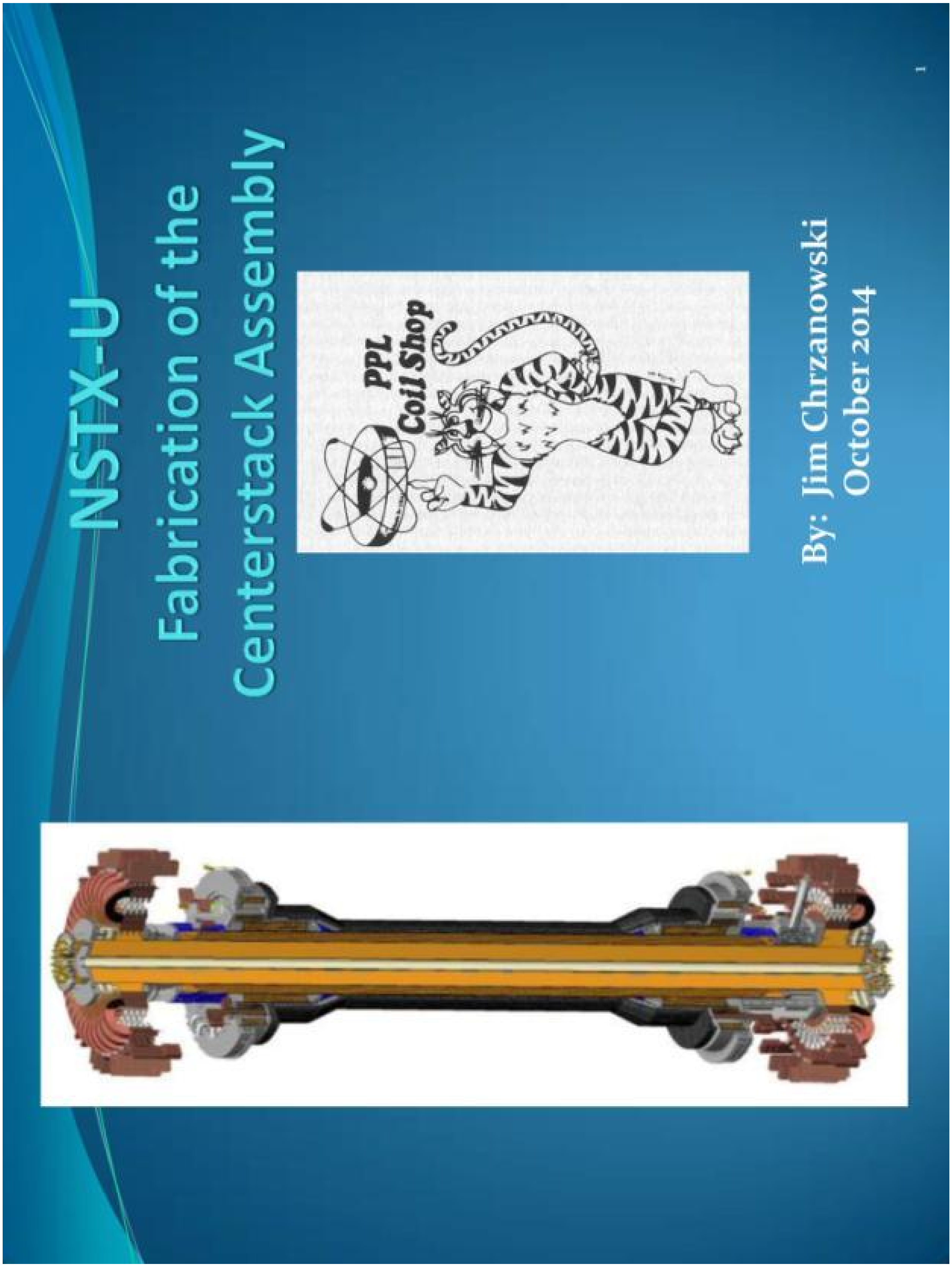
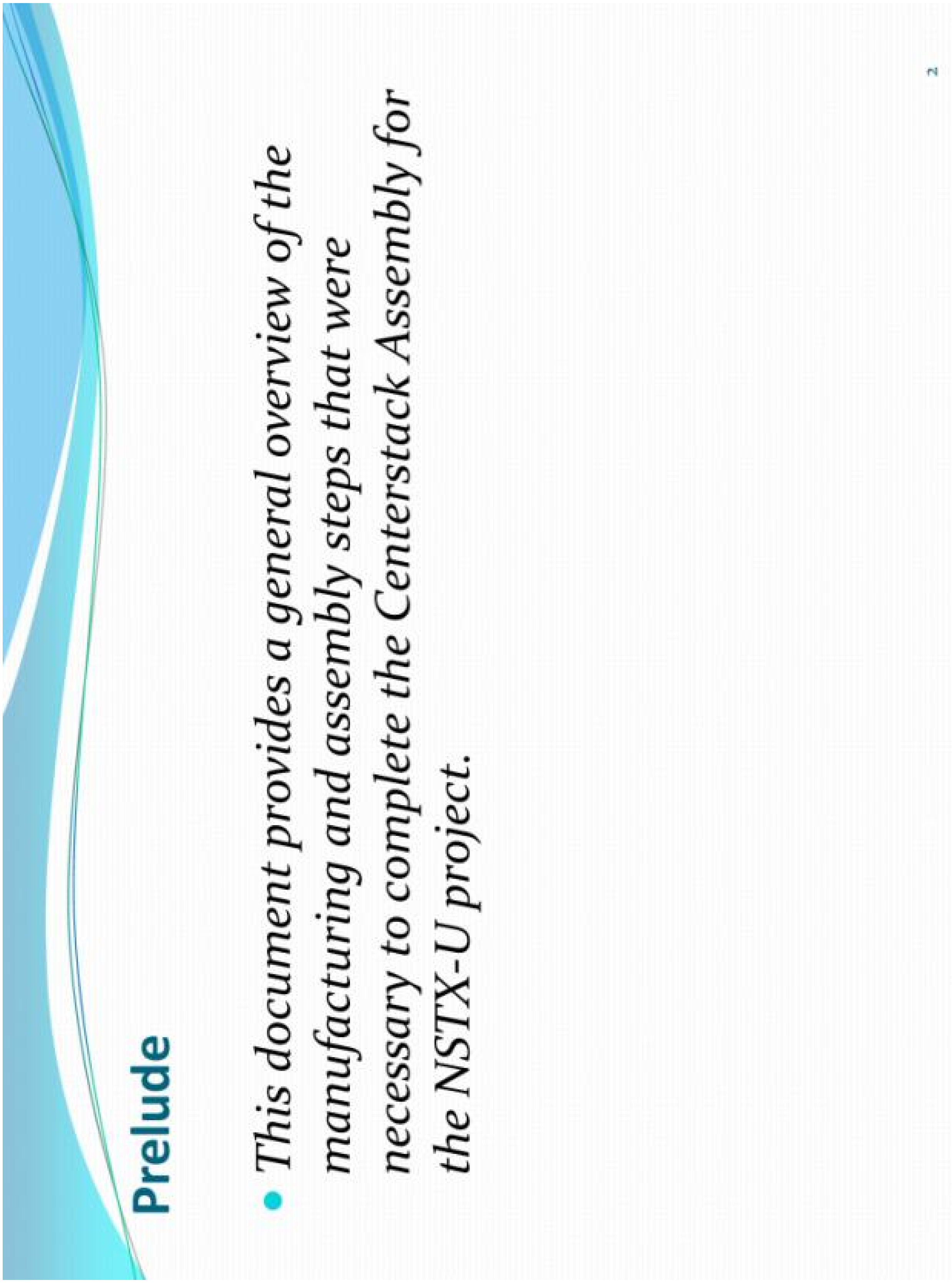
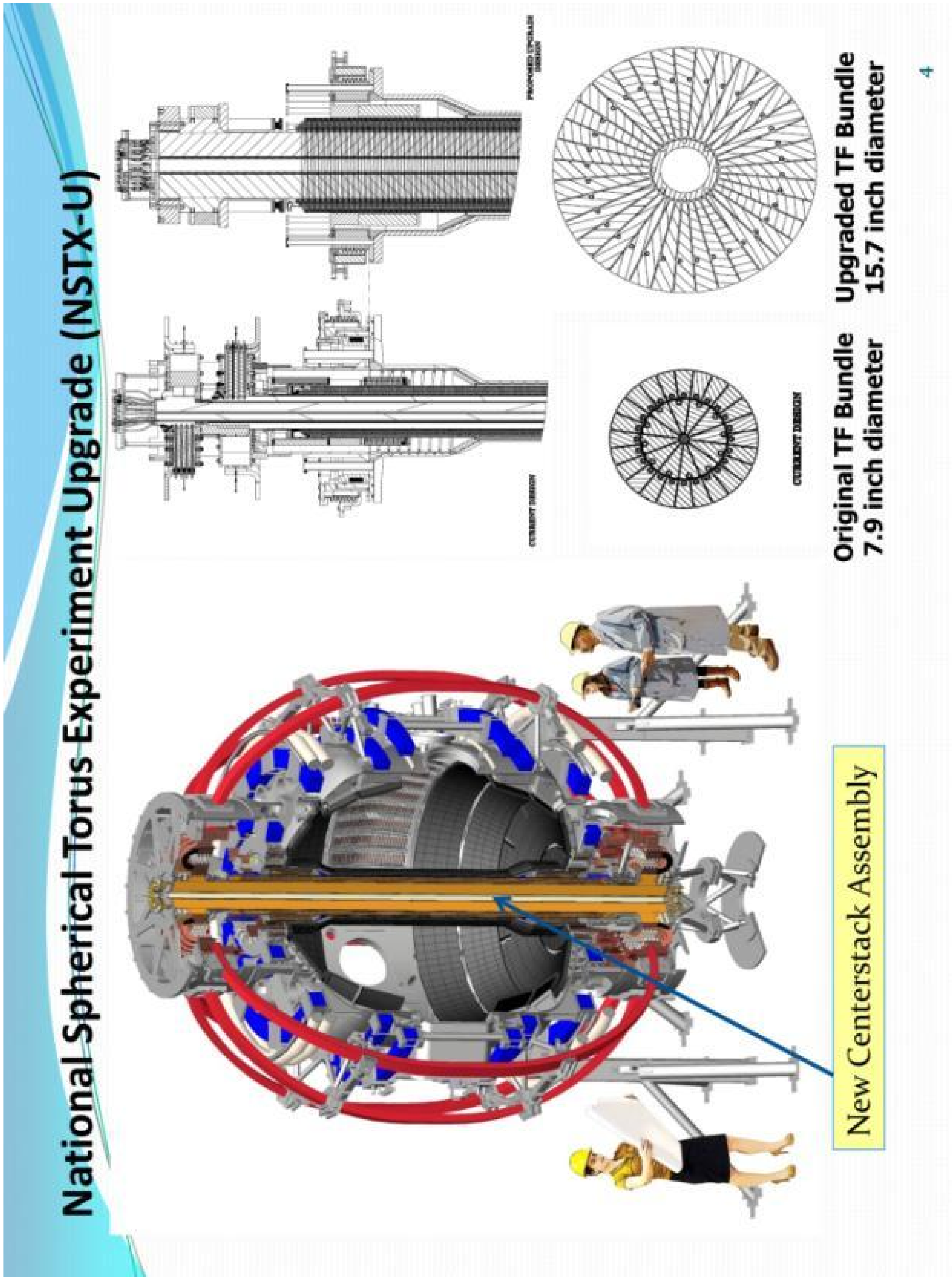
Appendix I

Centerstack Fabrication and Assembly

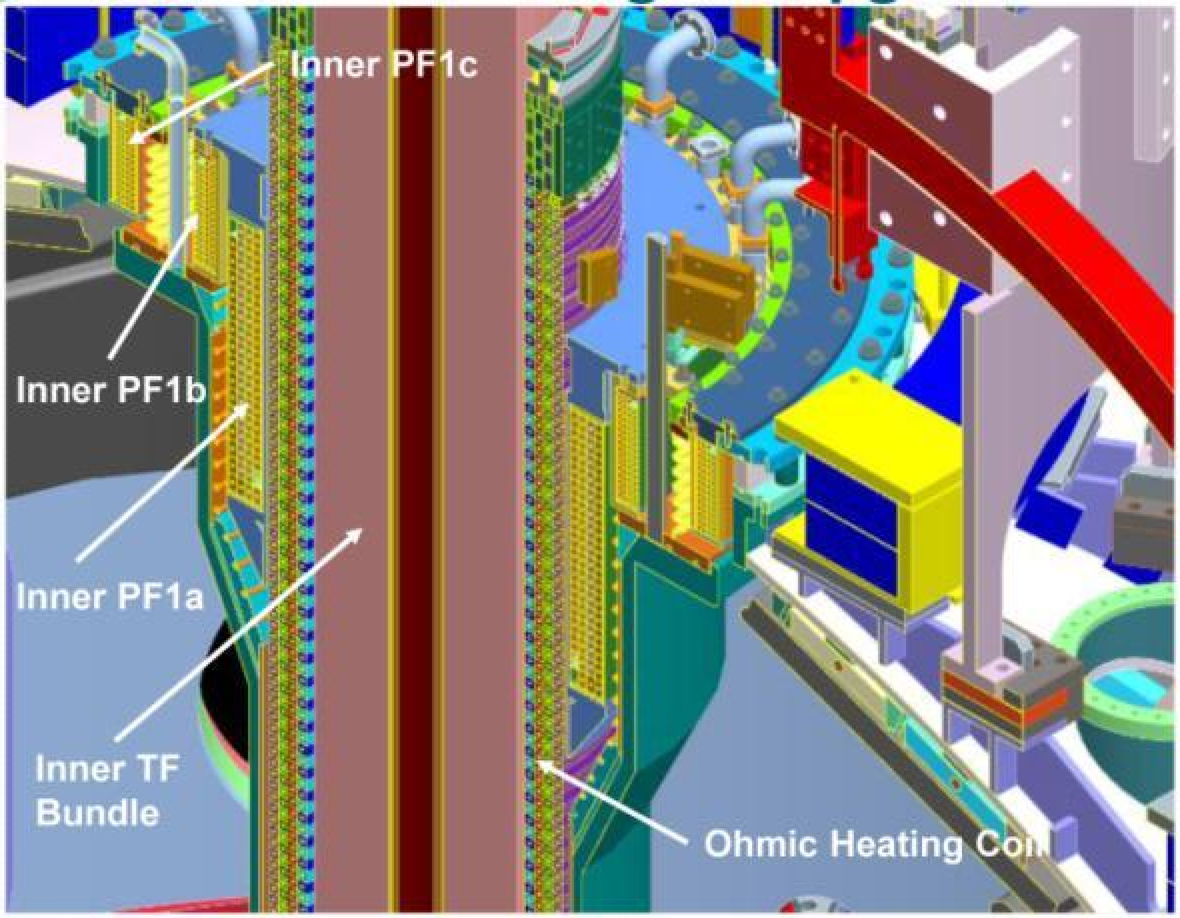



Prelude
This document provides a general overview of the manufacturing and assembly steps that were necessary to complete the Centerstack Assembly for the NSTX-U project.
2


Introduction
In 2009 the US Department of Energy approved the initiation of a project to update the NSTX for approved performance. A new Centerstack was included as part of the upgrade activities. The CS assembly includes:
Inner TF Bundle
Ohmic Heating Coil
Inner Poloidal Field Coils
Centerstack Casing
Plasma Facing Components
3


National Spherical Torus Experiment Upgrade (NSTX-U)
New Centerstack Assembly
Original TF Bundle
7.9 inch diameter
Upgraded TF Bundle
15.7 inch diameter
4

NSTX-U Magnet Upgrade



- New TF/OH coil- fabricated was by PPPL
- New Inner PF Coils were fabricated by Everson-Tesla

5

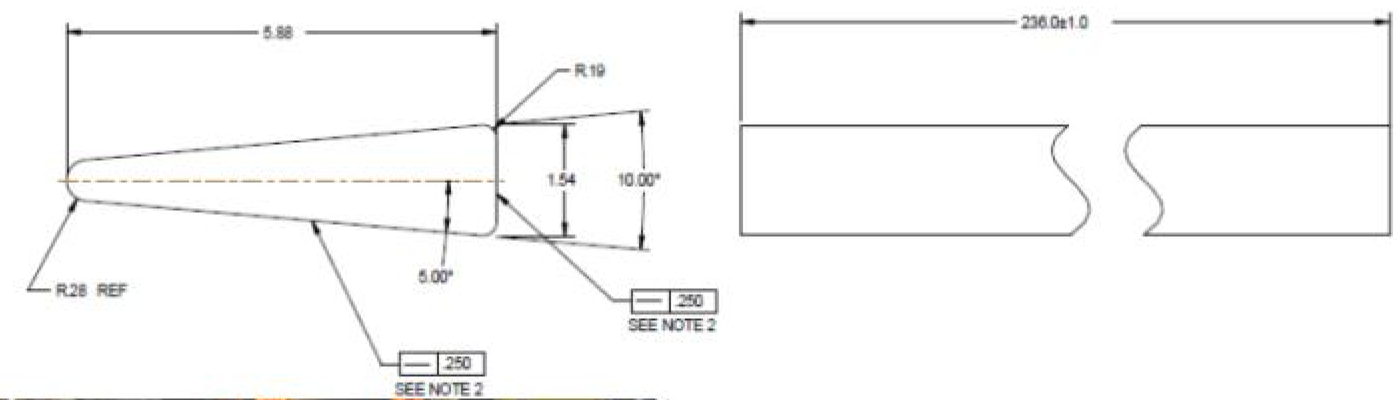
Inner TF Bundle

- **General Description:** The Inner TF bundle is a thirty six (36) turn copper coil bundle that forms the inner legs of the Toroidal field coil system. The coil is constructed using pie shaped oxygen-free silver-bearing copper conductors that are, sandblasted, primed and insulated with multiple half-lapped layers of S2 glass tape. Each conductor end has (CDA18150) Copper-Chromium-Zirconium lead extensions that were added via a friction stir welding [FSW] process. The coil was constructed into quadrants that allowed better dimensional control. Each quadrant of (9) conductors were epoxy impregnated using CTD-425 a 2-part system with Epoxy (EP) and Cyanate Ester (CE) catalyst in Part A and Cyanate Ester (CE) in Part B. The finished quadrants were then over wrapped with multiple half-lapped layers of S-2 glass insulation to form the outer ground-wall. The entire insulated coil was then epoxy impregnated using the CTD-425 system.

6

Inner Toroidal Field Conductors

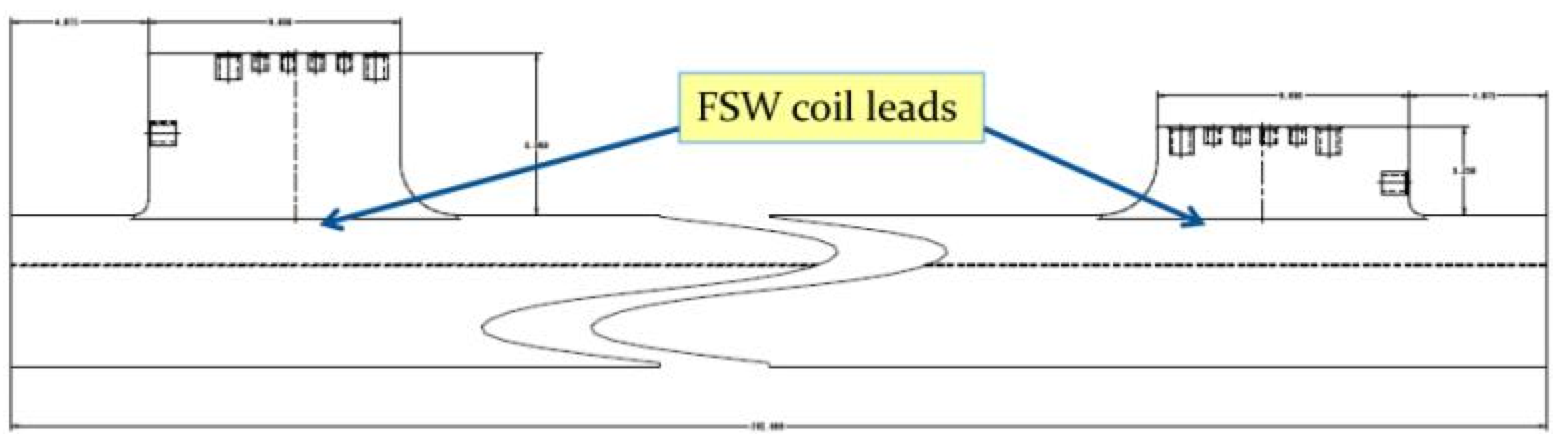
- Inner TF copper extrusions were procured from Luvata-Pori, Finland
- Oxygen-free silver-bearing copper CDA10700



7

Inner Toroidal Field Conductor Assemblies

- The contract for manufacturing the Inner TF conductor assemblies was awarded to Major Tool located in Indianapolis
- The manufacturing was a (3) step process.
  - Initial machining by Major Tool
  - Friction Stir Welding (FSW) of the coil leads to the TF conductor was sub-contracted to Edison Welding Institute, located in Columbus, Ohio.
  - Final machining of the completed conductor was then performed by Major Tool



8


TF Conductor Assembly Manufacturing Sequence
Start- Bars shipped to Major Tool
Bars inspected at Major Tool & preliminary machining performed
Bars shipped to EWI
Leads extensions are FSW to TF conductors
FSW joints are Non Destructively Tested
Bars are shipped to Major Tool
Final machining of TF Assemblies
End- Bars shipped back to PPPL
PPPL
9

TF Conductor Friction Stir Welding

High strength coil leads, Copper-Chromium-Zirconium (CDA18150) were added to each end of the oxygen free silver-bearing copper conductors (CDA10700) by a process known as friction stir welding (FSW). This work was completed by Edison Welding Institute (EWI) in Columbus, Ohio

10

Finished Inner TF Conductor Assembly

Completed TF Conductor Sub-Assemblies in Major Tools Quality Control Inspection room.

