narrow the operating space at the combined highest fields, currents, and pulse durations. That algorithm is conservative as it limits the projected temperature difference between the OH and TF to less than zero; i.e. this enforces the new requirement that the OH temperature is never lower than the TF.

11. Almost all of the simulations for coil temperatures appear to be 0-D. Are important gradient effects being missed? It appears that all of the planned DCPS algorithms assume single uniform temperatures for each coil (OH and TF). Is that sufficient for protection?

    Answer: The cooling analyses with the F-Cool code were 1-D, and these demonstrate that 0-D is sufficient for protection. The analyses have addressed 3-D thermal gradients in the coils.

12. If Aquapour degrades during operations, what keeps the OH centered on the TF? Slide 22 of Gerhardt presentation implies centering shims will no longer be used since there is no room for them now anyway, because of the Aquapour.

Answer: Shims can easily be added on the top end of the solenoid if we do observe Aquapour debris beneath the machine.

13. How will the DCPS changes be implemented, reviewed and tested? A detailed plan is required. What about software bugs, hardware reliability, redundancy, common mode failures?

    Answer: Out of scope for this review, but will be addressed in Operations Procedure OP-DCPS -779. A Failure Modes and Effects Analysis (FMEA) was performed which includes failure modes. Reliability analysis will be included in the DCPS system description which is currently being written.

14. Extensive failure analysis and testing of interlock and temperature difference control and protection systems are necessary.

    Answer: Agree. This will be addressed in the PTP's (Preoperational Test Procedure) and ISTP (Integrated System Test Procedure).

15. How is the temperature evolution algorithm to be calibrated against outlet water temperature and other measurements, and how often is this calibration to be done?

    Answer: See (4) above. Calibration will be performed at the beginning of the run period, which is typically 12-16 weeks. This data is stored for each shot and used for periodic review.

16. What is the range of OH coil temperatures required during normal and off-normal operation? What effect will this have on OH coil insulation over time? When will engineering tests be done for the mock-up section of OH winding for fatigue testing?

    Answer: It will be in the range of 12 ^{0}C to 110-120 ^{0}C, (to support 5s, 2 MA operation) with the exact upper limit decided after the data for the planned insulation creep tests is examined. These tests will be performed in the next year. For the first year, only 70-80% of the GRD I^2 t is required, (Trise~75 ^{0}C). The creep test is being performed to ensure that the OH insulation will not be adversely affected over time. The temperature increase being proposed is modest and far from the glass transition temperature of 180 ^{0}C and will not cause any aging degradation of the insulation.

17. Will DCPS and interlock systems safely handle test shots with TF only and other required test or calibration pulses? The system should be designed to allow them.

    Answer: "TF only shots" will be led by OH preheats sufficient to provide the required thermal headroom. Should this not be done, the DCPS will issue a Level 1 fault.

18. Pete Titus recommends several tests and qualifications for the two possible solutions he presents in slide 19. Are these to be done and, if so, when? These include:

    a. First solution (slide 19)
        i. Recommends strain controlled tension fatigue tests of insulation systems.

    ii. Properties of epoxy impregnated Aquapour should be better characterized.

b. Second solution (slide 19) this is our preferred solution.
    i. Plumbing and new operational controls needed.

Answer: We plan to go forward with the solution which avoids interactions between the OH and TF and with 110 -120 ^{0}C max. temperature operation, as discussed on p. 1. Creep tests at 110-120 ^{0}C will be performed. Only operational controls are needed for the elevated temperature operation.

MAST Group Comments:

M1. Several of us considered that it must be possible to do micro-hardness tests on the chips of removed impregnated Aquapour.
Answer: We do plan to perform tests on VPI'd Aquapour samples (see Charge Question B responses above).

M2. I liked the idea raised by someone else of simply measuring the density of the chips and mocking up to some decent sized samples by deliberate impregnation with CTD-450 to cover a range of densities, to check the mechanical behavior, yield strength, etc.
Ans: See Charge Question B response above.

M3. The hi-pot test was helpful and reassuring in its results, but as I said at the time, the wires will create electric field stress concentrations and could conceivably shorten the insulator life against micro-discharges (miniature break-downs within the insulator, exacerbated by electric field cycling), so worth getting someone to analyze sometime, I think.
Ans.: As stated in (7) above, An ANSYS 2-D electrostatic model indicated no risk electrically since the calculated electric field is 1.8 MV/m compared to a dielectric strength of 30 MV/m for G-10 (which has comparable electrical properties to VPI impregnated fiberglass) and 3 MV/m for air.

M4. Temperature rise profiling and control was extensively covered and seemed perfectly OK to me, but I got the impression there had been less work on the temperature fall after each shot. The adverse effects of the cold wave propagating up the solenoid (so it bites the TF vault if that has not been thoroughly cooled beforehand) seemed to be of some concern, and not just because of the Aquapour issues. Indeed, it was said that the solenoid shrinkage being inhibited by it contacting the TF vault would help to reduce the stresses caused by the solenoid diameter transition.
Answer: You are correct; the adverse effects of the "cooling wave" are issues independent of the Aquapour issue. We are re-visiting previous analyses of the cooling wave.

