National Spherical Torus eXperiment Upgrade

Heat Transfer Plate (HTP) & Heat Transfer Tubing (HTT)

WBS 1.01.02.04

NSTX-U Recovery Project FDR – March 17-19, 2020

D. Cai - Cognizant Engineer

Last edit: 03/09/2020

Outline

1. Overview
2. Scope
3. Requirements and Interfaces
4. Analysis/Prototyping
5. Chit Closure
6. Procurement, Fabrication, Installation, and Test
7. Risk - Project Risks and Design FMECA
8. Quality, Environmental, Safety, and Health
9. Summary

Overview - WBS 1.01.02.04

WBS Title	HTT & HTP	WBS #	1.01.02.04
Project Cog.	D. Cai	Assoc. Proj. Man.	Gary Swider
Design Scope	Design heating/cooling features for the divertor parts of the CS casing		
Technical Impact of Scope	Heat transfer plate provides primary means to heat (bakeout) and cool (normal operations) the horizontal target tiles; heat transfer tube is same for vertical target		
Design Status	FDRs completed on 11/01/2018 (link) and 12/17/19 (link) Chit resolution report: link Calculations: link Drawings: link SoW/Spec.: link		
Fabrication Status	Center Stack casing related parts are fully fabricated. Interconnection parts not yet started		
Installation Status	Center Stack casing related HTT and HTP will be installed in CS casing by the casing vendor (Holtec).		

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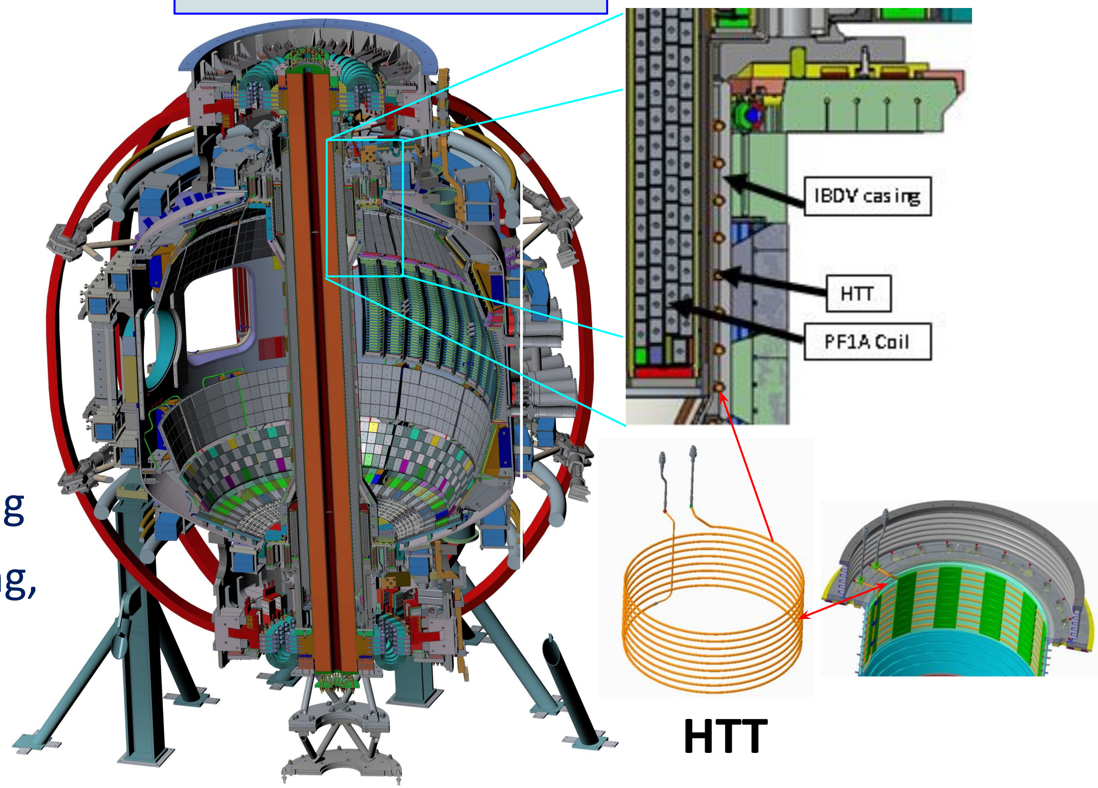
Scope - Heat Transfer Tube (HTT)