Delivery of TF Conductor Assemblies

The finished TF Conductors were delivered to PPPL via truck from Major Tool located in Indianapolis, Indiana

12

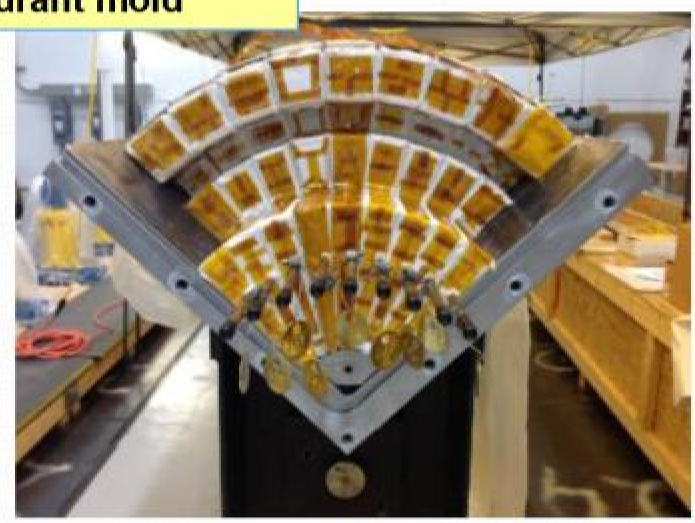

Soldering Operation
The copper cooling tubes were soldered into the TF conductor assemblies using
Solder paste- 96.5 Sn /3.5 Ag w/ GMS based "R" flux [Glyceryl Mono-stearate, Terigitol (a detergent) and Cyclohexlamine Hydro-bromide]
13


TF Conductor Preparation
Conductors were Post Solder Baked to 170° C to remove any excess flux
Grit blast conductors
Prime conductors w/CTD-450 primer & Cured
14


Applying S-2 Glass TF Turn Insulation
15

Assembly of Inner TF Quadrants

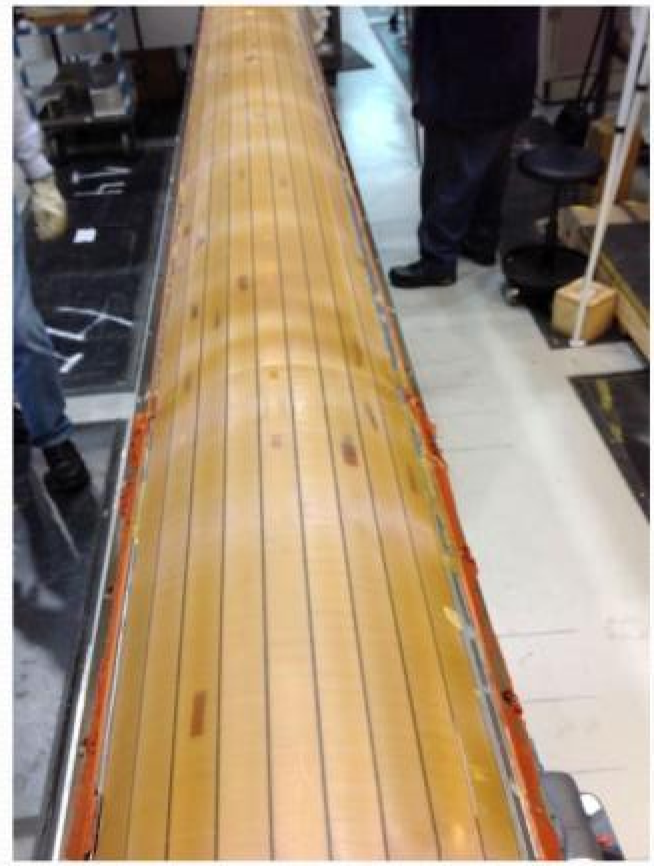
Assemble (9) individual conductors into each Quadrant mold



16

Assembly of Inner TF Quadrants

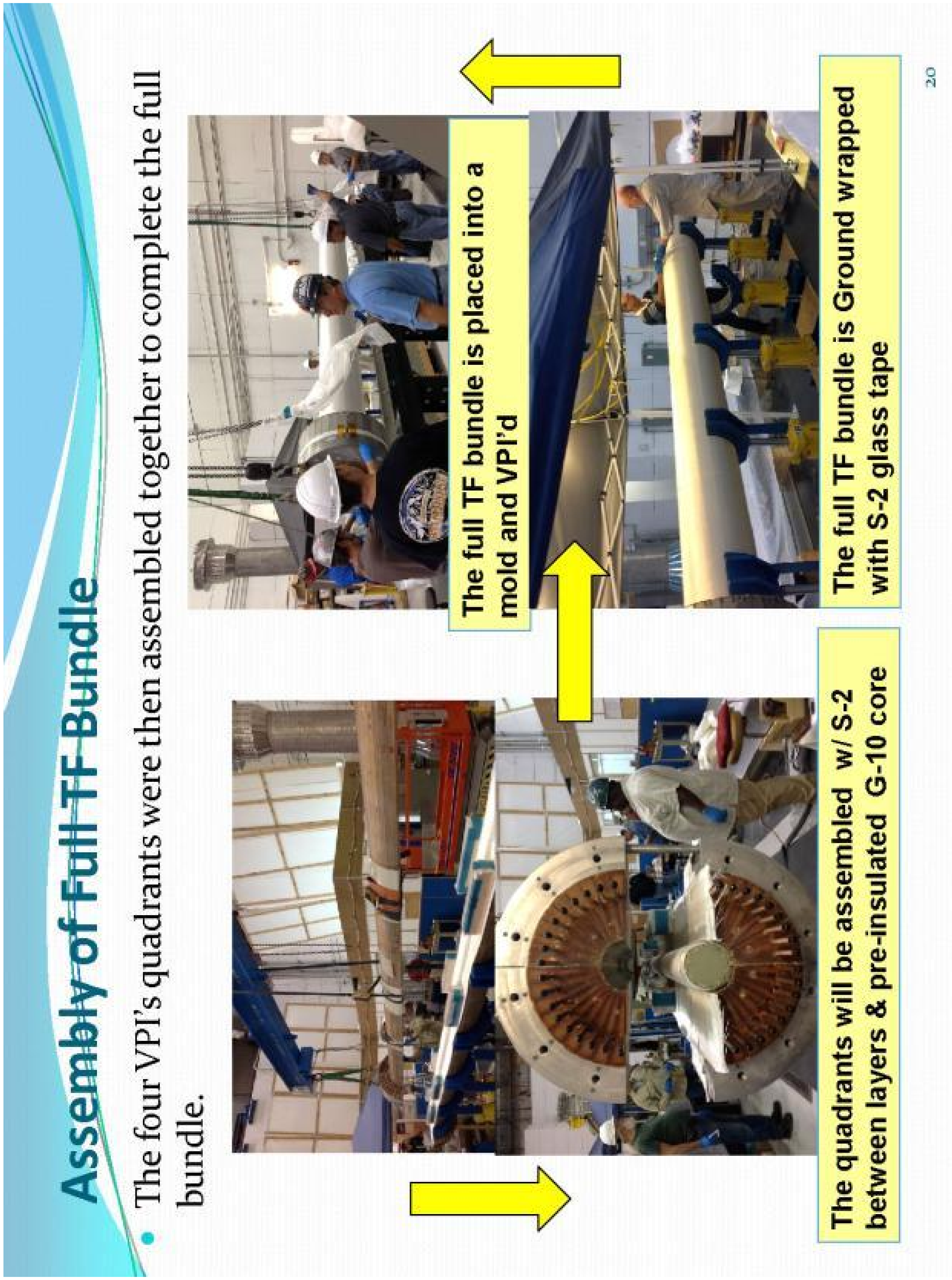
- Once the conductors were assembled into the mold, each TF Quadrant was successfully Vacuum Pressure Impregnated (VPI) using CTD-425 epoxy system



17

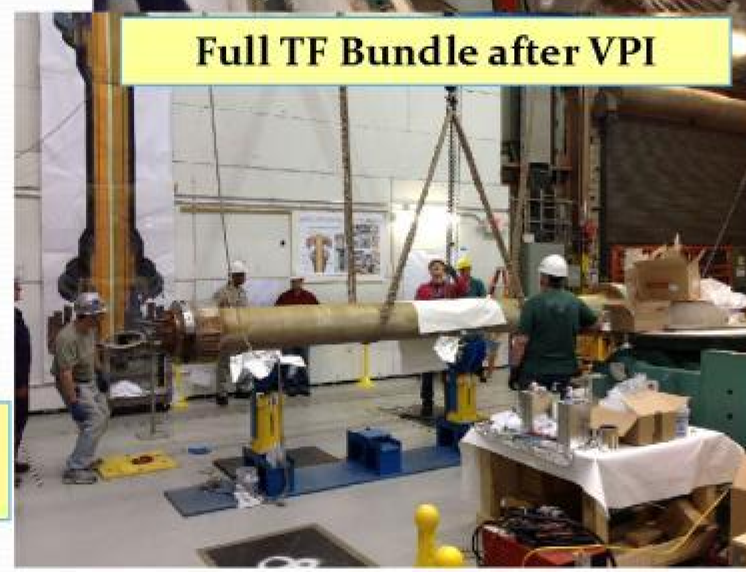

TF Quadrant Electrical Tests
Each of the (4) TF Quadrants successfully pasted their electrical acceptance tests.
18


Completion of First TF Quadrant
19


Assembly of Full TF Bundle
The four VPI's quadrants were then assembled together to complete the full bundle.
The quadrants will be assembled w/ S-2 between layers & pre-insulated G-10 core
The full TF bundle is placed into a mold and VPI'd
The full TF bundle is Ground wrapped with S-2 glass tape
20

Full TF Bundle VPI'd

Full TF Bundle in oven and ready for VPI

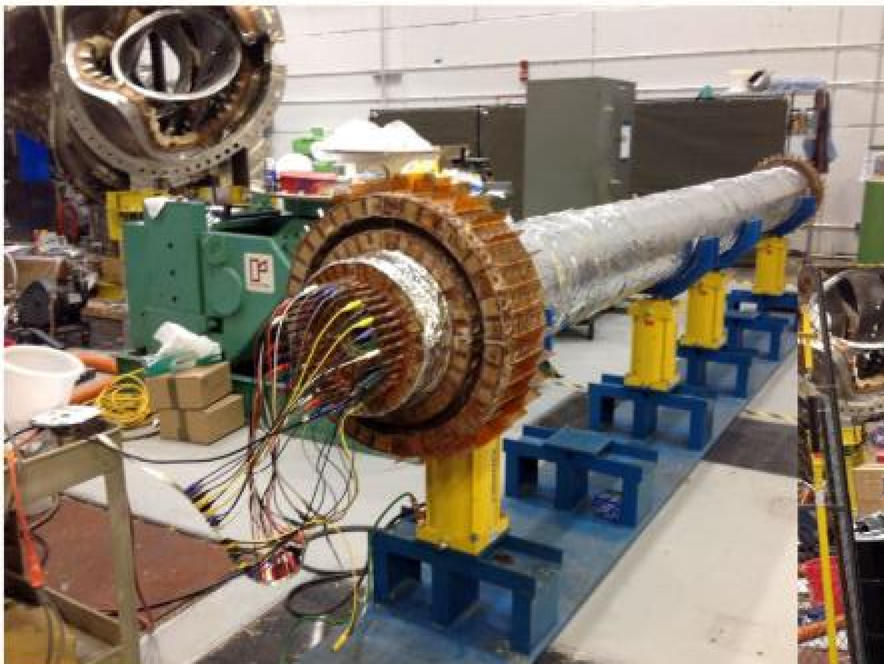


Full TF Bundle after VPI

21

Full TF Bundle Electrical Tests

- The Full TF Bundle successfully pasted its electrical acceptance tests.



22

Raising the Full TF Bundle

- Following testing, the Inner TF Bundle was transported to the vertical positioning fixture.
- The TF Bundle was raised to the vertical position in preparation for the application of the Aquapour.

23

Installation of Aquapour Layer

During bakeout

- Installation of Aquapour layer was successfully completed

"Aquapour" is used as a temporary spacer that will be used to maintain 0.100 inch gap between the TF OD and OH ID surfaces. It is removed post VPI of OH coil

24

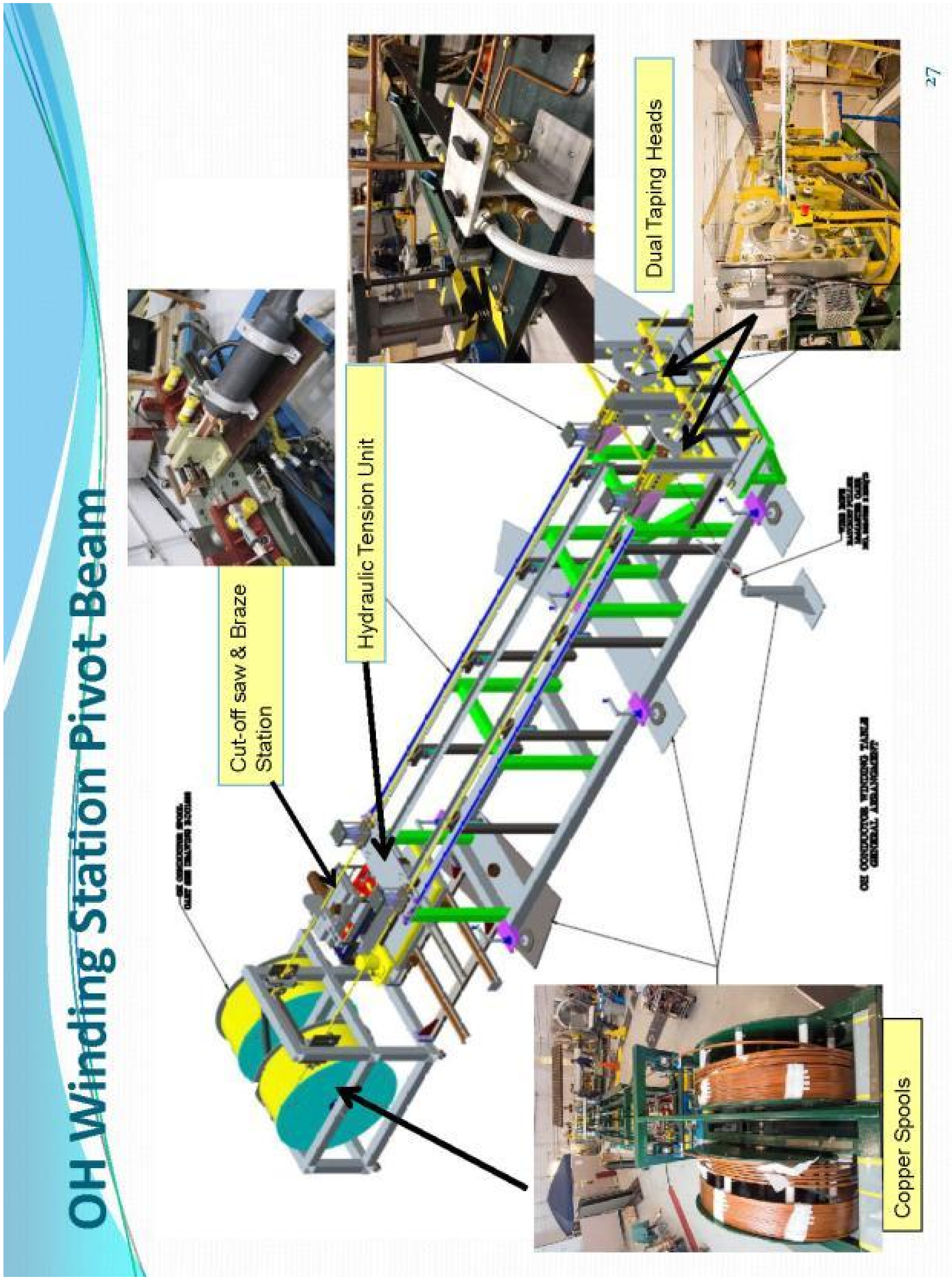
OH Winding Preparations

OH support structure was installed

Epoxy/glass layer was applied over the Aquapour surface to provide a solid winding surface

25


Transfer TF to OH Winding Station
The TF bundle was transferred to the OH Winding station
Applying Inner ground wrap insulation
26


OH Winding Station Pivot Beam
Cut-off saw & Braze Station
Hydraulic Tension Unit
Dual Taping Heads
Copper Spools
27

Ohmic Heating Solenoid

- **General Description:** The Ohmic Heating (OH) solenoid is a 4-layer [884 turn] copper coil. The coil was constructed using extruded oxygen-free silver-bearing copper conductor w/cooling hole. The conductor is first grit blasted and primed, similar to the TF conductors. Individual turns were insulated with co-wound glass/Kapton insulation applied in multiple half-lapped layers. The OH solenoid conductor was wound (2-in-hand) over the outside diameter of the inner TF coil bundle. A 0.100 inch gap was maintained between the OD of the TF bundle and the ID of the OH solenoid to allow for thermal growth of the components. S-2 glass ground-wrap was then applied over the finished wound coil. The entire wound coil was then epoxy impregnated using CTD-425 system a 2-part system with Epoxy (EP) and Cyanate Ester (CE) catalyst in Part A and Cyanate Ester (CE) in Part B.

28


OH Coil Lead & cooling fittings were Torch Brazed to OH Conductor
29


OH Winding Station
OH primed Conductor
30


Coil Winding Activities
31

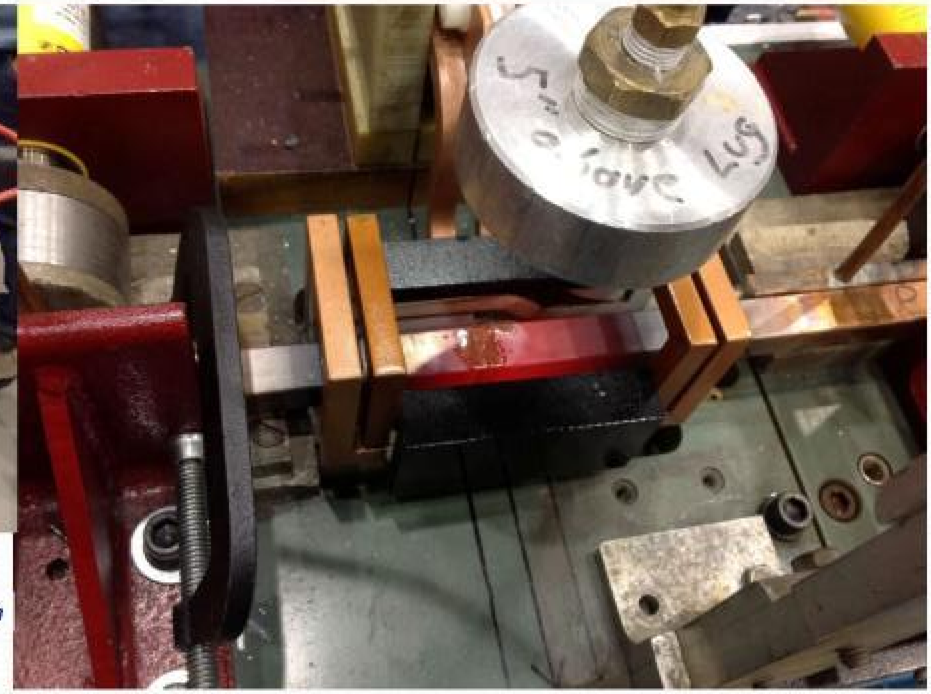
Coil Winding Photos -continued

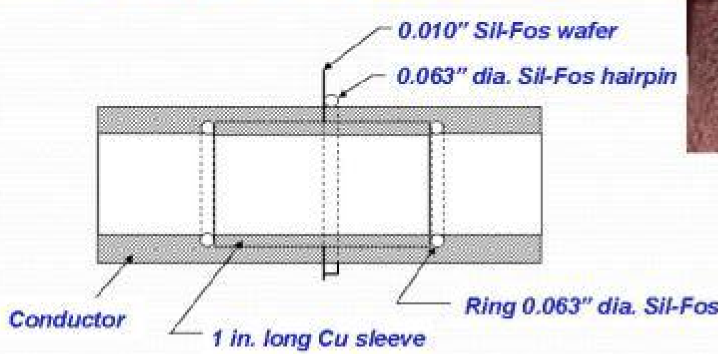
Photos of some of the winding activities and personnel

32

OH In-Line Brazing

- (32) in line brazes were performed during the OH winding operations.
- Each braze joint was mechanically loaded (stretched) and helium leak tested to ensure a quality braze joint.