M5 However I agree that a trivial cure to the TF-OH differential temperature problems during cool-down is simply to delay the active cooling of the solenoid until after the outlet temperature of the TF has shown it to have cooled sufficiently. This will work if, as we were told, the thermal time constant between them is measured in hours rather than minutes, and the physicists don't mind waiting an additional five or ten minutes between

high-performance shots.
Answer: In normal operation the TF cools down faster than the OH coil. Simulations show similar cool down wave response with and without Aquapour.

M6. Not closely related to this Aquapour problem, I observed that the machine protection system, as sketched perhaps overly simplistically for this presentation, seemed to have many common-mode failure points that could prevent it from carrying out its function rather too often. This would need detailed exploration by more of us with Machine Protection Working Group experience!
Answer: Indeed, the sketch was simplified to provide an overview of the system and should not be considered as an engineering drawing. A FMEA for the DCPS system was performed and has been successfully reviewed.

M7. Similarly it was said that the machine protection would only trip all power supplies simultaneously, by means of electronic shorting switches to force zero voltage on all bus-bars. Compared to JET and MAST systems, this is oddly limited and somewhat brutal to the supplies, and also (I think it was Jon Menard who noted, near the end of the meeting) stops the control systems from being allowed to initiate a controlled termination e.g. when something important has tripped (e.g. the TF or OH), in order to avoid precipitating a high current major disruption. JET uses a cascade of different trip types as any operational limit (single parameter or combined) is approached, in a sequence like power supply internal current clamp, thyristor trigger blocking to create essentially a bridge voltage going to zero, open mains input breakers, fire brutal crowbar. Before all that, we send an alarm to the plasma control system telling it what is likely to trip, so that it can choose one of about a dozen different soft termination scenarios to minimize the chance of a disruption given the specific power supply loss.

Answer: Prior to year 3 of operation, we will have developed and tested algorithms inside the plasma control system analogous to the DCPS which will anticipate exceeding an OH-TF temperature differential limit and other DCPS faults and initiate a controlled plasma current ramp-down before a DCPS trip is triggered.

M8. There was mention of letting the coils cool down on their natural L/R time, but some slides showed a steep TF current decay all the way to zero, as though the supply has two-quadrant behavior. Maybe it has, when not shorted?

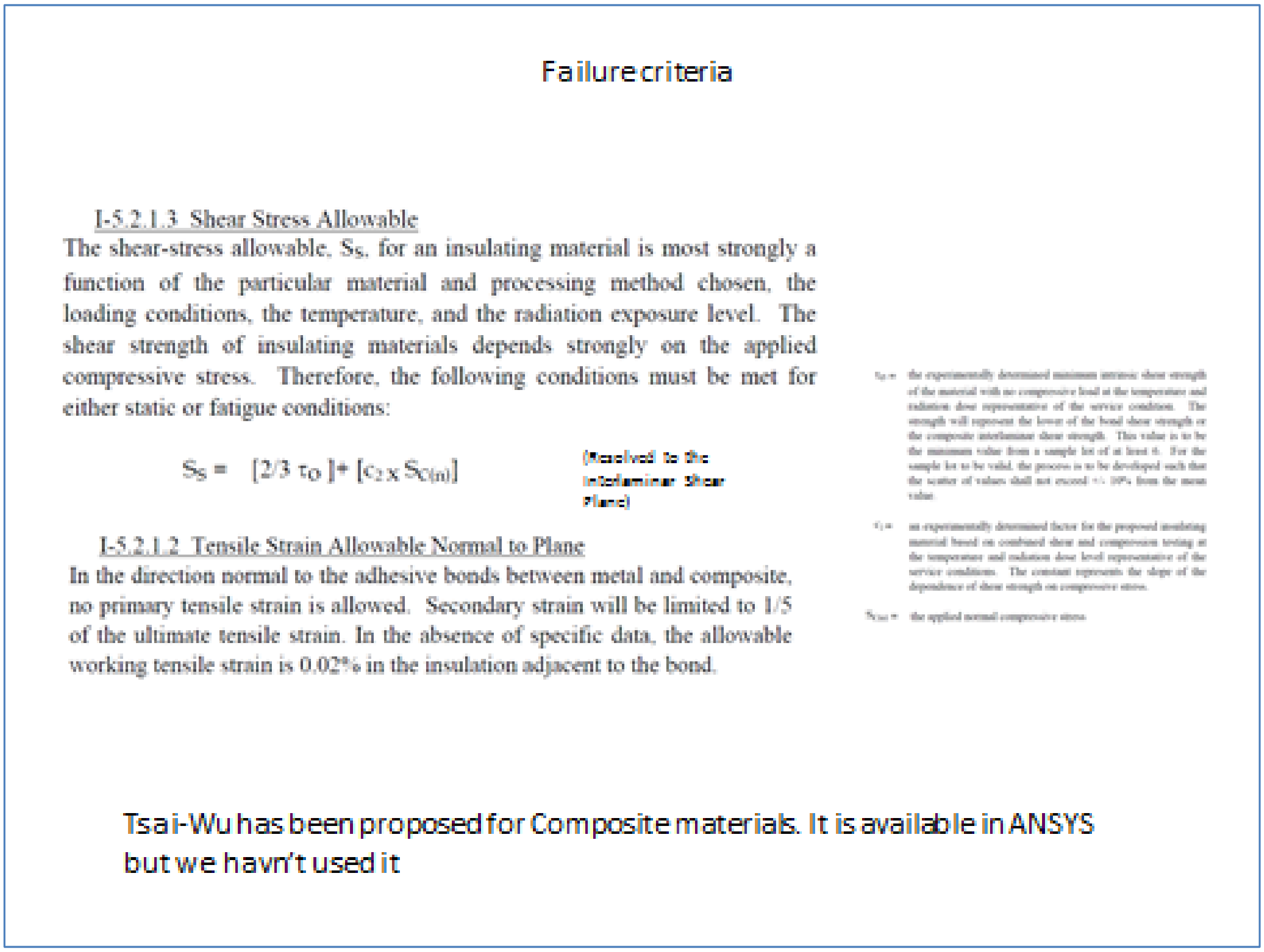
Answer: The standard Transrex power supply section has two-quadrant behavior (current in one direction, but voltage in both). The plots that show the TF ramping down quickly are cases where the supply is controlling the current rapidly back to zero, under digital command and NOT in a fault condition.