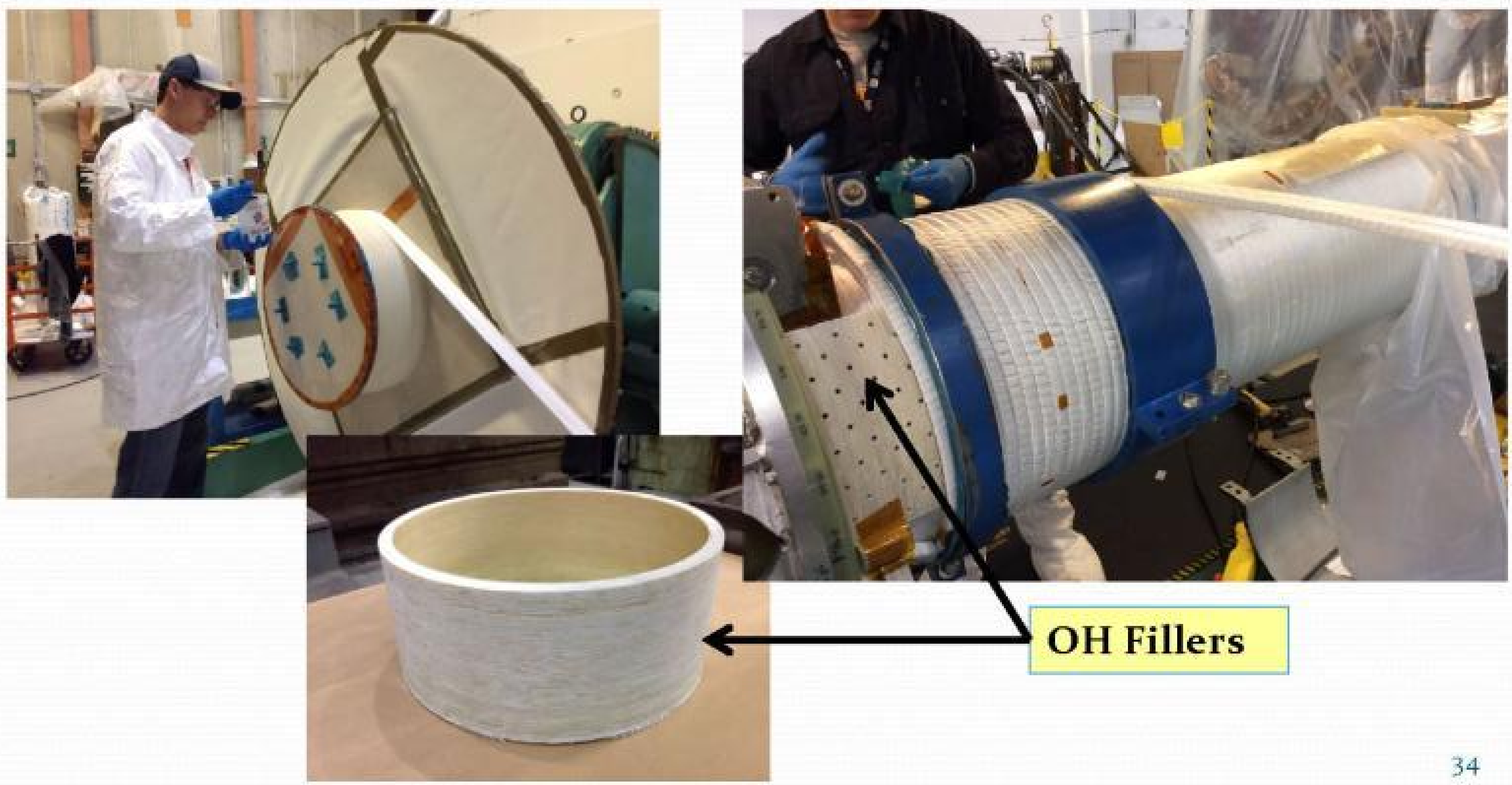




33

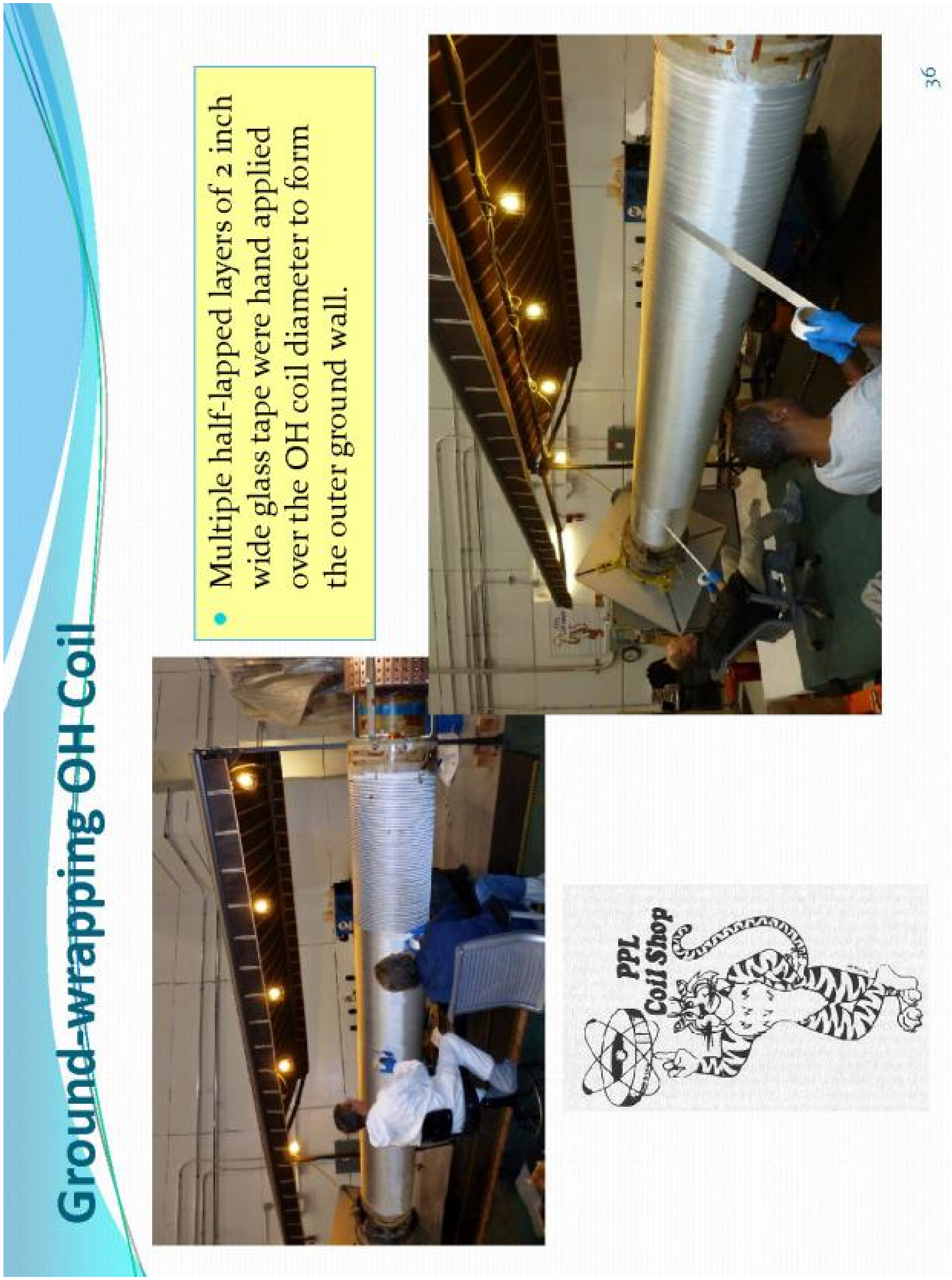
OH Coil Fillers

- The OH insulating fillers located at each end of the OH coil were fabricated in-house using a wet layup process with glass tape and CTD-425 resin system.
- The cured fillers were then machined and cut to fit the layer to layer transition areas

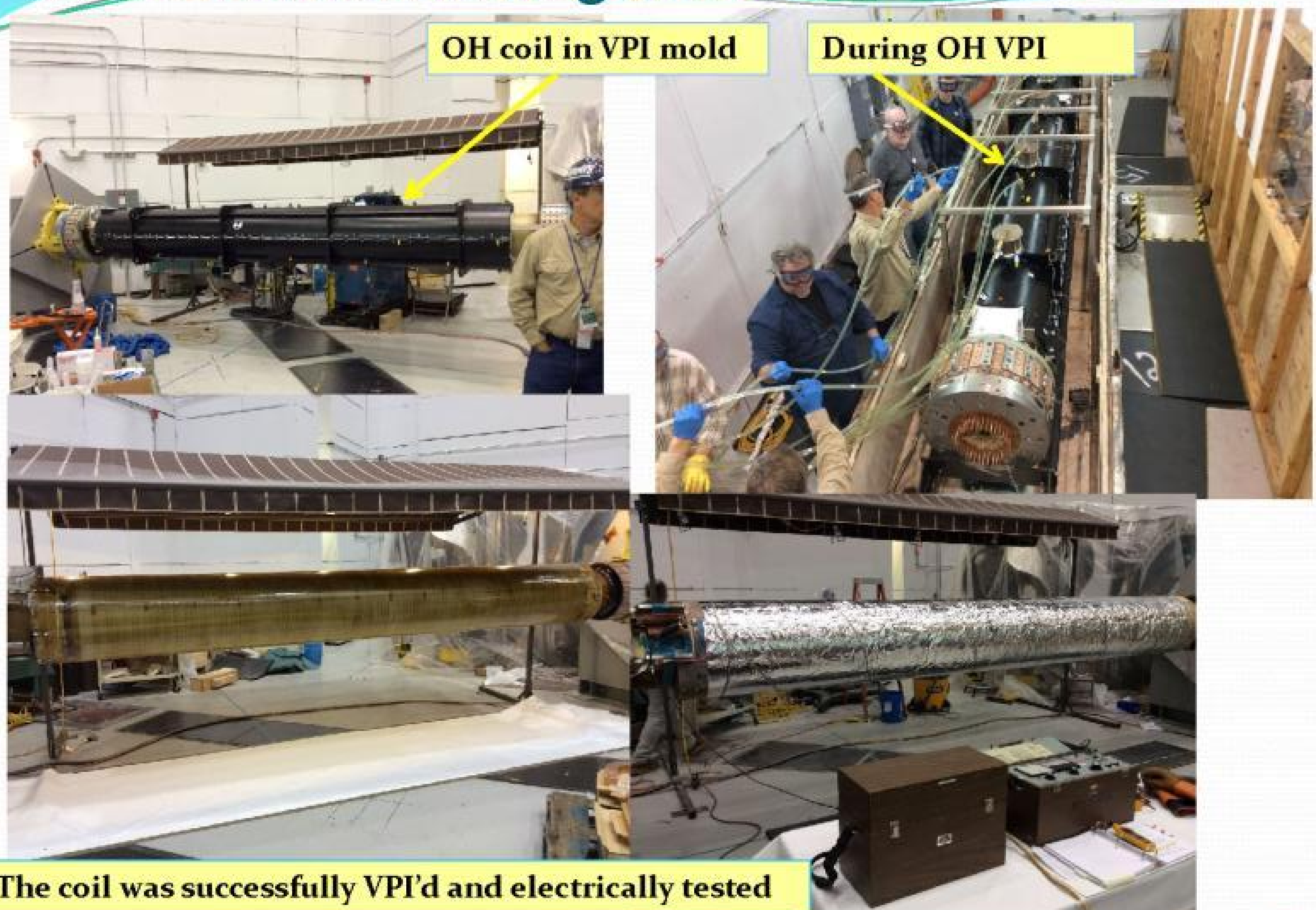


34


Completion of Coil Winding- OH Winding Team
Most of the OH coil winding team members
35


Ground-wrapping OH Coil
Multiple half-lapped layers of 2 inch wide glass tape were hand applied over the OH coil diameter to form the outer ground wall.
PPL Coil Shop
36

VPI & Electrical Testing of OH Coil



The coil was successfully VPI'd and electrically tested

37

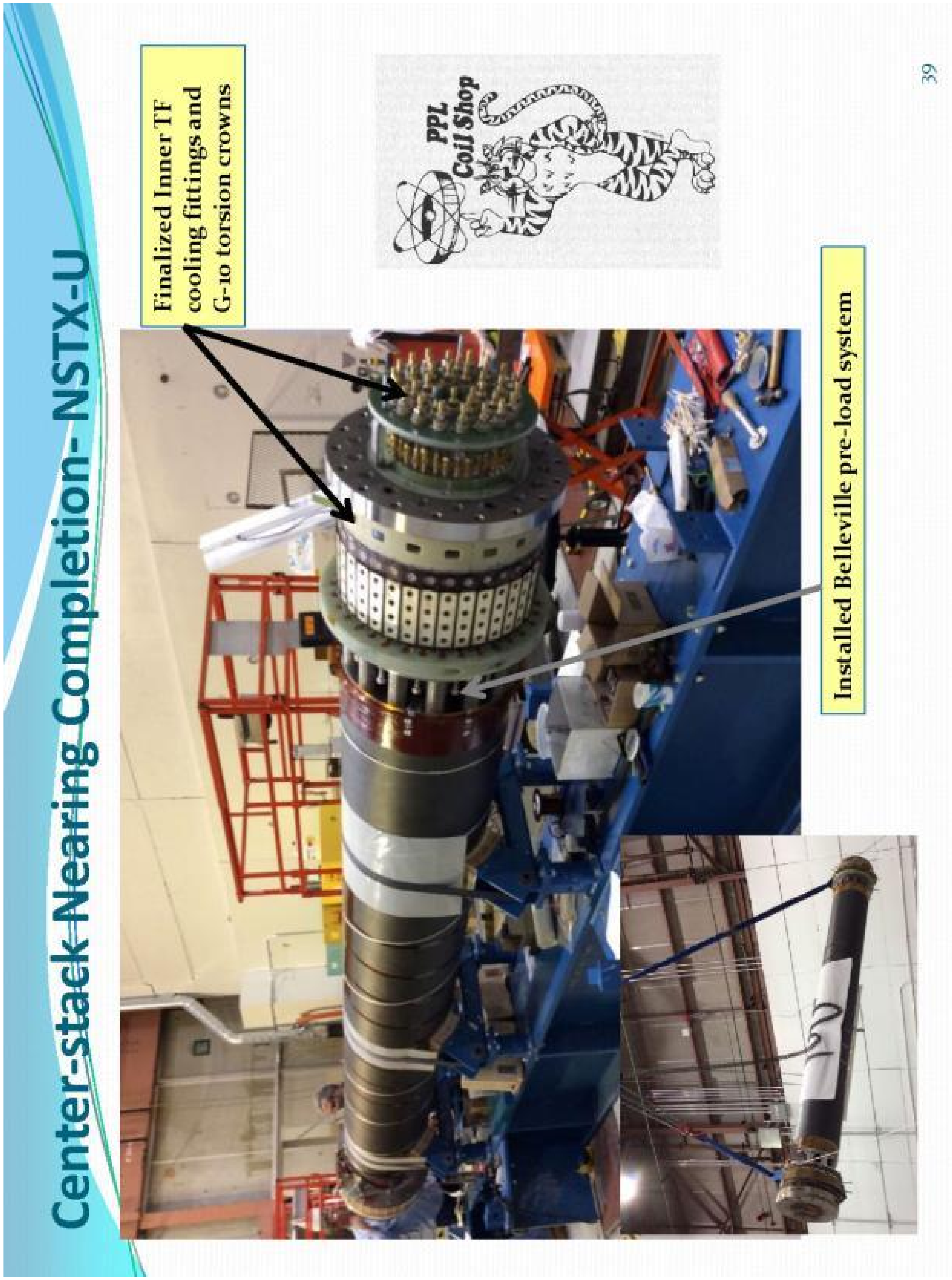
Outer Ground-plane and Pre-load Assembly

- ***The "Aquapour could not be removed as planned because epoxy had migrated into the "Aquapour" material. Project decision was made to abandon "Aquapour" in place.***
- The outer surface of the OH coil was then painted with a ground-plane coating.
- The Belleville washer pre-load assembly was then installed

Ground-plane outer coating

Belleville washer pre-load assembly

38


Center-stack Nearing Completion- NSTX-U
Finalized Inner TF cooling fittings and G-10 torsion crowns
PPL Coil Shop
Installed Belleville pre-load system
39

Raised OH/TF Bundle for final assembly details

The OH/TF bundle was raised to the vertical position so that the surface diagnostics and micro-therm thermal blanket could be installed.

OH/TF Bundle weighs approximately 23,000 pounds without PF coils or casing

40

Installing Lower PF1A Coil Assembly

- PF1A had to be lowered over the entire length of the OH/TF bundle prior to the installation of diagnostics

PF1A coil weighs approximately 1800 pounds

41


Installed OH Diagnostics and Thermal Blanket
Micro-therm insulating jacket
Surface diagnostics include- flux loops, thermocouples and (3) Rogowski coils
42

Lower OH/TF Assembly & Prepare for Transport

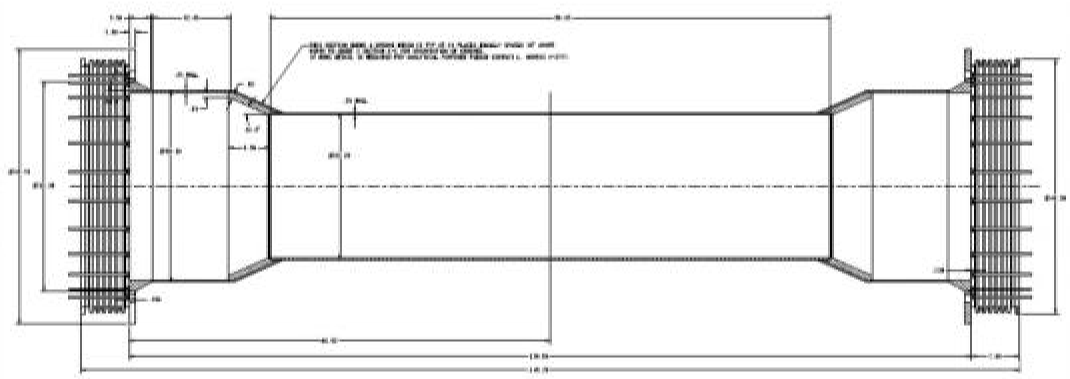
Quality Trademark

43


OH/TF Assembly Ready for Transport to D-Site
44


Transport OH/TF Assembly to D-Site
45

Centerstack Casing



- The Centerstack casing and bellows are fabricated using Inconel 625 and provides the inner vacuum vessel wall for the NSTX vacuum vessel. It also provides the structural support for the plasma facing components and surface diagnostics. Active cooling in the IBD regions has been incorporated in the upgrade.
- The casing was fabricated by Martinez-Turek, Inc. in California

46

Center Stack Casing Fabrication

fabricated by Martinez-Turek, Inc.

47

Tile Installation on Casing

- Carbon tiles and diagnostics were added to the surface of the Centerstack casing by PPPL personnel.

48

Inner Poloidal Field Coils

- **General Description:** Includes three pair of Poloidal Field coils [PF1A, PF1B and PF1C]. These coils were constructed using extruded oxygen-free silver-bearing copper conductor w/cooling hole. Individual turns are insulated with co-wound glass/Kapton insulation applied in multiple half-lapped layers. Multiple half-lapped layers of S2 glass ground-wrap is applied over the finished wound coils. The wound coils were epoxy impregnated using epoxy impregnated using CTD-425 system a 2-part system with Epoxy (EP) and Cyanate Ester (CE) catalyst in Part A and Cyanate Ester (CE) in Part B.
- The Poloidal Field coils were wound directly onto their support structure and VPI'd into the structure.
- The Inner PF coils were fabricated by Everson-Tesla Co.

49

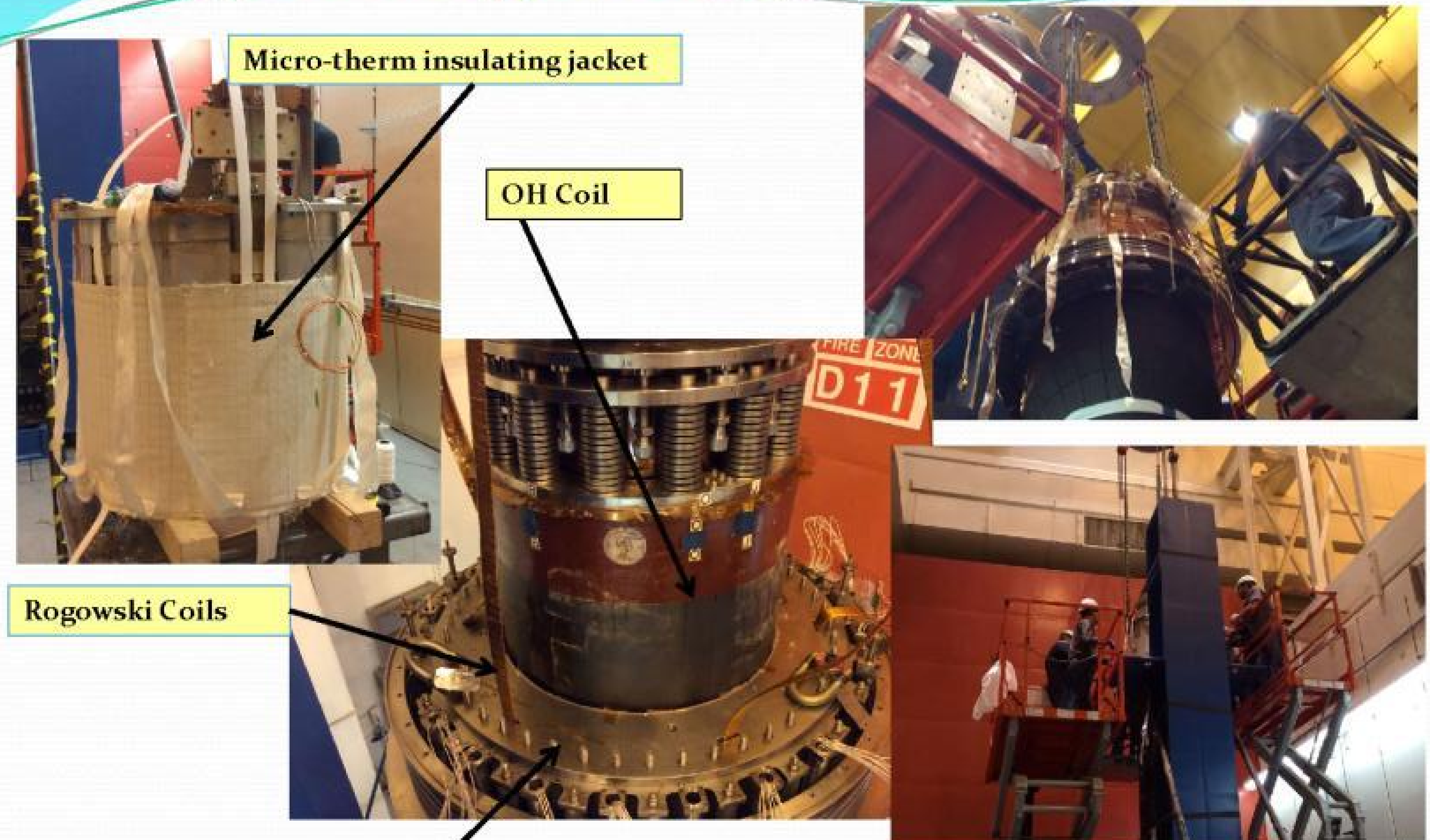

Fabrication of Inner Poloidal Field Coils
50

Installation of CS Casing with OH/TF Bundle

- Photos of the Centerstack casing being lowered over the OH/TF bundle

51

Installation of Upper PF1A Coil



- The PF1A was installed on the upper end of the Centerstack Assembly

52

Final Installation of the New Centerstack Assembly

- The Completed Centerstack Assembly was installed into the NSTX vacuum vessel on **October 24, 2014**
- The full Centerstack with rigging weighs less than **30,000 pounds**

53


Final Installation of the New Centerstack Assembly
Installation photos
54

Appendix J

Objective Evidence for KPP's

>50 mA plasma shot

NSTXU Demonstrated Performance Objective Evidence #1

KPP: The major milestone marking the transition from a fabrication project to an operating facility is the first plasma milestone (CD-4). First plasma is defined as an ohmically heated discharge > 50 kA at a toroidal magnetic field of > 1 kG.

Status: Achieved 8/10/2015.

	KPP Goal	Achieved
OH Discharge	>50kA	>100kA
TF Magnetic Field	>1kG	5kg

Supporting objective evidence attached.

Independent Certification

David A. Gates
Digitally signed by David A. Gates
DN: cn=David A. Gates, o=PPPL, ou=Advanced Projects, email=dgates@pppl.gov, c=US
Date: 2015.08.11 14:43:34 -05'00'

David Gates
Head, Advanced Projects-Stellarators

Approval

Ron Strykowsky
Digitally signed by Ron Strykowsky
DN: cn=Ron Strykowsky, o, ou=PPPL, email=rstrykow@pppl.gov, c=US
Date: 2015.08.11 15:49:58 -04'00'

Ronald Strykowsky
NSTXU Project Manager

Approval:

Stewart Prager
Digitally signed by Stewart Prager
DN: cn=Stewart Prager, o=Princeton Plasma Physics Laboratory, ou=Director, email=sprager@pppl.gov, c=US
Date: 2015.08.11 16:46:49 -04'00'

Stewart Prager
PPPL Director

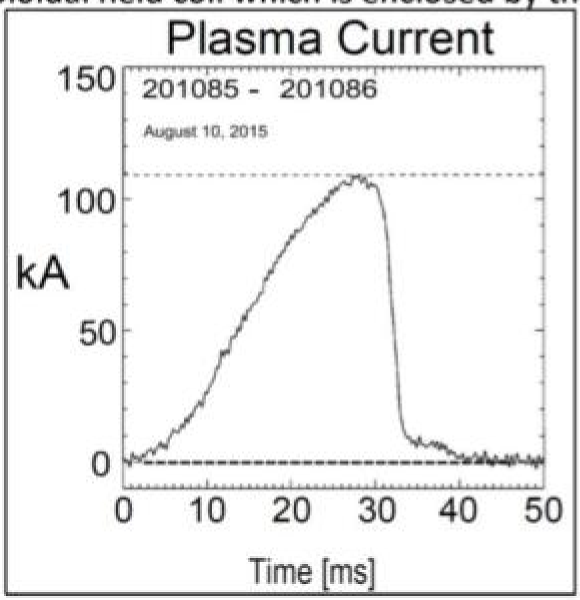
Appendix J

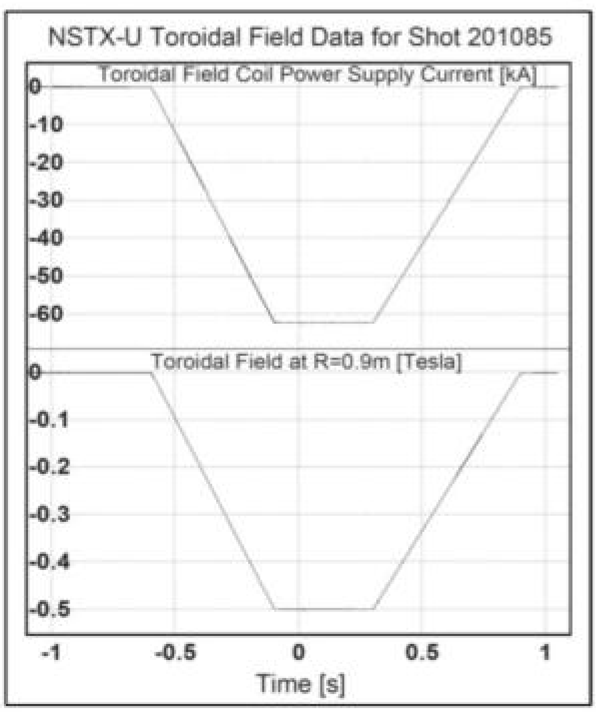
Objective Evidence for KPP's

<u>>50 mA plasma shot (continued)</u>

Plasma current (top) and toroidal field data (bottom) for ~100kA, B_T = 0.5T plasma in NSTX-U for CD-4 KPP (note: 0.5T = 5kG).

The NSTX-U plasma current Rogowski loop was calibrated using the PF1C Lower poloidal field coil which is enclosed by the Rogowski.





2

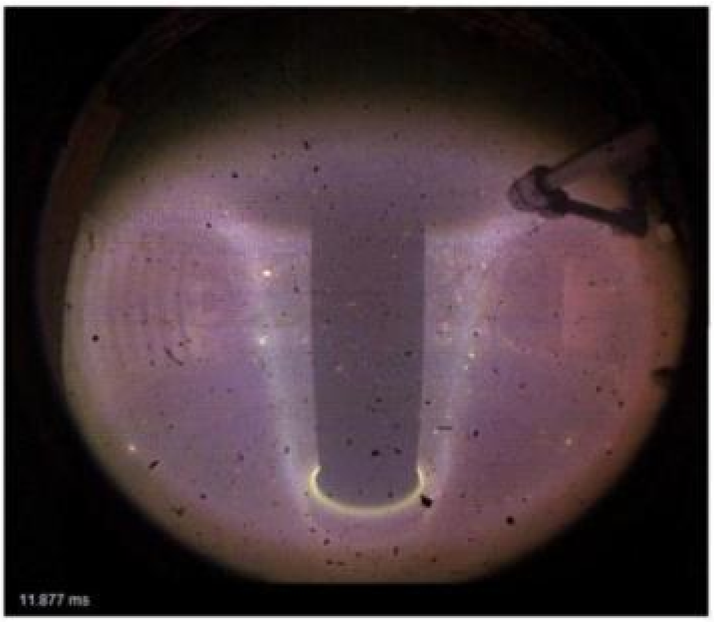
Appendix J

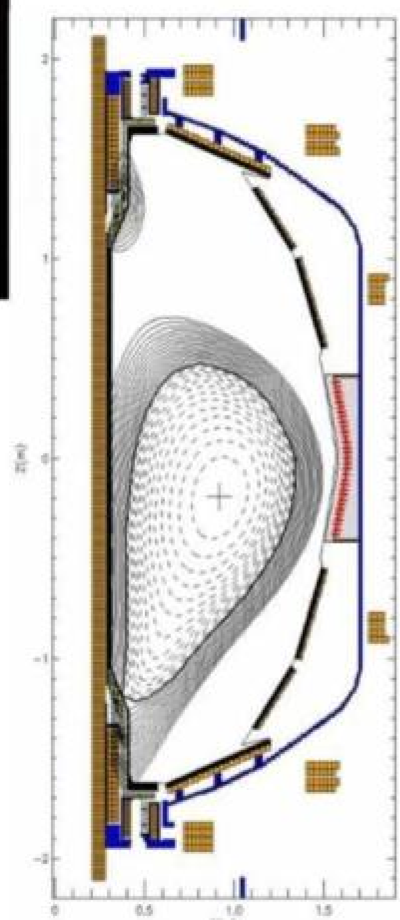
Objective Evidence for KPP's

<u>>50 mA plasma shot (continued)</u>

Camera image (left) and EFIT reconstruction (right) for NSTX-U CD-4 KPP plasma

NSTX-U Shot 201085





Appendix J

Objective Evidence for KPP's

<u>>40 kV Neutral Beam Shot</u>

NSTXU Demonstrated Performance Objective Evidence #2

KPP: The installation of the second neutral beam on NSTX shall be considered complete at the stage where each item below has been demonstrated:

a. Beamline water, vacuum, cryogenics, and feedstock gas services have been attached to the beamline;
b. A Torus Isolation Valve and duct interconnects the NSTX vacuum vessel and the neutral beamline;
c. Local Control Centers have been powered on to monitor power supply status, and;
d. Project will be verified as complete when a 40,000 electron-volt beam has been produced and injected into the armor for .050 seconds.

Status: Achieved 5/11/2015.
Five 45KV @ 12 amps shoots into the armor for >50ms. Attached are PDF's of the armor TC's(pre and post shoots), RSView page showing the status of the beam systems, and the scope traces showing the wave forms.
Supporting objective evidence attached.

Independent Certification

David A. Gates 8/6/2015

David Gates
Head, Advanced Projects-Stellarators

Approval Ron Strykowsky

Digitally signed by Ron Strykowsky
DN: cn=Ron Strykowsky, o, ou=PPPL, email=rstrykow@pppl.gov, c=US
Date: 2015.08.06 12:38:15 -04'00'

Ronald Strykowsky
NSTXU Project Manager

Approval:

Stewart Prager

Digitally signed by Stewart Prager
DN: cn=Stewart Prager, o=Princeton Plasma Physics Laboratory, ou=Director, email=sprager@pppl.gov, c=US
Date: [illegible]

Stewart Prager
PPPL Director

Appendix J

Objective Evidence for KPP's

>40 kV Neutral Beam Shot (continued)

Armor shot

Armor shot probes

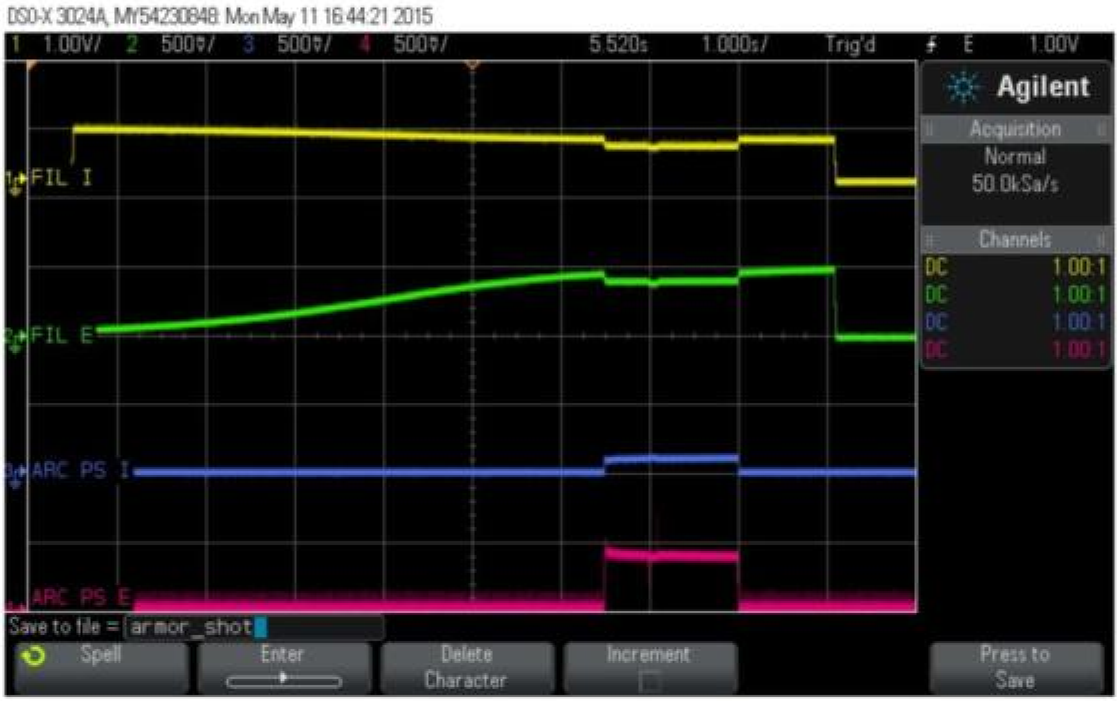
Armor shot

Armor shot fast

Appendix J

Objective Evidence for KPP's

<u>>40 kV Neutral Beam Shot (continued)</u>



Appendix J
Objective Evidence for KPP's

>40 kV Neutral Beam Shot (continued)

Appendix J

Objective Evidence for KPP's

>40 kV Neutral Beam Shot (continued)

NB ARMOR TC rev 2.vi
C:\Users\grossi\Desktop\NB injection sys Armor TC project\NB ARMOR TC rev 2.vi
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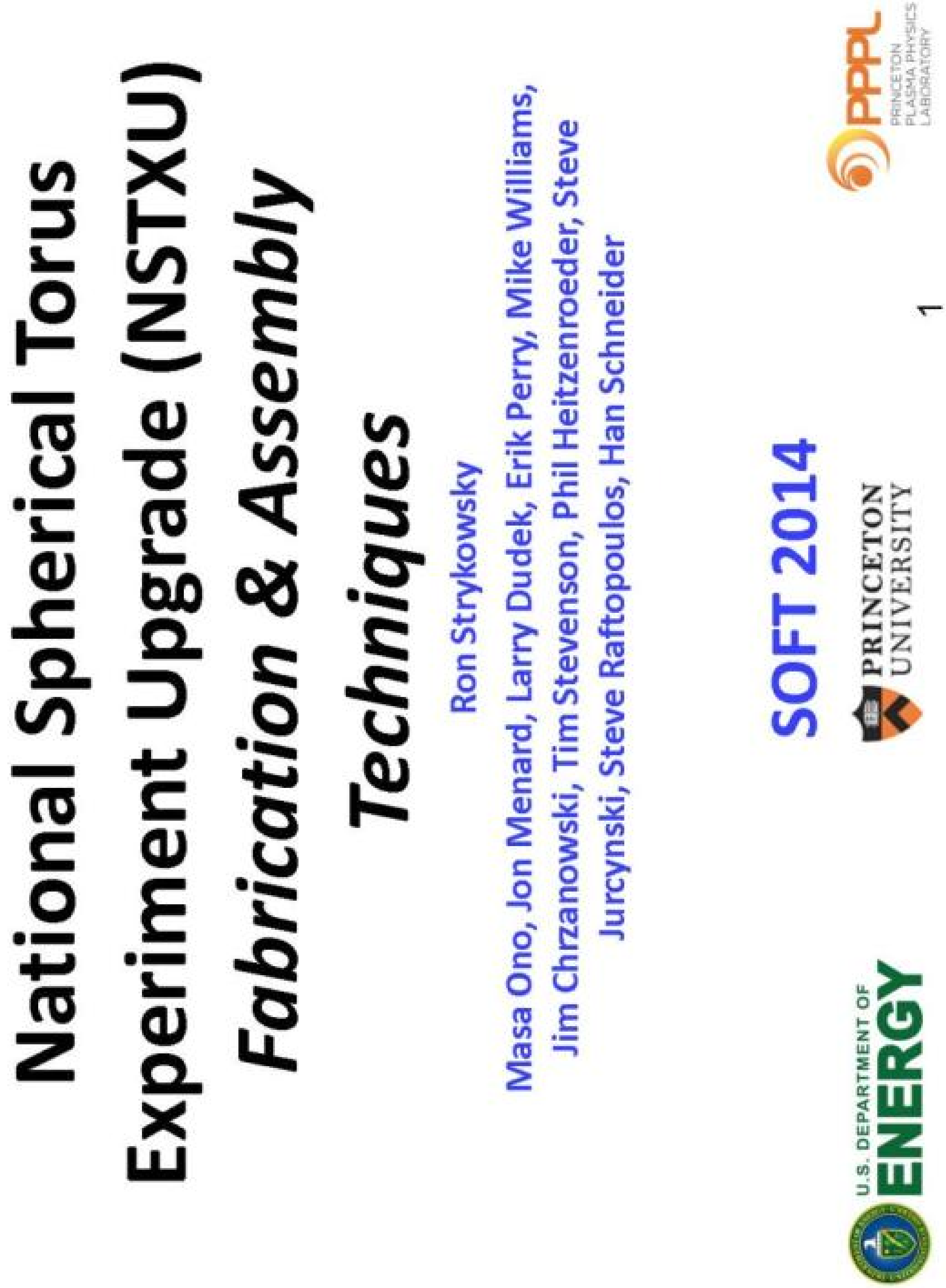
Printed on 5/11/2015 at 4:21 PM

Appendix K

NSTXU Fabrication and Assembly Techniques



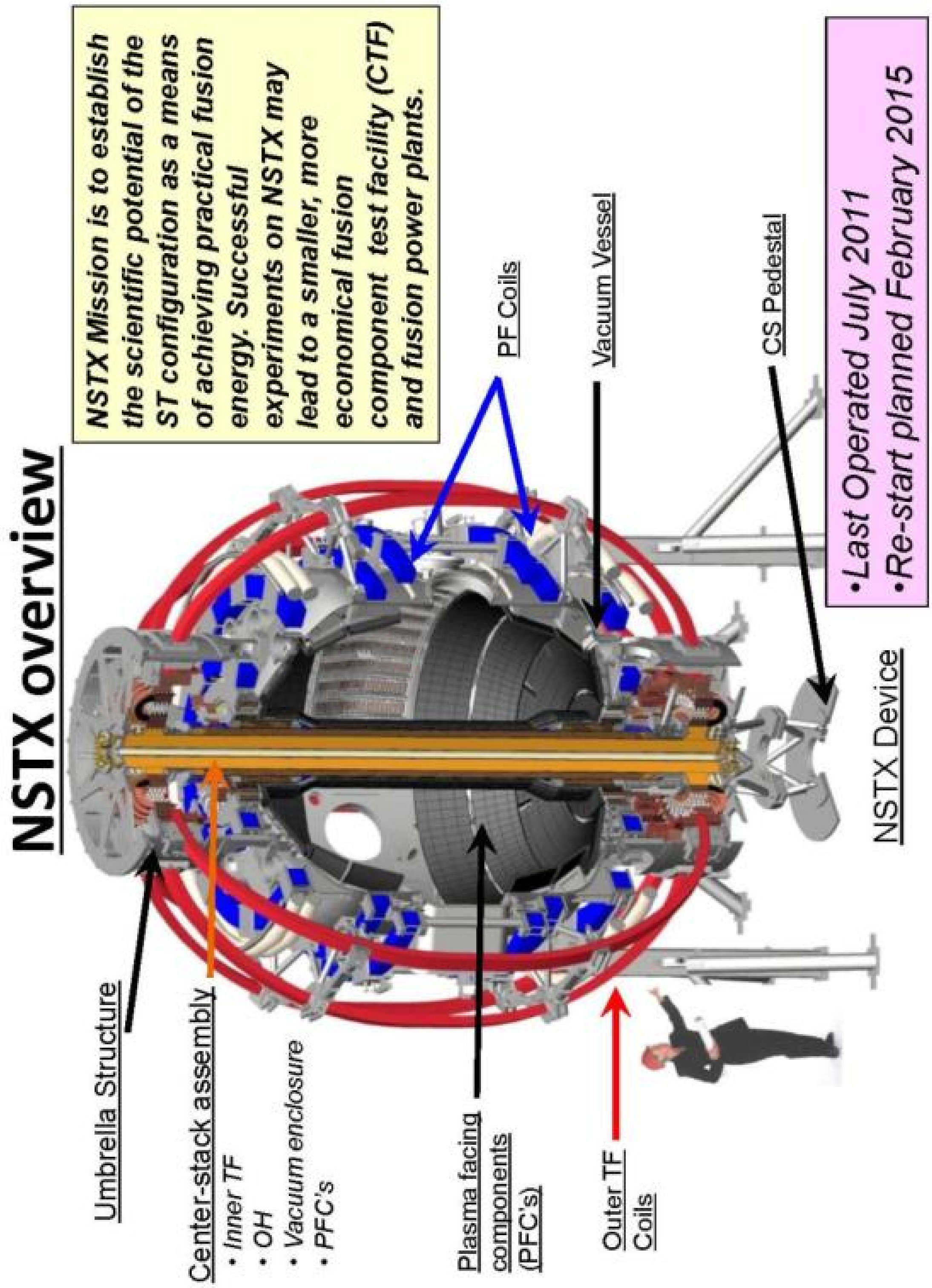
Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

Acknowledgement

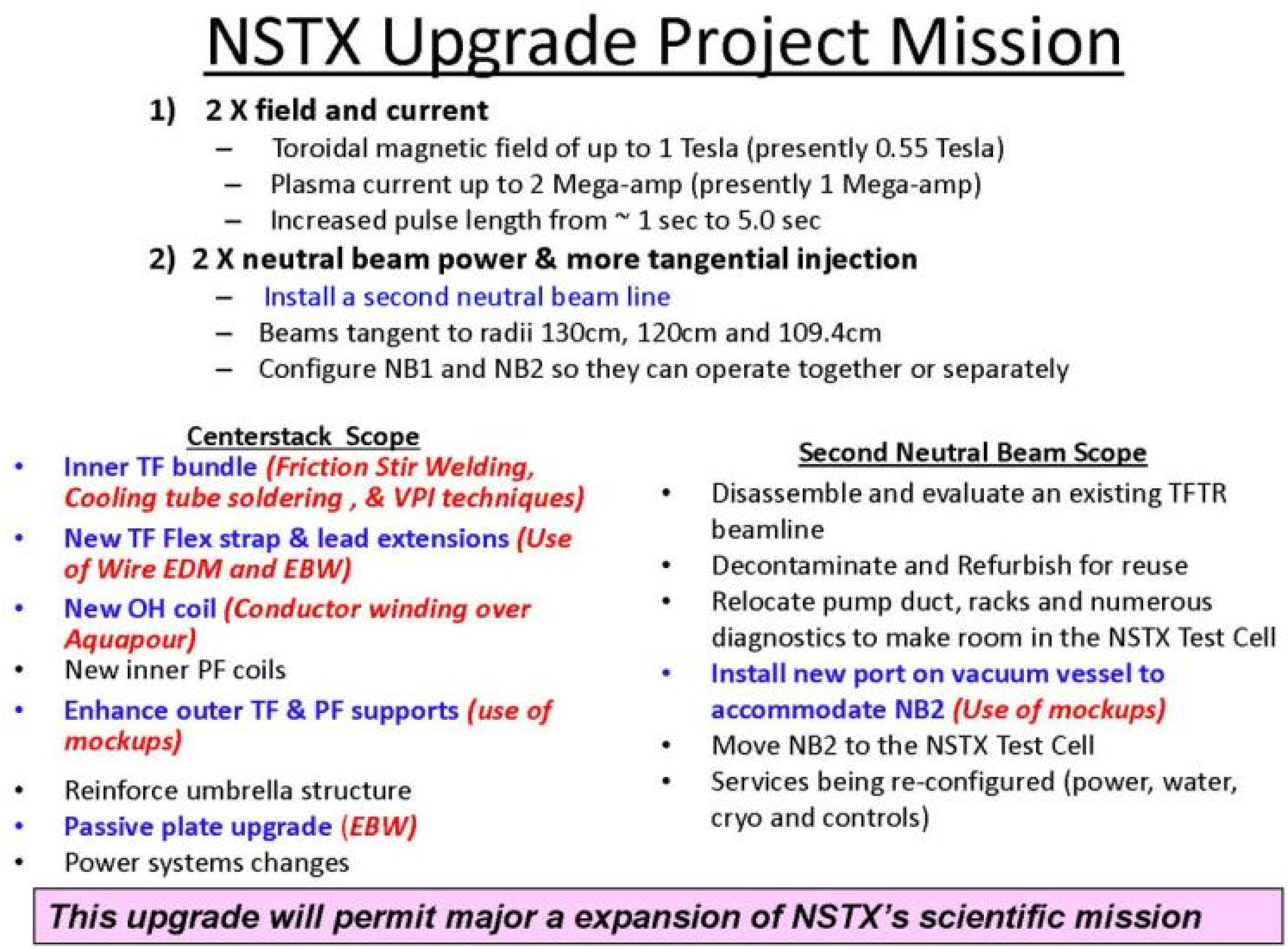
- Our thanks to the many PPPL physicists, engineers, designers, technicians, machinists and support staff and subcontractors whose combined expertise and efforts made this upgrade possible.