M9. It was said that sub-cooling TF might exacerbate creep failure, but I don't understand this since creep phenomena are associated with elevated temperature. If the impact of one coil system upon the other was meant, the detail was not explained.
Answer: Sub-cooling of the TF was mentioned as an alternative way of generating the required dT between the OH and TF. This could potentially avoid having to qualify the OH for operation above 100 ^{0}C. If sub-cooled, the TF water temperature would be reduced to 8 ^{0}C. This would require improving the dehumidification of the test cell. We

expect the creep level to be manageable, as discussed in “Increasing the maximum OH operating temperature” on p. 1 of this report; this is the more cost effective solution.

M10. My proper engineering colleagues can comment, but I thought Tresca stress, while recognizing the superposition of shear and compression/tension in a generally appropriate way to represent total stress, did not intrinsically relate this to the loci of allowable shear and tension/compression in a composite material at various temperatures and desired fatigue lives, as Mohr plots do?

Answer: The failure criteria we generally use are described in the slide below. Mohr’s Circle analysis is used to determine the shear stress in the plane of the composite.



Failure criteria

I-5.2.1.3 Shear Stress Allowable

The shear-stress allowable, S_S, for an insulating material is most strongly a function of the particular material and processing method chosen, the loading conditions, the temperature, and the radiation exposure level. The shear strength of insulating materials depends strongly on the applied compressive stress. Therefore, the following conditions must be met for either static or fatigue conditions:

$$S_S = [2/3\ \tau_O] + [c_2 \times S_{C(n)}]$$

(Resolved to the Interlaminar Shear Plane)

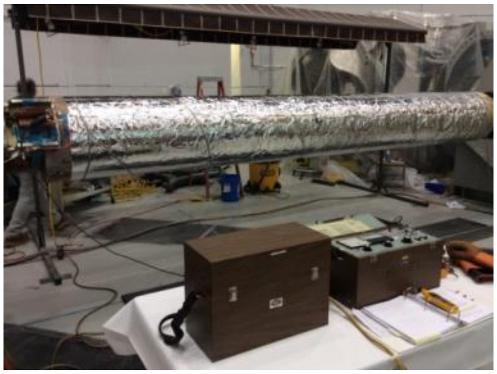
I-5.2.1.2 Tensile Strain Allowable Normal to Plane

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% in the insulation adjacent to the bond.

Tsai-Wu has been proposed for Composite materials. It is available in ANSYS but we havn’t used it

Electrical Hi Pot Test of OH Coil

Details of the OH coil electrical hi pot test were requested during the review. The photo below shows the center stack during the test. The TF turns were connected together and grounded, the foil over-wrap over the OH coil was grounded, the structure was grounded, and the (4) wires embedded in the Aquapour were grounded. The leakage current from the OH coil to ground was 12µA at 13 kV after 1 min.



References: (posted at ftp://ftp.pppl.gov/pub/Heitz/NSTXU_8SeptPeerRev/).

1. Peer Review Introduction
2. NSTX-U TF-OH Design & Manufacturing
3. Aquapour/CTD-425 Composite Implications for NSTX-U Operations and Research Goals
4. Aquacement problem (Analyses)