Appendix K
NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

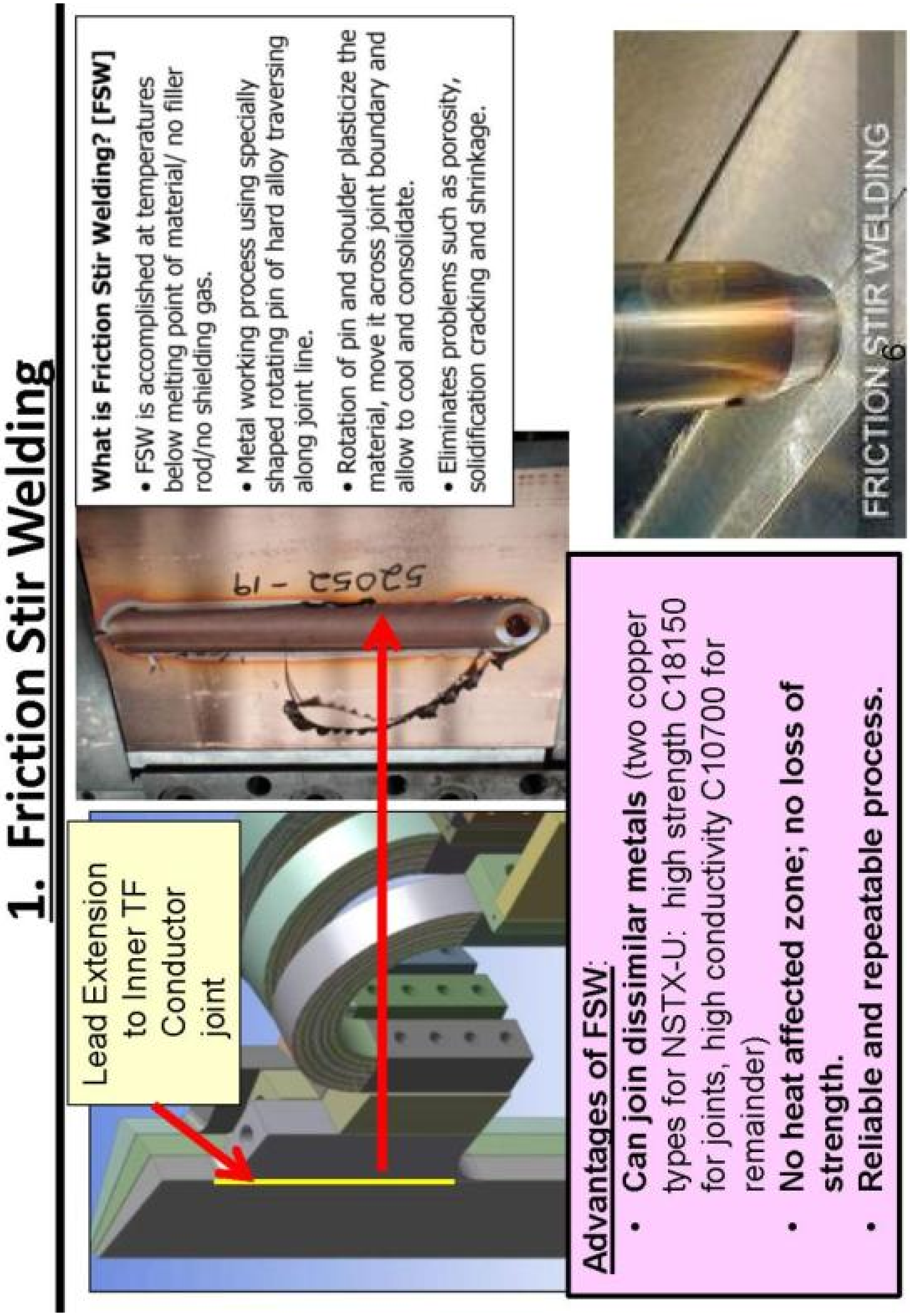
NSTX-U Fabrication & Assembly Techniques

Manufacturing techniques and processes were carefully chosen (or developed):

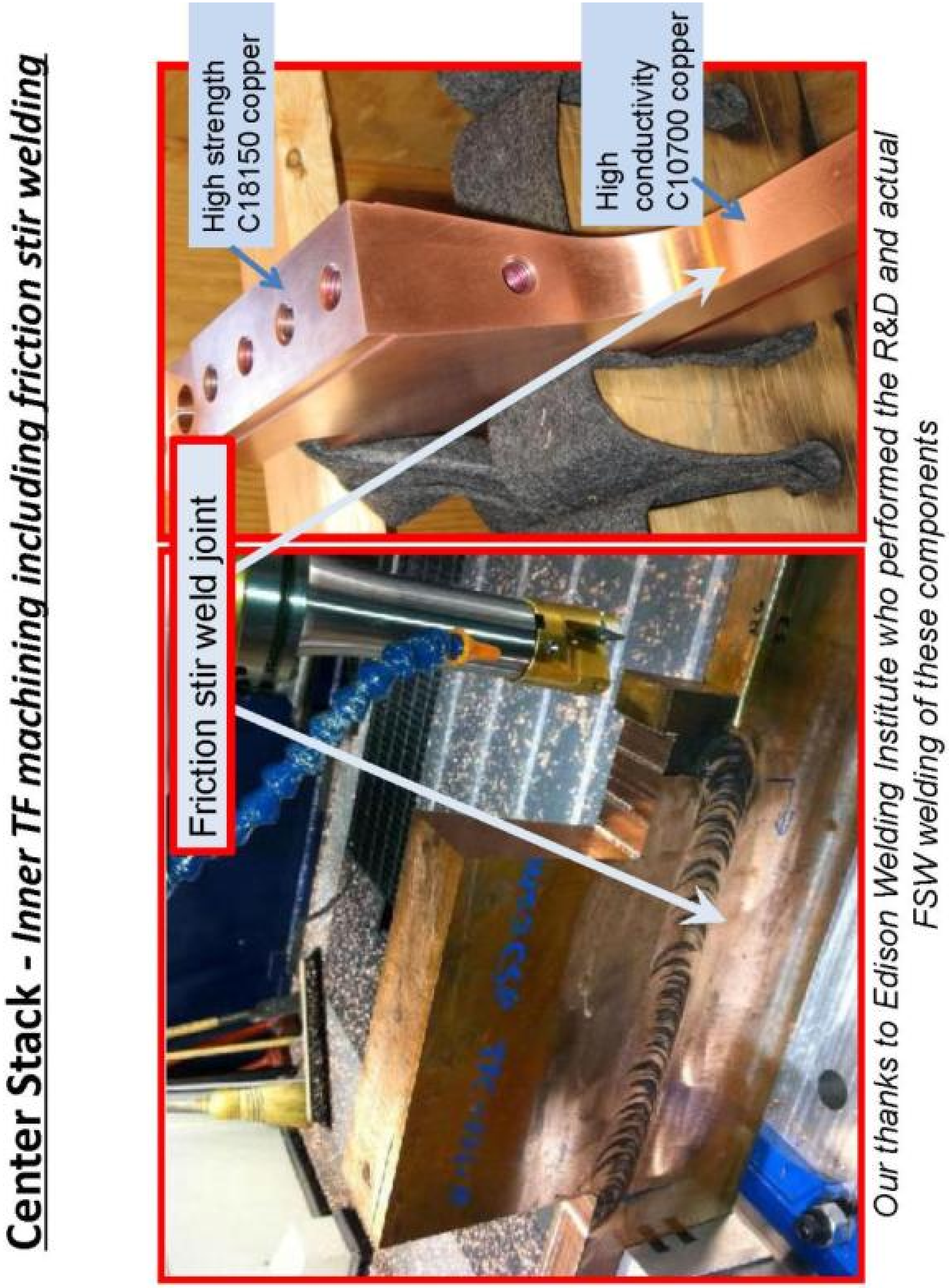
1. **Friction stir welding of copper** was used to join high strength to high conductivity copper grades in the TF center bundle conductors.
2. A new **non-ionic soldering process** was developed.
3. **Wire Electric Discharge Machining (EDM)** was used in the manufacture of the critical TF High-Current Connector.
4. A carefully planned **Vacuum Pressure Impregnation (VPI)** process with hard metal molds were used to assure the strength and electrical integrity of the center stack.
5. **Cyanate Ester / Epoxy Resin** was chosen because of its maintenance of strength at elevated temperature.
6. **Electron Beam Welding** was used to manufacture the TF Lead Extensions and Passive Plate expansion connectors.
7. A **water-soluble casting material** was used to maintain a thermal expansion gap between the center stack TF and OH winding. Difficulties in its implementation will be discussed.
8. **CAD solid models and mock-ups** assisted in design and assembly planning.

Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

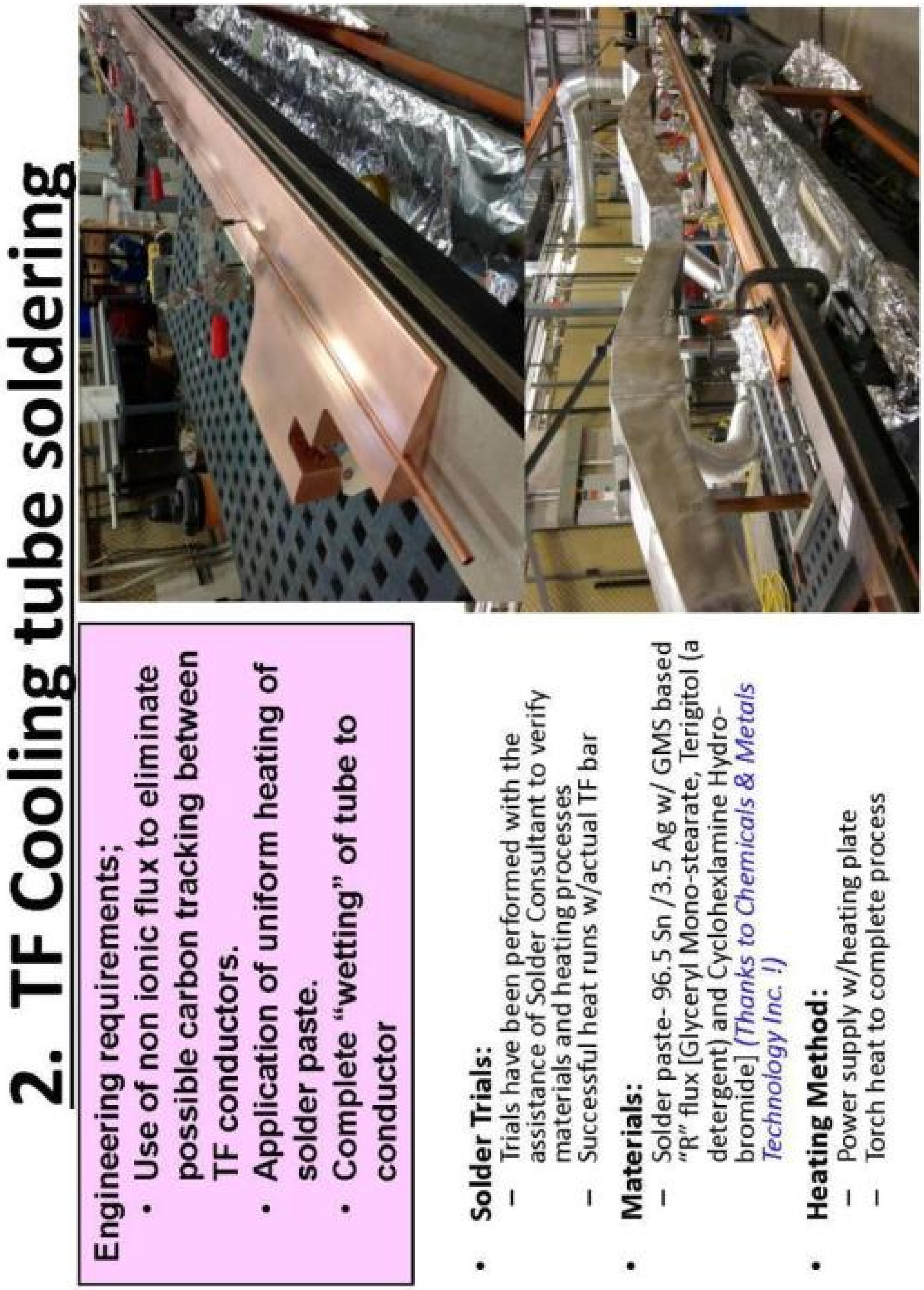


Appendix K
NSTXU Fabrication and Assembly Techniques (continued)



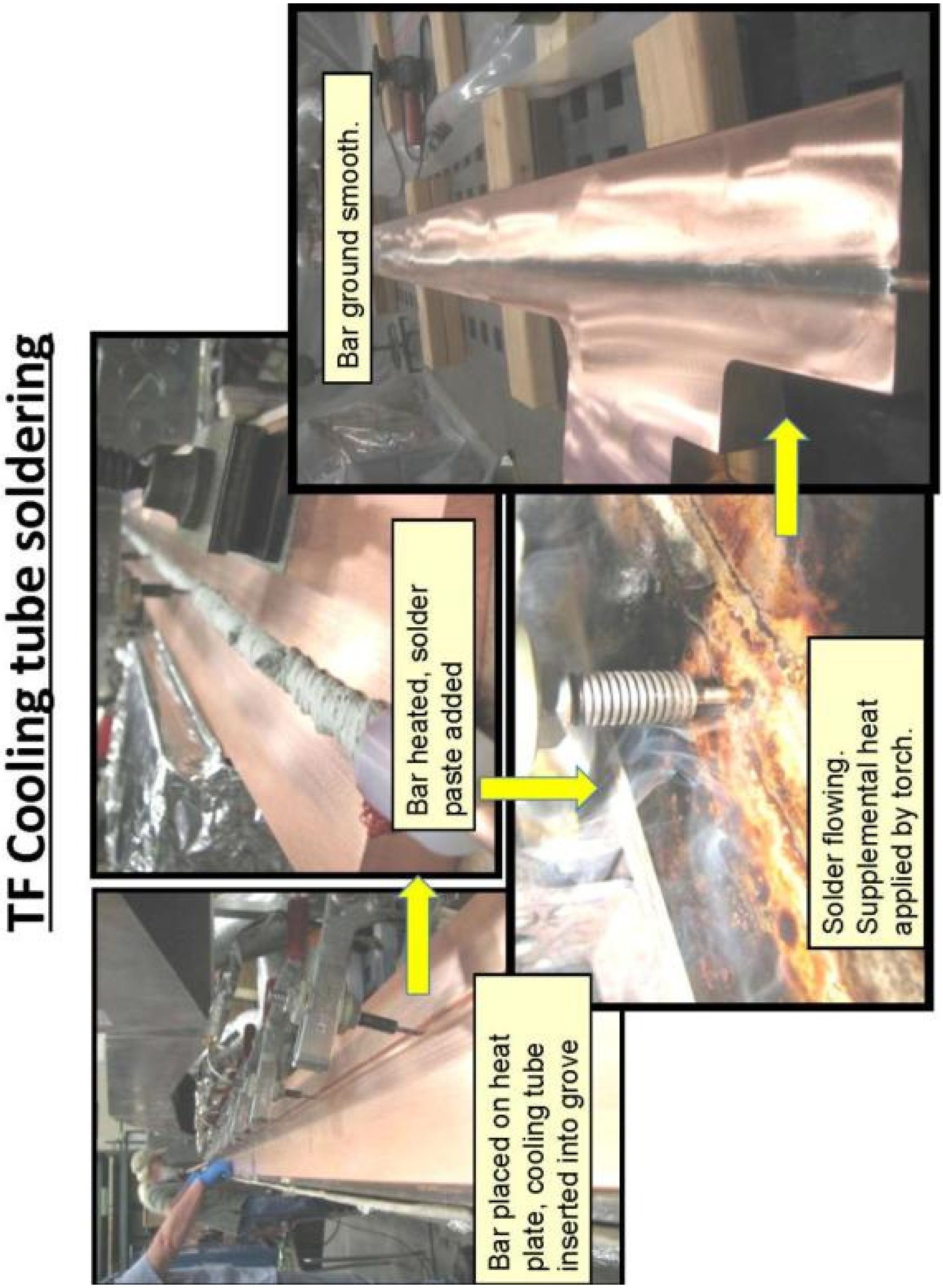
Appendix K

NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

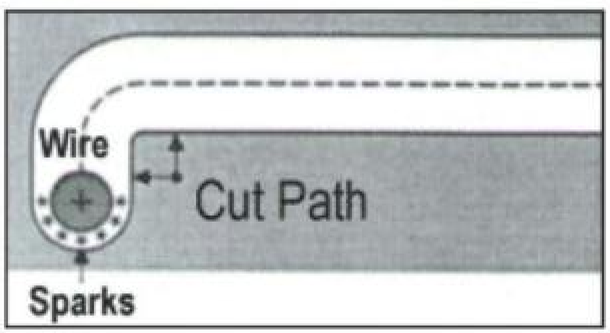
NSTXU Fabrication and Assembly Techniques (continued)



3. Wire EDM – What it is

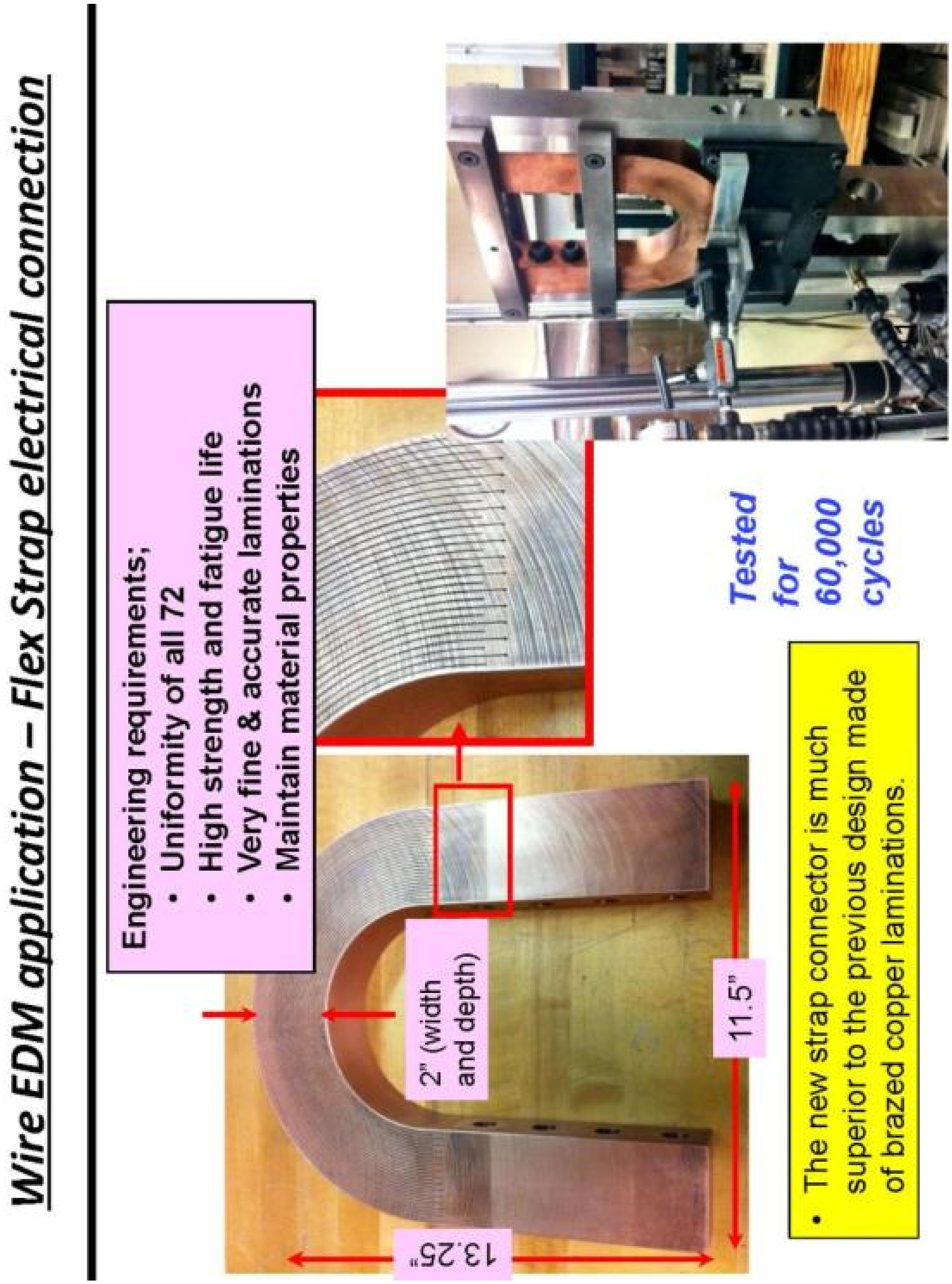
From Wikipedia, the free encyclopedia

An electrical discharge machine
Electric discharge machining (EDM), sometimes colloquially also referred to as spark machining, spark eroding, burning, die sinking, wire burning or wire erosion, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks).[1] Material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the 'tool' or 'electrode', while the other is called the workpiece-electrode, or 'workpiece'.



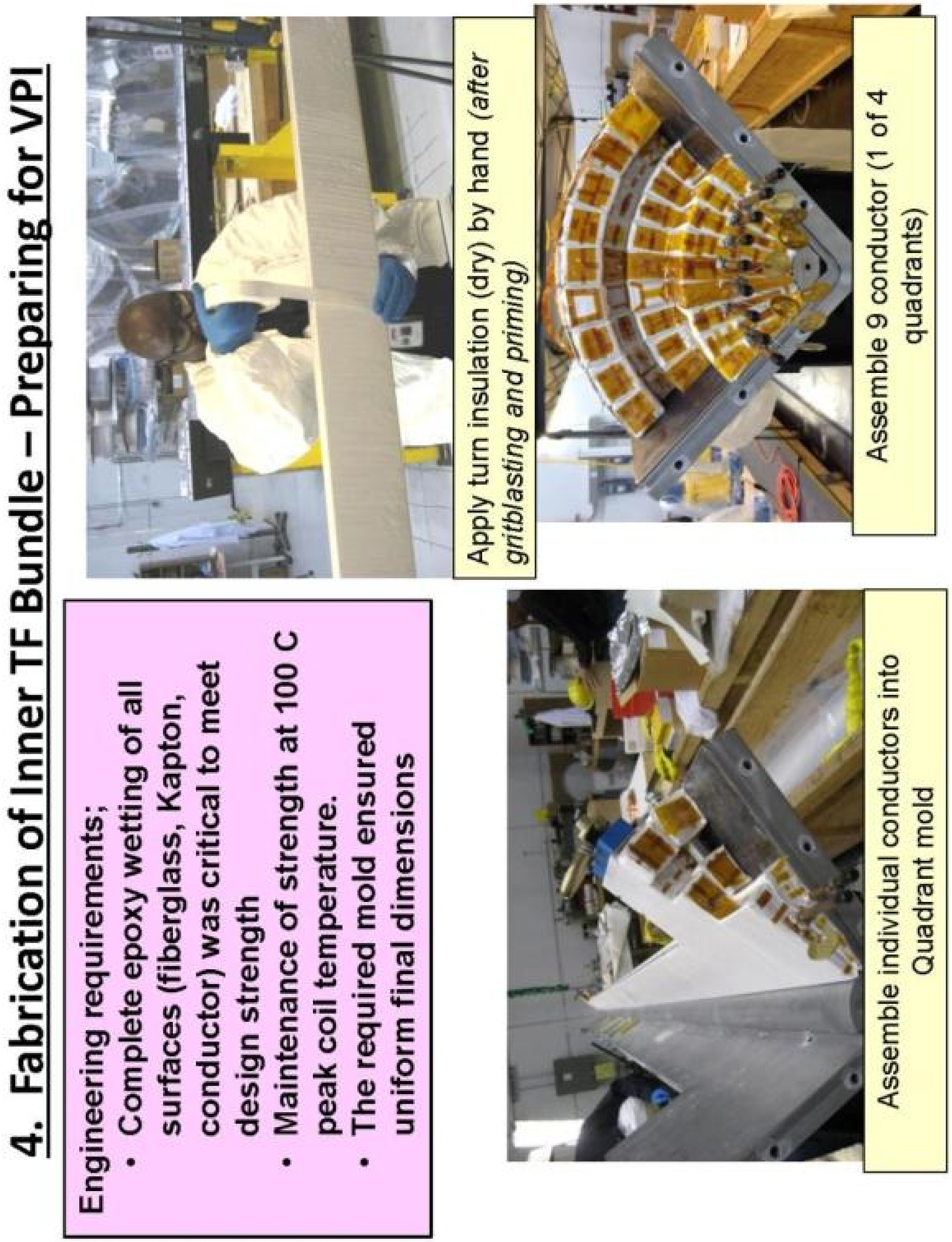
Appendix K

NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

5. Epoxy VPI of Inner TF Bundle

Risk:

•Exothermic reaction of resin- (CTD-425) *(special cyanate –ester / epoxy blend)*

• Dry areas

Benefit:

•Shear and bond strength

Sequence:

1. Pull vacuum
2. Heat
3. Inject epoxy
4. ramp up temp slowly to 100C and hold
5. Slowly ramp up to 170c cure temp
6. cooldown

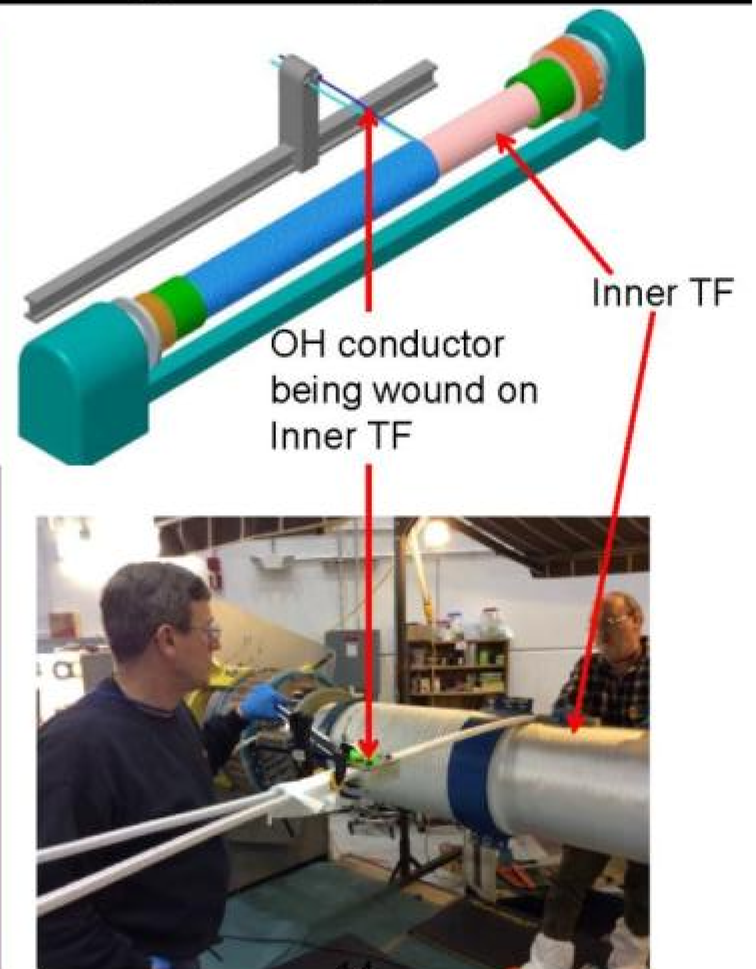
Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

6. Conductor Winding – *the plan*

Engineering requirements;

- Since the OH conductor will be wound around the TF coil and to maintain a 0.1" gap between the inner TF and OH coil. Advanced Ceramic Manufacturing's Aquapour™ water-soluble casting material will be used as a temporary winding mandrel.
- Required to allow differential lateral movement between the OH and TF conductor and radial expansion space for a powered "hot" TF coil and cool OH coil.
- The radial expansion of a hot TF coil will frictionally engage the OH winding; the axial thermal expansion of the TF coil results in tensile stresses between the OH turns which, if not controlled, could degrade the electrical properties of the insulation.



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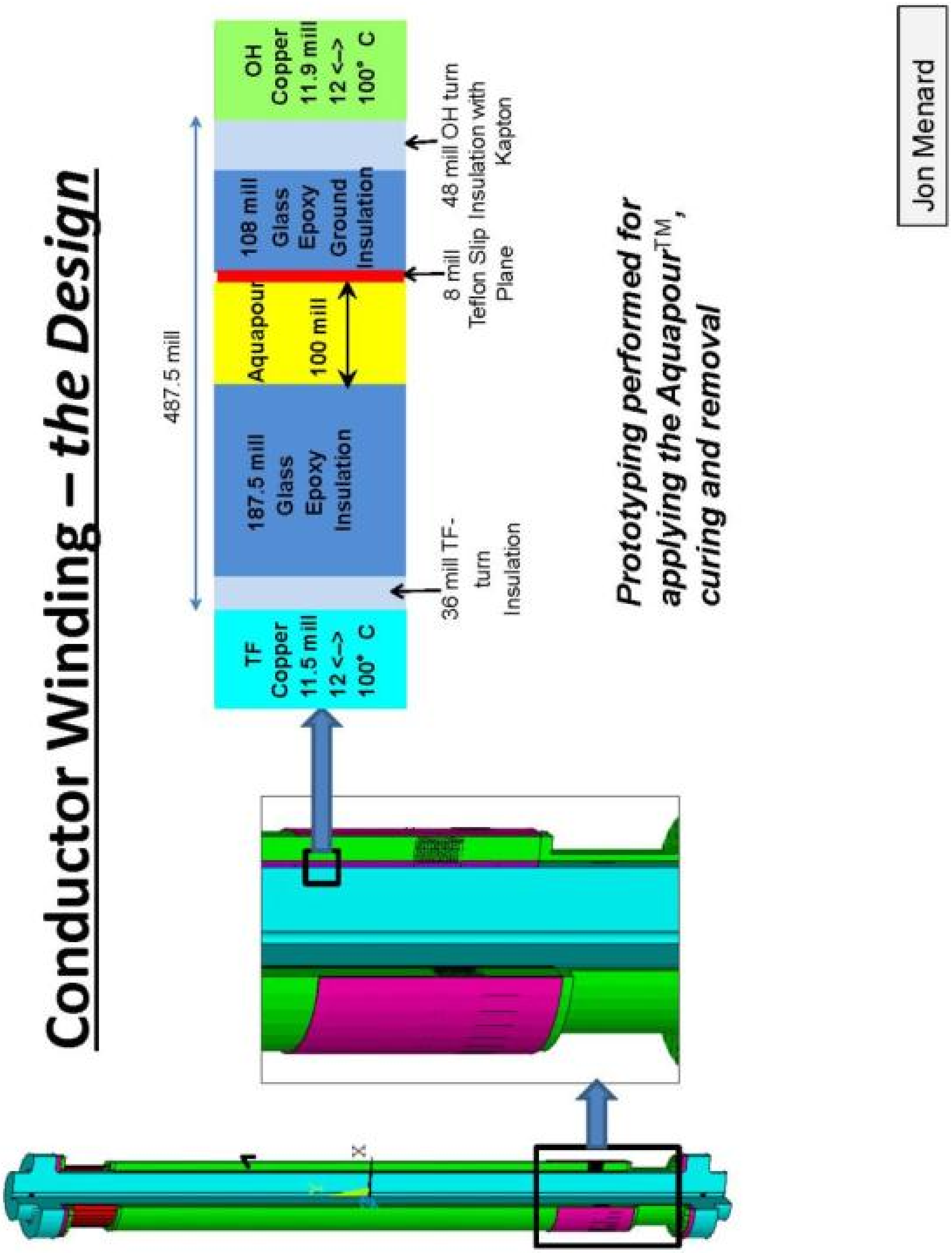
Appendix K

NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

Conductor Winding – *the execution*

- ✓ Aquapour Mandrel formed
- ✓ OH Winding completed
- ✓ VPI process completed as planned
- ✓ Visual inspection of VPI = no dry spots
- ✓ Hydro and flow test cooling passages (200 psi operating pressure)
- ✓ Megger to = 13kv (operating voltage 6kv)
- ✓ Major risk retired !
- ✓ Sanding complete to remove excess resin
- Aqua pour removal – UNSUCCESSFUL
  - Sealing failed and epoxy resin infiltrated the Aquapour™
  - Could not flush out with water
  - Used mechanical chisels on ends in an attempt to break through end-plug to no avail
- ✓ Attempted heating/cooling the OH/TF respectively to open gap and demonstrate the OH moved independent of the TF
- ✓ Decision to live with the "Aquament"

Conductor Winding – *epilog*

1. Anticipated thermal radial expansion must now be accommodated by employing engineering and administrative controls during operations.

2. Performance parameters can still be met.

3. Lessons learned! The VPI process is very, very effective. Next time:

   - If possible re-think the design solution (i.e., Teflon spacers, etc.)
   - When the Aquapour solution is best, take extreme care in designing the seals between the Aquapour™ and resin.

Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

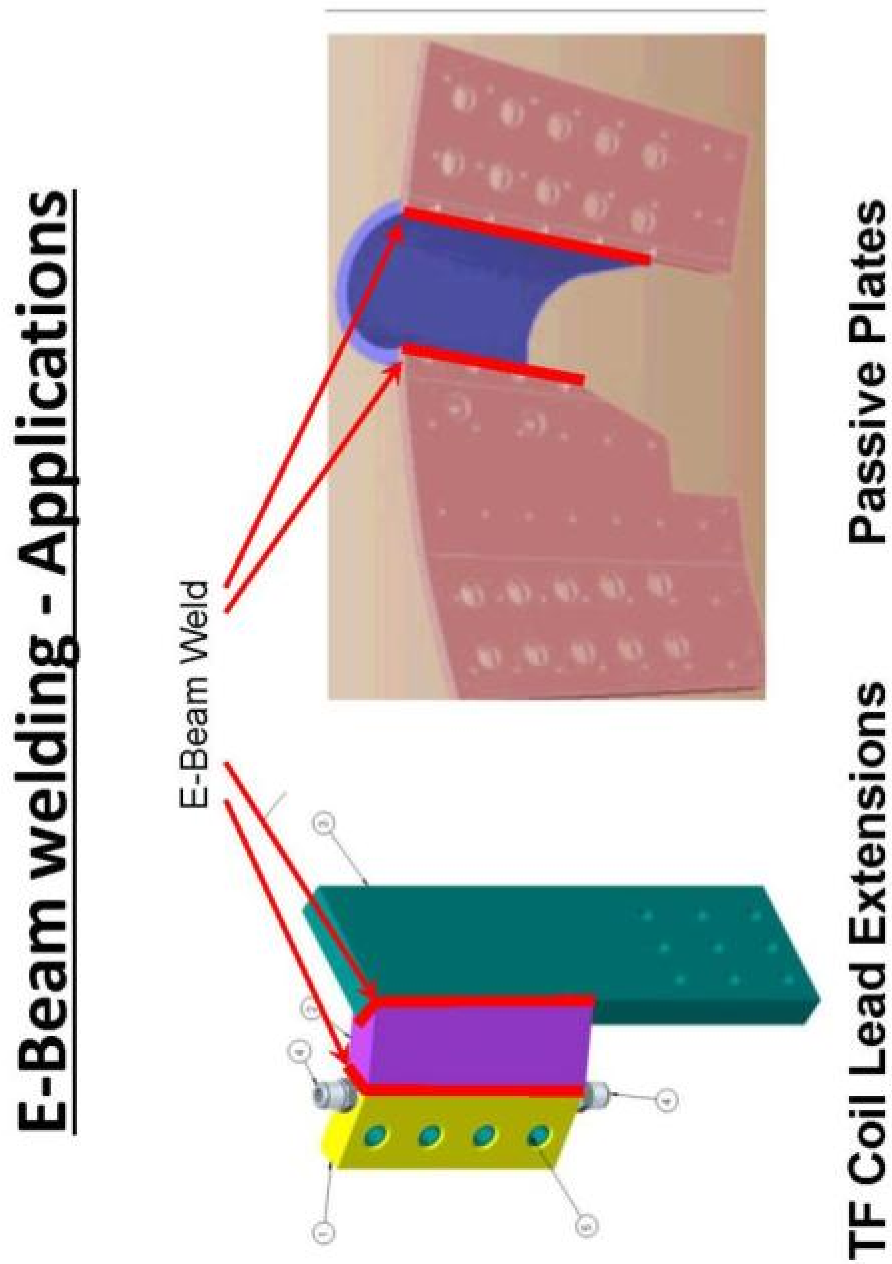
7. E-Beam Welding

From Wikipedia, the free encyclopedia

Electron beam welding (EBW) is a fusion welding process in which a beam of high-velocity electrons is applied to two materials to be joined. The work pieces melt and flow together as the kinetic energy of the electrons is transformed into heat upon impact. EBW is often performed under vacuum conditions to prevent dissipation of the electron beam. It was developed by the German physicist Karl-Heinz Steigerwald, who was at the time working on various electron beam applications. Steigerwald conceived and developed the first practical electron beam welding machine, which began operation in 1958.[1] American inventor James T. Russell has also been credited with designing and building the first electron-beam welder.[2][3][4]

Engineering requirements;
- Deep penetration of weld
- Low weld distortion
- Narrow application of heat thus the hardness of joined pieces not adversely effected by heat

Appendix K
NSTXU Fabrication and Assembly Techniques (continued)



Appendix K

NSTXU Fabrication and Assembly Techniques (continued)

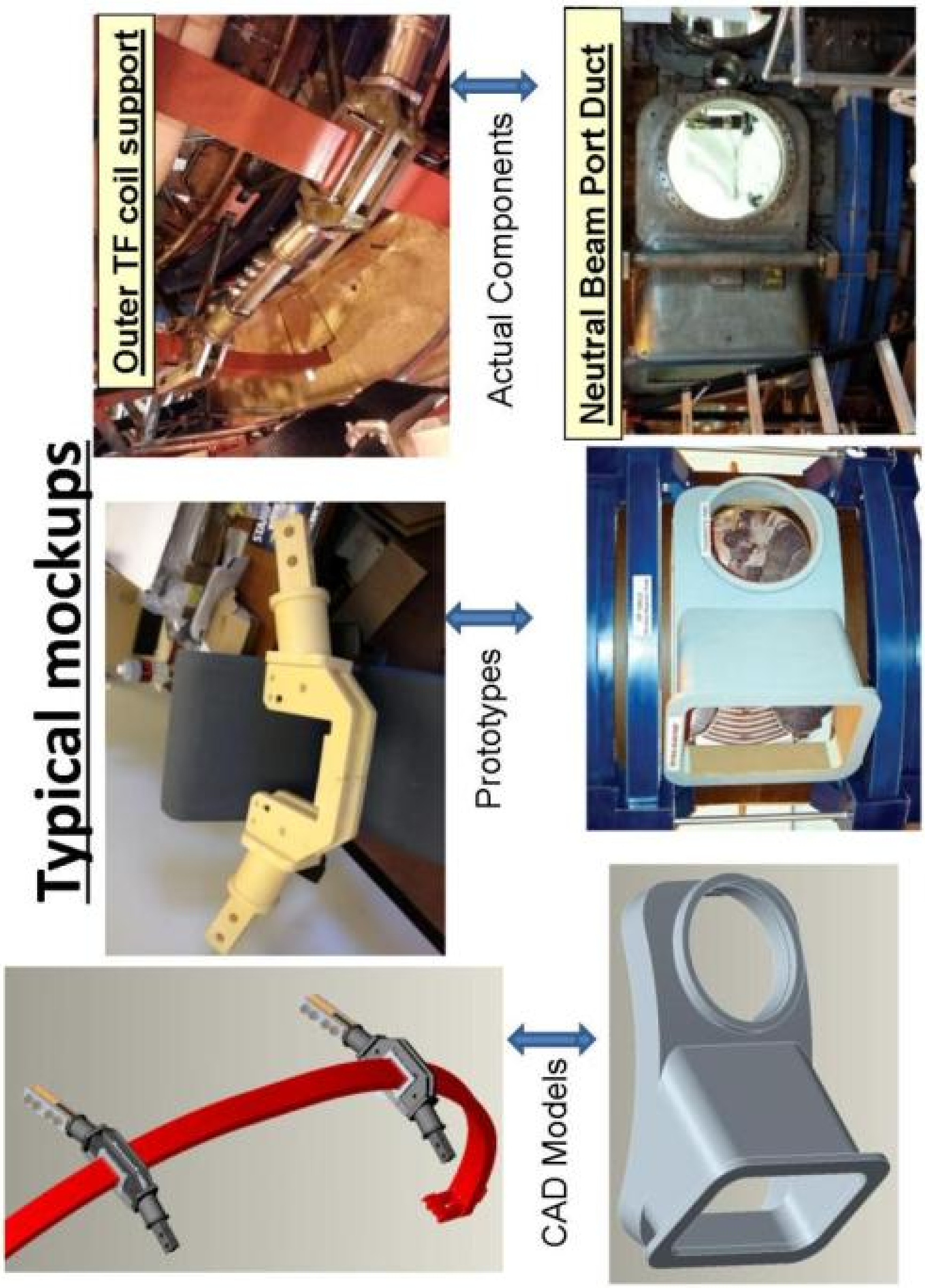
8. Use of CAD Solid Models & Mockup Prototypes

Engineering considerations

- CAD solid models are extremely helpful in developing designs and planning assembly, but mock-up prototypes provide an even higher level of realism for critical engineering details.

Appendix K

NSTXU Fabrication and Assembly Techniques (continued)



Appendix K
NSTXU Fabrication and Assembly Techniques (continued)

Summary

Turning an complex and difficult engineering vision (design) into reality required;

- An understanding of available industry manufacturing processes and techniques
- Value engineering - collaborative peer reviews and dialogue to benefit from the experiences from others
- Clever and pragmatic applications of those techniques and processes into a design that is constructible
- Talented physicists, engineers, designers, and technicians working together as a team

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?

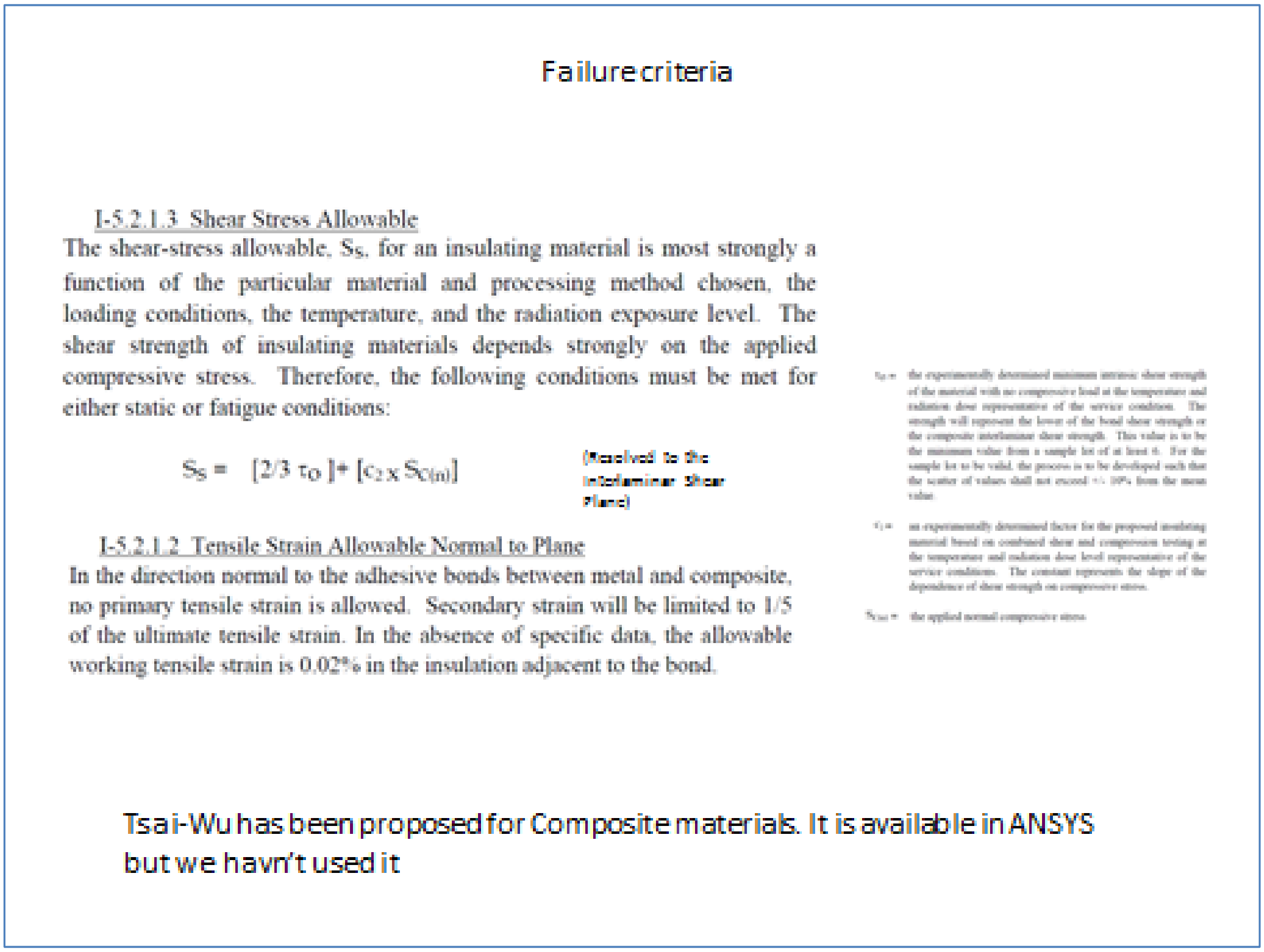
Answer: The standard Transrex power supply section has two-quadrant behavior (current in one direction, but voltage in both). The plots that show the TF ramping down quickly are cases where the supply is controlling the current rapidly back to zero, under digital command and NOT in a fault condition.

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 <u>"Increasing the maximum OH operating temperature" on p. 1 of this report;</u> this is the more cost effective solution.

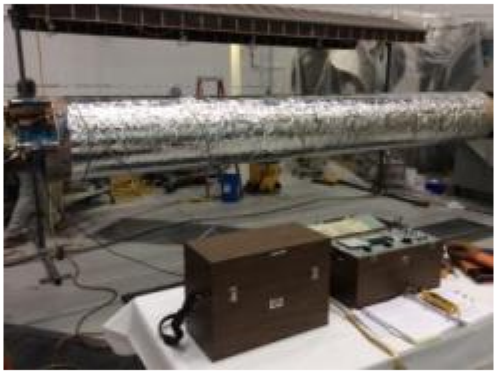
M10. My proper engineering colleagues can comment, but I thought Tresca stress, while recognizing the superposition of shear and compression/tension in a generally appropriate way to represent total stress, did not intrinsically relate this to the loci of allowable shear and tension/compression in a 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.



<u>Electrical Hi Pot Test of OH Coil</u>

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)

Appendix M

Report from NSTX-U Readiness Review Committee

FROM: Arnold Kellman

TO: Mike Williams

SUBJECT: Report from NSTX-U Readiness Review Committee

DATE: 1/20/2015

OVERVIEW OF COMMITTEE ACTIVITY

A Readiness Review Committee met at PPPL December 9 – 11. The purpose of this review was to ensure that the commissioning and subsequent operation of the National Spherical Torus Experiment Upgrade (NSTX-U) could be performed in a safe and environmentally responsible manner. The specific charge questions, prepared by Mike Williams and the NSTX-U staff, are listed below. During the meeting, the committee heard presentations from the PPPL staff, interviewed various PPPL staff members, read procedures, viewed additional documentation, and toured the facility, including the torus hall to address the specific questions in the committee charter. A closeout presentation was made to Stewart Prager, Mike Williams and some of the NSTX-U staff by the committee on Thursday December 11.

CHARGE TO THE COMMITTEE

The following questions were taken from the NSTX-U Readiness to Operate Charter:

1. Do the approved NSTX-U Safety Assessment Document (SAD) and pending Safety Certificate adequately define the safe operating envelope for NSTX-U operations?

2. Are there clearly defined roles, responsibilities and training for NSTX-U operations personnel?

3. Are there clearly defined operating procedures that ensure that NSTX-U is commissioned and operated within the safe operating envelope defined by the NSTX-U Safety Assessment Document (SAD) and Safety Certificate (including off-normal events)?

4. Does the PPPL Activity Certification Committee (ACC) process ensure that configuration changes are adequately reviewed and appropriately documented in the NSTX-U Safety Assessment Document (SAD) and Safety Certificate?

5. Does the PPPL Activity Certification Committee (ACC) process, including approval to proceed by the PPPL ES&H Executive Board Chairperson, ensure that PPPL is indeed ready to begin NSTX-U operations?

6. At the time of project completion, will the NSTX Upgrade Project have delivered the Project Objectives as defined in Section 2.2 of the NSTX-U Project Execution Plan?

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

COMMITTEE MEMBERS

- Arnie Kellman, General Atomics, Chairperson
- Dragoslav Ciric, Culham Centre for Fusion Energy
- Kevin Freudenberg, Oak Ridge National Laboratory
- Tim Scoville, General Atomics
- Jim Irby, MIT Plasma Science and Fusion Center
- Dave Terry, MIT Plasma Science and Fusion Center
- Will Oren, Thomas Jefferson National Accelerator Facility
- Edward Lessard, Brookhaven National Laboratory
- Tom Todd, CCFE (Retired)

GENERAL FINDINGS

- The committee was impressed with the project and the evidence of continued high quality of workmanship and project management.
- The project is ~95% complete with the major production and assembly milestones and the highest risk items completed (CS, DCPS, NB Vessel modification, and NB2 installation) almost complete.
- The recent setback with the Aquapour removal was handled effectively through a combination of internal and external review panels. The expected impact on the physics plan will be minimal.
- Present status gives high confidence in successful completion of project and completion of CD4 in March.
- This committee was not asked to perform a typical Readiness Review. NSTX-U is not ready to resume operations of either the new beamline or plasma operation, as defined by ISTP-001.
    - 20 Project and 28 Operations Engineering Work Packages (EWPs) remain open.
    - 25 chits remain OPEN, 4 are CLOSED but not VERIFIED
    - Some official signed off drawings remain to be updated to "as-built" conditions.
    - PTPs are not yet updated
    - Personnel are not trained in new PTPs or new hardware, software, user interfaces
- The committee was asked to evaluate the SAD, whether the processes, procedures, and training protocols were in place to allow an assessment of readiness to be made by an internal review panel through the ACC process.
- Main conclusions include:
    - Additional work is needed on SAD and definition of Safety envelope.

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

- An extensive set of procedures exists to track completion of project, appropriately test all project upgrade elements and existing operational subsystems, and safely operate the device. However, test procedures are not yet updated and would benefit from improvements in quality and uniformity, e.g. allowable ranges in measurements should be included in PTPs, missing signatures, incomplete feedback. An improved focus of the QC/QA group on preparation and completion of procedures is recommended.
- Personnel clearly understand their roles (in some cases multiple) and responsibilities and training is excellent.
- The ACC process is well developed and manned by highly experienced staff members with a broad range of skills. High confidence exists that this process will properly assess Readiness to Operate, similar to what it has done in the past. However, procedural changes to ACC could further improve this well-established process.
- A great depth of institutional and detailed system knowledge exists in present staff. This contributes greatly to thoroughness of reviews and proper functioning and oversight of systems during operations and on-going system modifications and upgrades.
- No commissioning sequence up to full design parameters was presented. The committee recommends that a full commissioning plan be developed including verification of critical stress calculations.
- A potential problem is that since some of the very experienced staff hold more than one key role in the safety and operational management of the facility, there is a tendency to obviate the need for procedures and document trails regarding communication of emerging issues, plant status etc. between these roles.

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

ANSWERS TO CHARGE 1

Charge 1: Do the approved NSTX-U SAD and pending Safety Certificate adequately define the safe operating envelope for operations?

- Conditional yes, subject to Items Requiring Resolution

Committee members for Charge 1

- Will Oren (TJNAF), Edward Lessard (BNL)

Method of review:

- Document review, interviews, observations, presentations

Findings

- SAD still in draft
- SAD does not cover entire system's hazards (e.g., ODH in all relevant enclosures)
- Safety basis for the limits in the safety envelope were not described in SAD, but it is tied to the design parameters
- Pressurized water/stress issues in CS are not addressed in SAD/FMEA
- Software QA not addressed in QA section of SAD
- Operating organization structure and authorizations not addressed in SAD
- Linked references or appendices on N2, He and SF6 ODH calculations needed
- Linked references or appendices on radiation calculations needed
- SAD did not have a Maximum Credible Incident section (e.g., max D gas event, max direct radiation exposure, etc.)
- Engineered and administrative controls for non-standard industrial hazards not included in safety envelope (e.g., SIS/HIS operability, ODH protection system operability, etc.)
- Safety envelope does not include engineered and administrative control supports such as calibration frequency, testing frequency, configuration management for shield drawings
- No documented practice to measure and track integrated neutron fluence in safety envelope
- Assurance processes beyond QA (e.g., ACC) not described in the SAD

Comments

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

- Safety of rf system not adequately analyzed in SAD

Items Requiring Resolution Before ISTP

- Finalize SAD/SE
    - Address all non-standard industrial hazards (NSIH) for all enclosures and the basis for inclusion in SAD
    - Include sections that describe the assurance processes such as ACC
    - Include methodology to determine NSIH controls, and link NSIH controls to safety envelope
    - Identify tangible controls in safety envelope and their supports
    - Supporting safety related calculations need to be linked or appended to SAD

Items Requiring Resolution After ISTP

- The web based work control system should automatically forward work related to limits and controls in the safety envelope to the ACC

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

ANSWER TO CHARGE 3

Charge 3: Are there clearly defined operating procedures that ensure that NSTX is commissioned and operating within the safe operating envelope as defined by the SAD and Safety Certificate (including off-normal events)?

- Conditional yes, subject to Items Requiring Resolution

Committee members for Charge 3

- Will Oren (TJNAF), Edward Lessard (BNL)

Method of review:

- Document review, interviews, observations, presentations

Findings

- Non-standard industrial hazards that are controlled by engineered safety systems or administrative safety programs (NSIH controls) are not clearly identified in the Safety Assessment Document, e.g. SIS

- There are no tangible NSIH controls or NSIH control supports in the Safety Certificate

- There is no implementing procedure that ties responsible positions to credited controls in a Safety Certificate (e.g. identify responsible authority for assuring SIS is tested and operational).

- The limits in the Safety Certificate are not related to tangible controls that must be present during operations (e.g. what is tangible control for the lithium limit?)

- 19 NBI procedures have been expanded to include preparation for and safe operations of beam line 2

- Administrative procedure OP-NSTX-02, which is managed by the COE, lists the sub-systems and integrated system procedures for startup and operation of NSTX-U

- ACC is an assurance process/program that addresses technical ESH issues, reviews projects and modifications against the requirements in the safety envelope and assumptions in the SAD, and it performs readiness review activities. However, implementing procedures beyond the charge were not documented (e.g., procedure to request a review, procedure that describes the ACC activities, tracking of ACC issues to closure, records of the reviews, authorizations to operate the facility or to modify safety systems identified in the Safety Certificate).

- No discussion of purge procedures in SAD regarding D gas event and NSIH controls such as mandatory purge gas volume

- Work packages and controlled documents are readily retrievable; but not completely error free
- Some procedures out of date
- Software QA process not defined

Comments

- Findings indicate inadequate QA/QC on procedures, which is needed to assure they are implemented as intended

Items Requiring Resolution Before ISTP

- Administrative controls, such as procedures, are needed to stay within limits in safety envelope and need to be included in the safety envelope (e. g., procedures associated with limiting the LITER lithium capacity, boronization, neutron limit logging, and shield configuration management)
- Engineered controls such as minimum purge gas volumes, operability of SIS, etc. must be in Safety Envelope

Items Requiring Resolution After ISTP

- QA procedures/programs to regularly audit the thoroughness of use of installation, checkout and operations procedures needs to be established
- Develop auditable procedures for ACC process/program/authorization as it relates directly to implementation at NSTX
- Develop associated training for ACC process/program as it relates directly to implementation at NSTX

ADDENDUM TO CHARGE 3

Although not specifically asked to comment on machine protection in either Charge 1 or 3, it was felt by the committee that the role of the Digital Coil Protection System in the machine protection was significant enough to be worthy of comment.

Findings

- The hardware of the Digital Coil Protection System has a comprehensive redundancy and fail-safe architecture.
- The physical architecture employed modern low-cost 16-core chips in a standard rapidly exchangeable plug-in format, so that an adequate spares stock could easily and usefully be achieved.

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

Comments

- The system makes extensive use of a custom, made-to-order design of a multi-channel digitizer with multiplexed fiber-optic output, raising questions of design validation and lifetime, or Mean Time Between Failures. It would seem worthwhile to identify their failure modes in a simulation of their anticipated workload and working environment.

- In the longer term, the importance of the DCPS for machine protection surely warrants a comprehensive verification and validation process, not just for the early usage but evolving with the machine and the physics program and developing understanding of the potential threats to the tokamak assembly.

Items Requiring Resolution – URGENT

- To the extent that resources permit, develop a suitable testing plan, including a hardware simulator to challenge one or more examples of these digitizers, both inputs and outputs, over an extended period, in order to:
  - Prove longevity by burn-in (at least some hundreds of hours);
  - Identify repeated types of failure and redesign or acquire spares to suit the full set of such digitizers used in NSTX-U and its hot spares.

Items Requiring Resolution After ISTP

- Depending on the results of the simulator trials, acquire suitable spares and consider modifying the design to obviate any weaknesses identified.
- Continue monitoring the success or failure rate of the digitizers and adjust spares holdings, preventative maintenance planning, and design evolution accordingly.
  - Validation and verification of the coding within DCPS should be undertaken by suitable procedures such as by modeling (evolving with increasing physics understanding) and by cross-correlations with strain sensors, temperature sensors etc. on the load assembly.

ANSWER TO CHARGE 2

Charge 2: Are there clearly defined roles, responsibilities and training for NSTX-U operations personnel?

- Conditional yes, subject to Items Requiring Resolution

Committee members for Charge 2

- Jim Irby (MIT Plasma Science and Fusion Center), Dave Terry (MIT PSFC), Will Oren (TJNAF), Edward Lessard (BNL)

Method of review:

- Document review and interviews. Interviews included COE, Operations supervisor, Responsible Line Management, Cognizant Engineer, System Operator, and Entry Level engineer

Findings

- There is an outstanding culture of safety. All employees felt safe at PPPL and all commented on their own about how impressed they were with the safety program

- The people we interviewed gave very similar answers to the questions indicating there was a very good training in roles and responsibilities

- We found that all but one of the employees interviewed have been at PPPL for many years (> 20), and have extensive experience in many areas. Some concerns were mentioned about the need to train new people and transfer information as long-term people leave. Our one new employee indicated to us that this process is underway. Others said they were working with other engineers to make sure knowledge is not lost.

- Training requirements are documented and approval process is in place. All employees knew about this process, and how to use the online training tools.

- The situation regarding multiple-role position holder succession seems not to be recognized by some of the position-holders interviewed, whose response to queries on this issue was to debate which of the other near-retirement, highly skilled staff could be further trained to successfully to take over the multi-role posts.

- Several people were concerned about out of date procedures or new incomplete procedures for NSTX-U, but they felt the system in place would make sure these procedures were ready before CD-4. One person was concerned about the DCPS. One person was concerned about the CHI system readiness because of loss of experienced personnel. Finally, someone mentioned there are too many acronyms (but improved with webpage update)

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

- Process to determine what type of training for each procedure not defined in a procedure
- Roles, Responsibilities, Authorities and Accountabilities (R2A2) of COE not defined/represented in operating org chart
- The structure with roles and responsibilities of each position beneath the COE was not presented
- Conduct of Operations Order Matrix not developed

omments

- Shift supervisor and COE roles could be better defined and made more clear in the documentation
- What role does the physics operator play in machine operation? How do physics operator and COE interact to ensure safe operation of the machine? The roles should be better defined.
- Suggest more training for COGs and COEs in ACC process and SAD and safety envelope
- It would serve the lab better, against the various reasons for loss of staff, if there was one person (and a deputy) per key role. While there is currently no evidence of the multiple roles carried by any one person leading to any conflict of interest (such as science program expediency versus the priority of definite safe working) we do not feel that this is a good policy.
- Above findings indicate R2A2s not well documented for operations organization
- Other attributes of the Conduct of Operation Order may not be documented or clearly implemented.
- Continued attention should be paid to succession planning since many of the staff are approaching retirement age. This is especially important in light of the fact that some of the staff performs multiple roles.

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

ANSWER TO CHARGE 4 and 5

Charge 4: Does the PPPL Activity Certification Committee (ACC) process ensure that configuration changes are adequately reviewed and appropriately documented in the NSTX-U Safety Assessment Document (SAD) and Safety Certificate?

Charge 5: Does the PPPL Activity Certification Committee (ACC) process, including approval to proceed by the PPPL ES&H Executive Board Chairperson, ensure that PPPL is indeed ready to begin NSTX-U operations?

- Yes, subject to items requiring resolution.

Committee members for Charges 4 and 5

- Kevin Freudenberg (ORNL), Dragoslav Ciric (CCFE), and Tim Scoville (GA)

Method of review:

- Document review and interviews.

Findings

- The existing ACC review process is functioning as an internal readiness review, but in places there is no evidence of external input, to the extent that some serious issues have been missed.
- The experience of the ACC members, and their "hands-on" approach to checking the plant has been and continues to be of immense value for the human safety and plant protection of the facility.
- The guideline for determination of the scope of the ACC review is based primarily on the OP-NSTX-02. However, the ACC review has full authority to expand its scope into any area it sees fit.
- The NSTX-U safety certificate is issued by the ES&H Executive Board based on the recommendation of the ACC review. The safety certificate is required for NSTX-U operation.
- Maintenance activities are not directly input into NSTX-02 or the ACC review process.
- Spot checks of the commissioning procedures and the FMEA, reveal some shortcomings most easily explained as arising from the familiarity of practically every key post-holder with the old plant and its hazards.
  - The typical problems are, in the commissioning procedures, inadequate descriptions of how exactly to perform certain tasks (such as "check the type of gas in the [SF6 towers]", and inadequate requirements for recording findings or branch conditions if certain conditions were not met (e.g. vacuum pressure achieved).

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

- For the FMEA the old plant and the new differ more than the NSTX-U FMEA recognized (although it is unclear to what extent ACC had approved this document at the time of this Review). One example is that the turbo-pumps will see higher stray magnetic field from the tokamak poloidal fields, which will create higher eddy current heating in the rotor blades, exacerbating their creep behavior and raising the likelihood of explosive disassembly – a serious failure mode of TMPs guarded against by modern suppliers and by many other MFE installations but not mentioned as a hazard in the FMEA.

Comments

- The ACC review was stated to be on time and within schedule but this was not shown explicitly. There is concern that many systems, most notably the DCPS, need to be fully approved and ACC assessment is only half done on that system.
- Responsible line manager decides (engineering judgment) when modifications are big enough to make change to SAD.
- The schedule for bringing NSTX-U up was not discussed in any detail. The ACC stated that their involvement was "just in time" and driven by the new systems coming up that needed review.
- The ACC effectiveness relies heavily on their considerable years of experience to guide activities. However, as senior staff retires, an improved process become more important.
- Since ACC members are themselves part of the long-term cognoscenti of the facility, it is not clear that their further efforts alone will identify the new hazards raised by the change from NSTX to NSTX-U or the unstated things in the commissioning procedures that are not obvious to trainees and other new-comers.
- It would be beneficial to create and maintain a preventative maintenance database.

Items Requiring Resolution Before ISTP

- The NSTX-U Operations group should provide a well-defined startup schedule for use by the ACC and other groups. Hold points should be used to trigger the involvement of the ACC in approvals.
- Consider how to identify the unstated reliance upon prior knowledge in the commissioning procedures. Improvements should be made such as recording values observed (useful for maintenance guidance and confirmation of tasks actually completed).
- Preventative maintenance (PM) activities should be input into NSTX-02 or the ACC review process when applicable, since PM activities may impact assumptions in safety analysis. Explicit decisions should be required by Cog and approved by RLM on whether completeness of maintenance activities is appropriate for startup.

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

- Arrange for external peer review of the FMEA and evaluate whether any new issues identified must be resolved prior to ISTP.

- **Issues Requiring Resolution After ISTP** Any changes to the NSTX-02 that impacts a control identified in the Safety Certificate or an assumption in the SAD document must automatically trigger an ACC review. This should be included in the PPPL tracking/change system to remove the ambiguity of when an ACC review is required.
- A skill profile for future ACC members is needed.
- At a suitable interval, reassess the ease of use of the procedures by new trainees.

Appendix M

Report from NSTX-U Readiness Review Committee (continued)

ANSWER TO CHARGE 6

Charge 6: At the time of project completion, will the NSTX Upgrade Project have delivered the Project Objectives as defined in Section 2.2 of the NSTX-U Project Execution Plan?

Yes. It is the opinion of this committee that the demonstration of the two items listed above (Section 2.2.2.2 in the NSTX Project Execution Plan (PEP)), coupled with the successful completion of the required action items, and the completion of the integrated testing OP-NSTX-U will demonstrate that NSTX has been upgraded to permit operation at the desired technical baseline parameters. This will meet the project objective, as defined in Section 2.2.1 of the PEP.

Method of review:

- Document review and presentations during the Readiness Review.

Findings

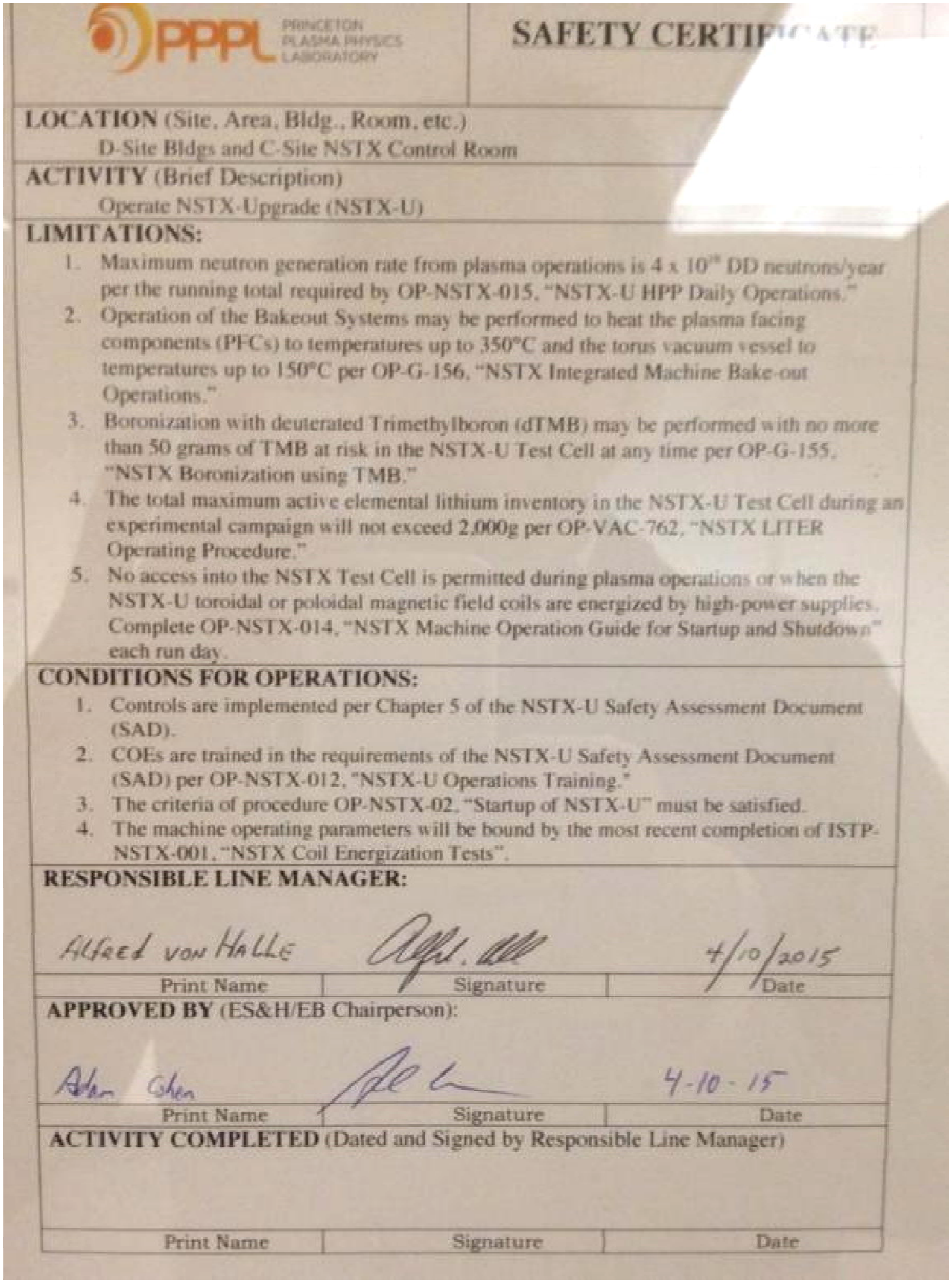
- The Technical Baseline Parameters for the NSTX Upgrade Project are the following: TF = 1.0 Tesla, Pulse length = 5 seconds, Plasma current = 2 MA, and NB Power = 10-14 MW
- The Center Stack Upgrade and the additional of the second Neutral Beamline will provide the device capabilities to meet the baseline parameters.
- All systems have been designed to meet the baseline parameters. Design reviews have been held for all key systems and have been reviewed by internal project personnel as well as external reviews through the final design review stage. All action items (Chits) identified during the reviews were listed and tracked in a master action item file.
- A procedure exists and is being executed to verify that all action items are resolved, that appropriate personnel have reviewed the resolutions, and that the resolutions are completed prior to the start of integrated testing OP-NSTX-02.
- The execution of the design was reviewed periodically during the project by external review committees and all recommendations of those committees were followed.
- Formal project completion requires demonstration of (1) an ohmic plasma with Ip > 50 kA at a toroidal field greater than 1 kG and (2) installation of the second neutral beamline, including all support services and control systems, and injection of a 40 keV neutral beam into vessel armor for 0.050 seconds.

Comments

- Actual achievement of the baseline parameters over the course of the next few years will require continued testing, including validation of design simulations against measurements.

Appendix N

NSTXU Safety Certificate



PRINCETON PLASMA PHYSICS LABORATORY

SAFETY CERTIFICATE

LOCATION (Site, Area, Bldg., Room, etc.)

D-Site Bldgs and C-Site NSTX Control Room

ACTIVITY (Brief Description)

Operate NSTX-Upgrade (NSTX-U)

LIMITATIONS:

1. Maximum neutron generation rate from plasma operations is 4 x 10[illegible] DD neutrons/year per the running total required by OP-NSTX-015, "NSTX-U HPP Daily Operations."
2. Operation of the Bakeout Systems may be performed to heat the plasma facing components (PFCs) to temperatures up to 350°C and the torus vacuum vessel to temperatures up to 150°C per OP-G-156, "NSTX Integrated Machine Bake-out Operations."
3. Boronization with deuterated Trimethylboron (dTMB) may be performed with no more than 50 grams of TMB at risk in the NSTX-U Test Cell at any time per OP-G-155, "NSTX Boronization using TMB."
4. The total maximum active elemental lithium inventory in the NSTX-U Test Cell during an experimental campaign will not exceed 2,000g per OP-VAC-762, "NSTX LITER Operating Procedure."
5. No access into the NSTX Test Cell is permitted during plasma operations or when the NSTX-U toroidal or poloidal magnetic field coils are energized by high-power supplies. Complete OP-NSTX-014, "NSTX Machine Operation Guide for Startup and Shutdown" each run day.

CONDITIONS FOR OPERATIONS:

1. Controls are implemented per Chapter 5 of the NSTX-U Safety Assessment Document (SAD).
2. COEs are trained in the requirements of the NSTX-U Safety Assessment Document (SAD) per OP-NSTX-012, "NSTX-U Operations Training."
3. The criteria of procedure OP-NSTX-02, "Startup of NSTX-U" must be satisfied.
4. The machine operating parameters will be bound by the most recent completion of ISTP-NSTX-001, "NSTX Coil Energization Tests".

RESPONSIBLE LINE MANAGER:

Alfred von Halle	[signature]	4/10/2015
Print Name	Signature	Date

APPROVED BY (ES&H/EB Chairperson):

Adam Cohen	[signature]	4-10-15
Print Name	Signature	Date

ACTIVITY COMPLETED (Dated and Signed by Responsible Line Manager)

Print Name	Signature	Date

Appendix O

NSTX OH Fault Corrective Action Plan

NSTX OH Fault Corrective Action Plan Rev. 1

Reviewed by: ______________________

M. Ono

Jon Menard

Digitally signed by Jonathan Menard
Date: 2015.08.01 13:37:19 -04'00'

Reviewed by: ______________________

J. Menard

Ronald L. Strykowsky

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Date: 2015.08.02 13:13:19 -04'00'

Reviewed by: ______________________

R. Strykowsky

Alfred von Halle

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Date: 2015.08.03 06:33:05 -05'00'

Reviewed by: ______________________

M. Williams

Adam Cohen

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Date: 2015.08.02 21:51:44 -04'00'

Reviewed by: ______________________

A. Cohen

Stewart Prager

Digitally signed by Stewart Prager
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Date: 2015.08.02 22:04:41 -04'00'

Approved by: ______________________

S. Prager

Appendix O

NSTX OH Fault Corrective Action Plan (continued)

Background:

On April 24, PPPL ESU responded to alarms from the NSTX-U experimental area. An active water leak from NSTX-U was observed. Staff discovered that several of the Ohmic Heating coils external cooling paths were damaged at the top end of the OH coil. Additionally, indications of electrical arcing were observed in the vicinity of the water leaks. Initial inspection showed no damage to the OH or other coil systems. The water was secured and investigation into the cause was initiated.

Review Teams:

As a result of this event, the Laboratory has commissioned a number of reviews to evaluate the cause, determine what actions are necessary to repair the coil, what actions are necessary to improve processes and prevent recurrence. The following teams were commissioned:

- An Internal Independent Review team, comprised of: Robert Ellis, Chair, Michael Bell, John DeLooper, Joel Hosea, and Charlie Neumeyer conducted a formal review on May 8. Their report, issued on May 12, identified 32 recommendations. The recommendations for this report are label as no's 1 (IRR) through 32 (IRR).
- The PPPL Advisory Board meet on May 13 and 14 and were given a summary of the event. Their report, issued May 15, identified 3 recommendations. The recommendations for this report are labeled as no's 33 (PAC) through 35 (PAC).
- An Extent of Condition Review Team, comprised of: J. Hosea, chair, R. Ellis, N. Greenough, D. Mueller, issued their report on May 26, with 25 recommendations. The recommendations for this report are labeled as no's 36 (EOC) through 60 (EOC).
- An Independent External Review Team, comprised of: Arnie Kellman, chair, General Atomics; Jim Irby, MIT Plasma Fusion Center; Brad Merrill, Idaho National Laboratory; and George Ganetis, Brookhaven National Laboratory issued their report on May 28, with 14 recommendations. The recommendations for this report are labeled as no's 61 (IER) through 75 (IER). Note that item 75 was in error and is not associated with any recommendation.
- A formal Root Cause Analysis Team, comprised of Irving Zatz, John Lacenere, Judy Malsbury and Mike Mardenfeld was commissioned. This report identified some 20 Judgements of Need (JONs). These JONs are label as no's 76 (JON) through 95 (JON)

Corrective Actions:

Since many of the recommendations were related, this corrective action plan groups the recommendations into major areas for action and tracks the items by these groupings.

This plan also specifies which actions need to be done before CD-4 and which can be accomplished after CD-4. Category A corrections must be done before CD-4 while Category B actions can be actions can be accomplished subsequently.

Revision 0	Original Issue
Revision 1	Added Judgements of Needs (JONs) from Root Cause Analysis Report and updated status column as of July 30, 2015

Appendix O

NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
1	A	1 (IIR)	Determine the root cause of the ground plane connector design/installation errors [Separate committee using procedure QA-019]	1-1 Form a team to Conduct a Root Cause Analysis per QA-019 before CD-4 1-2 Complete Root Cause Analysis report 1-3 Incorporate recommendations (Judgments of Need) into this CAP	Zatz	OPEN (Root Cause Rpt, rev 0 issued; rev 1 of this CAP will allow closure)
		20 (IIR)	Complete root cause analysis and be prepared to present to external committee			
		64 (ER)	A Root Cause Analysis must be delivered to the ACC prior to approval of restart of high power test operations.			
		34 (PAC)	Ensure that PPPL identifies and addresses the correct fundamental root causes and complete extent of conditions for the external review committee to validate			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
1A	B	1 (IIR)	Determine the root cause of the ground plane connector design/installation errors [Separate committee using procedure QA-019]	Issue Revision 1 of Root Cause report with attachments. Review for any further updates of this CAP	Zatz/Williams	OPEN

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
2	A	15 (IIR)	The project needs to develop a comprehensive plan to address the Extent of Condition charge question and be ready to present to the external review committee	Extent of Condition committee was formed. Their report was issued May 26. The recommendations from that report have been incorporated into this corrective action plan.	Hosea	Closed – 5/26/15
		16 (IIR)	Form a small "task force" (with appropriate expertise) to walk down all the high-voltage parts of NSTX-U to determine anything out of the ordinary, or potentially questionable from an "high voltage hygiene" stand-point			
		17 (IIR)	Evaluate other gaps, creepage paths, and insulation on other coils and appendages to see if problems exist similar to CH			
		33 (PAC)	Evaluate PPPL conduct of engineering and conduct of operations policies and the execution of these policies, roles and responsibilities, accountability and authority, and organization, as part of the extent-of-conditions task force review. Include interviews with engineering and NSTX operations staff			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
3	A	2 (IIR)	Continue to perform diagnostic electrical tests including repeat of coil resistance measurement, inductance measurement and impulse test to confirm that the turn-to-turn insulation is intact	Conduct tests per PTPs and ISTP for restart. Engineering will determine which portions of the PTP's and ISTP need to be rerun once the machine is reassembled.	von Halle	OPEN #2 closed #68 closed #73 closed
		65 (IER)	An Impulse test should be done to fully qualify the OH coil			
		68 (IER)	The inner and outer vessel Hi-Pots must be successfully completed before returning to CD-4			
		73 (ER)	Careful attention must be paid to the recommissioning of the machine after the recovery effort. It may be best to err on rechecking more systems than less since some things may have been inadvertently affected during disassembly.			

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Appendix O

NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
4	B	18 (IIR)	Analyze and document electrical effect of Aquapour and dental floss wires in gap between OH and TF	Calculations complete being reviewed. No changes anticipated	Titus	Closed - 7/7/15
		56 (EOC)	Aquapour/Epoxy between TF inner bundle and OH Center Stack - Operation of OH and TF combined with PLC controlled water heater to program the water temperature profile; Controlled through DCPS using I^2t; Constrains the pulse repetition rate.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
5	A	6 (IIR)	Determine NSTX-U project line of authority - who must approve proceeding with operations if causes of ground fault (or other problem causing a trip) have not been determined and resolved	Project will determine appropriate lines of authority, roles and operational methodology for off normal events and then define in an administrative procedure new administrative procedure will be put in force to define the expected responses for each of the full set of protection systems..This will include directions to get approvals from the appropriate subject matter experts from engineering, research, and management. Key control room personnel will be trained on the requirements of this procedure. The procedure for the D---Site Control of System Status (Chain of Command), OP---AD---56, will be revised and approved	Ono/Menard/von Halle/Williams	OPEN #4 – Closed #6 – Closed #8 – Closed #10 – Closed #35 – Closed #60 – Closed #61 – Closed
		8 (IIR)	The Laboratory should determine whether the operators (e.g. COEs) report up to and through the NSTX-U organization rather than engineering			
		10 (IIR)	Project needs to demonstrate how it will prevent this type of management control failure from recurring in the future			
		60 (EOC)	Chain of command during operations. –Clear line of command to and from the COE during off-normal events			
		4 (IIR)	Revise operational procedures to require a full stop of operations upon a ground fault trip – need to understand what went wrong – require inspections to determine reason			
		61 (IER)	The procedure for handling off-normal events including ground faults must be completed prior to restart of testing. This must address the control room conduct of operations including required personnel, the amount of discretion that operations personnel have in continuing a given test campaign, i.e. when can protection systems be bypassed. Operations must stop until a serious fault condition is understood before proceeding.			
		35 (PAC)	Reinforce workforce authority to stop work, especially when anomalies are observed			
		93 (JON 19)	The Chain of Command for Control of Equipment and System Status, defined in OP-AD-56, failed to prevent the event and needs to be reviewed and corrected.			

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Appendix O

NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
6	A	5 (IIR)	COEs should have a collection of MDS Scope pages set up to monitor critical operations and diagnose faults under operations procedure. The pages used should be optimized for the type of operation underway (test shot, ISTP, plasma ops, etc.)	6-1 Develop and implement scope pages for PS EICs and COEs. Some optimization of critical info necessary to avoid overload 6-2 The available MDS scope pages will be evaluated and documented for use by key control room personnel. 6-3 Control Room personnel will be trained on their use. 6-4 Adequacy of COE station computers and displays will be reviewed with the COE's, and appropriate updates made.	von Halle	OPEN
		67 (IER)	The signals from all ground fault signals should be digitized and made easily displayable by the operations group.			
		58 (EOC)	Adequacy of control room computers and associated displays for the COE.			
		72 (IER)	Improvement in instrumentation to aid in identification of causes of off-normal events should be addressed. This is true not only for ground faults, but any signals that provide interlocks for serious machine shutdown conditions.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
7	B	14 (IIR)	Engineering needs to establish rules for grounding each experimental machine as part of the formal design review process	7-1 A formal grounding policy will be developed and deployed as well as a SME for grounding will be appointed 7-2 The PPPL System Engineer list will be reviewed and updated to include an equipment grounding Subject Matter Expert who will provide engineering input in establishing this policy	von Halle	OPEN
		63 (IER)	A policy for equipment grounding must be developed			

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Appendix O

NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
8	A	3 (IIR)	The design of the OH ground plane and its connections needs to undergo the standard PPPL design review, installation and inspection process, rather than relying on a "field fit-up."	8-1 Assure that all design changes undergo as a minimum, a final design review, per ENG-032 8-2 Assure that all appropriate design documentation is placed in the Operations Center	Dudek	OPEN #3 – Closed #11 – Closed #13 – Closed #70 – Closed #74 – Closed
		11 (IIR)	Project needs to verify design documentation packages (CDR, PDR, FDR) are available in the operations center for the NSTX-U centerstack and beamline 2			
		13 (IIR)	Incorporate electrical analysis and design into development of upgraded components			
		62 (IER)	A systematic check of all installation packages for NSTX-U must be performed with the object of identifying any other field installations and then evaluating whether they were installed properly. This review team should include at least the cognizant engineer and installation technician.			
		70 (IER)	Complete implementation of design changes identified by the team			
		74 (IER)	Assuming design reviews are properly completed, as per normal PPPL procedure, and installation process is carefully reviewed and inspected, the committee believes that the reassembly of the machine can proceed			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
9	B	32 (IIR)	Consider installing real-time camera(s) and arc flash detectors inside hub assemblies	Will evaluate and determine feasibility – incorporate post CD4	Dudek	OPEN October 15, 2015.
		59 (EOC)	Add cameras for real-time viewing of critical machine components			

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Appendix O

NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
12	A	26 (IIR)	For new design of clamps that support OH water lines: ensure adequate gaps, creepage, and insulation to pass hipot at 1.5 x Voh_hipot; use insulating boot over water line as it emerges from coil; do not use metallic screws; avoid splits in G10 blocks that provide line of sight creepage path	New design has been developed with input from electrical engineers. Design subjected to final design review and then issued to field for construction	Raftopoulos	CLOSED
		29 (IIR)	Evaluate whether or not method for clamping of OH water fittings allows for radial expansion of coil copper while support structure remains fixed, without placing undue stress on the water fittings. Consider placing a bend in the water fitting to avoid this issue			
		41 (EOC)	OH Water Connections: •Need an approved design with proper insulation - underway – Original parts were field fit. –New design must have electrical engineering input to insure proper high voltage insulating techniques - underway.			
		71 (IER)	Properly insulated the water cooling tubes while maintaining the ability to detect water leaks			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
13	B	23 (IIR)	Consider scheme to monitor load impedance in PSRTC (and/or DCPS) to sense situations where coil has become degraded	Code revised, tested and implemented	Gerhart	CLOSED

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
14	B	7 (IIR)	Engineering needs to establish a policy for field installations – when does a review have to be completed of field design	Develop field installation policy; Revise WP procedures accordingly. Issue statement of field change policy per PMO procedures to COGs and RLMs. Include in next COG/RLM training. Due 8/1/15	Perry/Stevenson	CLOSED

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Appendix O

NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
15	B	54 (EOC)	Bakeout Constraints on Machine Operations: Failure to reach desired 350C bakeout for divertor tiles is predicted. Refer to PF-1A, B, and C considerations; High temperature is needed for bakeout of divertor plates to provide for good plasma performance Preparations need to be made to add hot He gas heating to the divertor plates to reach desired temperature of 350C. Discoloration of CHI leads after Center Stack bake. Need to understand the cause	15-1 The urgent task is to install bakeout compatible tubes which are accessible from outside the umbrella structure compatible to be installed for the vertical and horizontal divertor sections. This task will be completed prior to CD-4. 15-2 Through realistic thermal modeling and on-going material temperature testing, a bakeout heating scheme will be chosen if any before the bakeout. 15-3 Risk- benefit assessment for PF-1B will be performed in deciding the heating system if any before the bakeout. 15-4 The cause of the CHI leads discoloration will be determined prior to the next bakeout 15-5 With the thermo-coupleplaced on PF-1C, we agree that the excessive heating of PF-1C can be avoided administratively. A clear set of operating constraints will be developed by the start of research operations	Ono/Titus	OPEN
		55 (EOC)	Bakeout Constraints on Machine Operations: Discoloration of CHI leads after Center Stack bake –Need to understand the cause			
		53 (EOC)	PF1A, 1B, 1C Considerations: Bakeout issue with PF-1B (Art Brooks analysis). Divertor tiles will not reach adequate temperature unless heated by the He system. If heated by He, the G10 spacer and ground wrap of PF-1B will exceed allowable limits. There is also the issue of stress in the welds securing PF-1B upper and PF-1A upper. Management must decide whether to bake to over 300C and accept risks to PF-1B. Connections to divertor plates must be able to accommodate the He heating system.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
16	B	51 (EOC)	PF1A, 1B, 1C Considerations-Shorting between PF-1A ground wrap and OH ground plane. It cannot be repaired without removing center stack. What are the ramifications? Minor.	Since PF-1A ground warp and OH ground plane are grounded to the same potential, we do not see any ramifications. With the thermo-coupleplaced on PF-1C, we agree that the excessive heating of PF-1C can be avoided administratively. A clear set of operating constraints will be developed by the start of research operations	Ono/Titus	OPEN
		52 (EOC)	PF1A, 1B, 1C Considerations: PF-1C can be heated by the plasma: Only a minor issue when PF-1B is not energized, but the strike point can still hit the PF-1C can; Energizing PF-1C so as to push the strike point towards the plasma will avoid this; Operations can administratively avoid the problem; A clear set of operating constraints needs to be developed.			

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NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
17	B	9 (IIR)	The Laboratory needs to determine whether sufficient high voltage electrical expertise is available for current and future projects	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15 Succession Plan – Von Halle effort to capture by posting of positions (addresses part of JON 7 and 8)	Cohen	OPEN
		82 (JON 7)	PPPL needs to capture the institutional knowledge held by experienced staff and current best practices by creating formal internal technical standards and ensure that they are readily available and applied uniformly			
		83 (JON 8)	PPPL needs to capture institutional knowledge held by experienced staff by expanding formal training systems for positions requiring critical technical skills that are specific to PPPL			
		84 (JON 9)	PPPL needs to evaluate the current skill mix among staff and develop a detailed succession plan.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
18	B	12 (IIR)	OH coil hipot level should be 2E+1=2(6+2)+1=17kV per approved design point documentation, which was also checked and signed off by coil designer. If operation requirements are to be revised (e.g. OH <=4kV with CHI, and/or Vchi = 3kV) then relevant documentation should be revised accordingly	Review hi-pot requirements and document accordingly. GRD will be revised to ensure consistency with PTP's.	von Halle	OPEN

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
19	B	19 (IIR)	Consider conducting a 'blind spot" review, similar to the laboratory process	Similar approach for Laboratory operations will be evaluated on the NSTXU facility by 10/31/15	Williams	OPEN

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NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
20	A	21 (IIR)	Ensure that ground plane connection does not form toroidal loop. If hose clamp approach is used to attach ground plane connector, ensure that type with thermal expansion spring is used. Demonstrate through measurement that the desired resistance is in the loop	Overall grounding plan will be incorporated in the final design. Required measurements will be taken via procedures and documented. Testing of grounds will become part of the operational procedures. The PPPL System Engineer list will be reviewed and updated to include an equipment grounding Subject Matter Expert. This engineer or designee will review, approve and inspect equipment grounds. All coil system power feeding into the umbrella structures should have ground fault sensors to measure any ground leakage current. Ground fault relaying should be provided with ground current sensor measurements and annunciation available in the Control Room	Raftopoulos/ Dudek	CLOSED
		22 (IIR)	Consider conducting elastomer solution to ground plane electrical attachment to avoid use of flex copper braid (ref. 13_010220_CLN_01.pdf, 13_010222_CLN_01.pdf, 13_010301_CLN_01.pdf). Provide documentation and drawings to justify and describe solution			
		25 (IIR)	Measure resistance of ground plane paint to confirm proper application and resistivity (200 ohms/square). Determine if OH groundwall thickness and composition is different than given in design point (as was mentioned during presentation) and provide explanation			
		28 (IIR)	Connect all metallic structures of inner vacuum vessel to Cat. 3 ground with 10 ohm resistors in each connection that can be opened up for troubleshooting. Provide an approved drawing of the electrical schematic			
		30 (IIR)	OH ground plane should be connected to Cat. 3 ground reference on both top and bottom ends through 10 ohm resistors. Analysis of ground plane behavior using PSCAD (W. Que "OHCoilGroundPlaneV3.ppt") should be updated accordingly and properly documented			
		36 (EOC)	OH ground plane and connection overall design: Do we need a lower ground plane connector? Evaluation is required. Design, fabrication, installation, connection and inspection of ground plane connector(s). Ground through a 10 Ohm resistor			
		31 (IIR)	Ensure that OH preload assembly fixture is connected to Cat. 3 ground via 10 ohm resistor			
		37 (EOC)	OH Compression Stack Grounding – Through a 10 Ohm resistor.			
		38 (EOC)	Grounding of buss supports at bottom of machine			
		39 (EOC)	Grounding of metal spacers to TF water connector supports			
		48 (EOC)	Who has an overall understanding of the machine grounding? Who is in charge of grounding, inspection thereof, and documentation on NSTX-U? The latter individual should have the qualifications of the former.			
		66 (IER)	Additional ground fault sensors should be added to the new OH ground straps, and the signals made part of a quickly acting ground fault relay. The OH preload stack should be grounded properly and sensors added and their signals recorded			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
21	B	27 (IIR)	Consider placing water sensor(s) on floor of NSTX-U Test Cell under machine and interlock with water system to turn off pumps	Will conduct a review to determine benefits and consequences by 10/31/15	Dudek	OPEN

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NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
22	A	57 (EOC)	Ground fault/loop detector sensitivity lessened by capacitors installed across HHFW transmission line DC breaks. Used in the past with the same capacitors. Loop faults are present in the diagnostic ground system.	Ground fault/loop detector sensitivity reduction due to capacitors installed across the HHFW transmission DC breaks has been measured, and the capacitors may now be reinstalled. Known loop faults in the diagnostic ground system need to be evaluated and dispositioned.	von Halle	CLOSED
23	A	69 (IER)	Install Lexan sheets or a similar insulator at the bottom of the machine to make sure that metal objects are not drawn up by the magnetic field into the bus work and connections	Peer review to determine requirement by June 12, 2015	Perry	CLOSED
24	B	73 (IER)	Although not unique to PPPL and NSTX, we believe that the lab and the fusion community as a whole could benefit from community workshops on best practices in engineering and operations. Discussions concerning measurements of joint resistance (periodic and real-time), ground fault detection highlighted areas in which techniques exist in different fusion and/or DOE labs that would benefit the larger community. While not truly a systemic weakness, such an initiative could strengthen NSTX-U and other device operations and safety.	Reinstitute Fusion Facilities Operations Committee by 10/1/15.	Williams	OPEN
25	B	75 (IER)	DELETED – NO SPECIFIC RECOMMENDATION WITH THIS ITEM	N/A	N/A	N/A

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NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
26	B	76 (JON 1)	PPPL needs to ensure that a comprehensive Technical Risk Assessment and Management Strategy provides direction for balancing resource allocation with technical assurance. This strategy needs to be appropriately graded for all levels of work.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN
		85 (JON 10)	PPPL management needs to evaluate if the Laboratory's Organizational Structure inadvertently encourages some of the issues highlighted in the Contributory Causes including staff accountability, staff assignments and competency, information access and communications.			
		86 (JON 11)	PPPL needs to clarify the roles and responsibilities of the Cognizant Engineer, the ATI, and the System Engineer as mentioned in the Work Planning System and Procedures. PPPL needs to ensure that they are being implemented properly, without overlapping or missing coverage.			
		95 (JON 20)	Protections need to be built into PPPL systems to prevent human performance issues from having a negative impact: Clear Goals, Roles, and Responsibilities; Appropriate Checks and Balances; Distinct Problem Solving Skills; Validation of Assumptions; Unfamiliarity with tasks; Recognizing Degraded Proficiency; Technical Stop Work; Inadequate communication.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
27	B	78 (JON 3)	PPPL needs to adopt and implement best practices from "Systems Engineering", especially for large complex projects which are composed of many subsystems.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN
		87 (JON 12)	PPPL needs a rigorous process to ensure that each component or system is assigned to a clearly identified individual who is aware of its current and ongoing status and history, and is someone who is both capable and responsible for its technical aspects.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
28	B	77 (JON 2)	PPPL needs to ensure that Lab—wide Procedures are clearly understood, used as a primary resource for directing work, and that they are properly implemented.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN
		79 (JON 4)	PPPL needs to ensure that the Work Planning System is utilized properly and consistently.			

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NSTX OH Fault Corrective Action Plan (continued)

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
29	B	80 (JON 5)	PPPL needs to continue to improve existing Project Planning and Control Tools.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN
		88 (JON 13)	The PPPL Design Review Process needs to be comprehensive, cover all important aspects or components of a work activity, and include all technical disciplines involved in the work activity.			
		89 (JON 14)	During the design phase and after the FDR, the project needs to ensure that the review process extends to as—built configurations including field changes.			
		90 (JON 15)	The Laboratory needs to assure that project specific technical procedures and drawings are appropriately and adequately reviewed.			

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
30	B	81 (JON 6)	PPPL needs to implement an information system (e.g. database) that relates all technical information to allow archiving and access.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
31	B	91 (JON 16)	An expansion of independent field oversight needs to be implemented.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN

CAP No.	Cat.	Recom. No.	Issue	Actions	Assigned to:	Status (as of 7/31/15)
32	B	92 (JON 17)	PPPL needs to review and clarify policies for Configuration Control of Experimental Devices to ensure that they are properly implemented with traceability and create adequate documentation of the device.	TBD – need meeting to establish long term corrective action – Cohen to call meeting by 9/15/15	Cohen	OPEN
		93 (JON 18)	Temporary configuration changes need to be formally documented and approved.			

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END OF REPORT