Purpose of HTT: Cool tiles during plasma operations

- IBDV Cooling: Deionized Water, 12 ^{o}C inlet, 60 PSIG inlet, 40 PSID, 3 GPM (Top+Bottom)
- 0.375” OD, 0.305 ID, 70 feet, Inconel 625 seamless tube
- 9 turns cooling groove in vertical casing
- 12 large clamps for HTT onto the casing, top and bottom, stitch welded
- 15 smaller clamps. Stitch welded

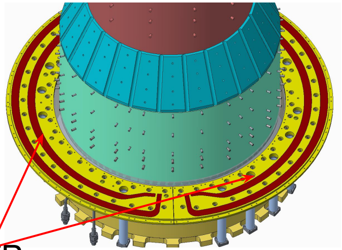
Cross-Section of NSTX-U

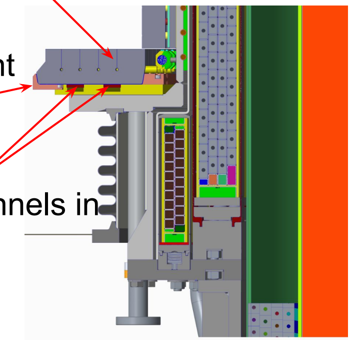


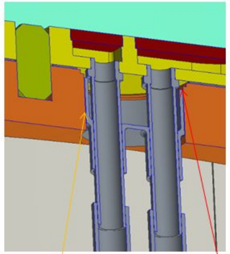
Scope - Heat Transfer Plate (HTP)

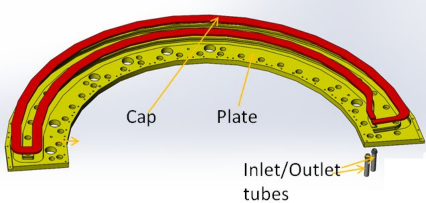
Purpose of HTP: Heat tiles during bakeout and cool tiles during plasma operations

- IBDH tile heating: Helium, 450 °C maximum , 300 PSIG maximum inlet
- IBDH tile cooling: Helium, 20 C, 300 PSIG inlet, 15 PSID minimum, 71 CFM (Top+Bottom)
- HTP: 45.5” OD, 32.3ID, 0.625” thick. Inconel 625. 2 at bottom and 2 at top. EB welded direct cooling channel
- HTP flatness requirement: 0.010”
- Tilt and offset requirement for HTP installed: 0.5 mRad and 0.02” to casing center line
- Electrically insulated from the NSTX-U pressurized helium system via ceramic insulators in the piping



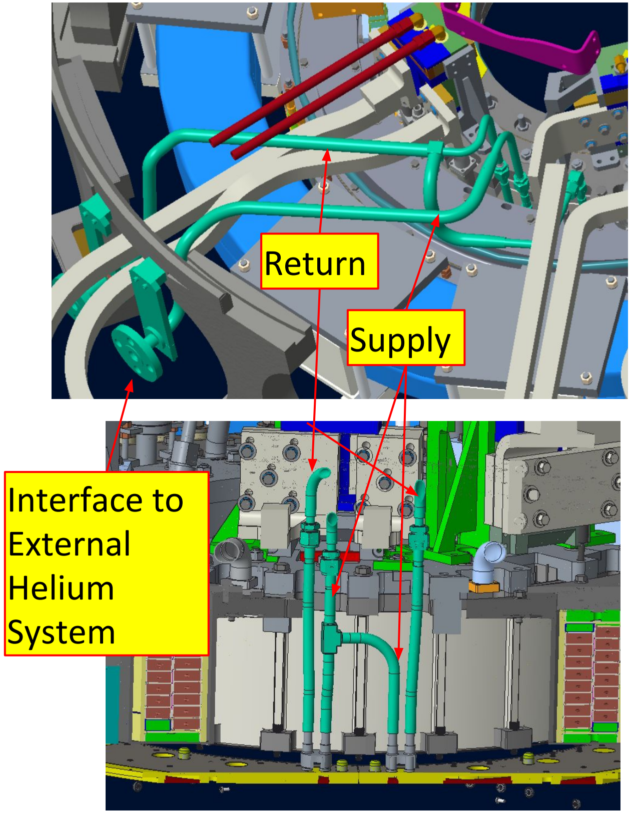




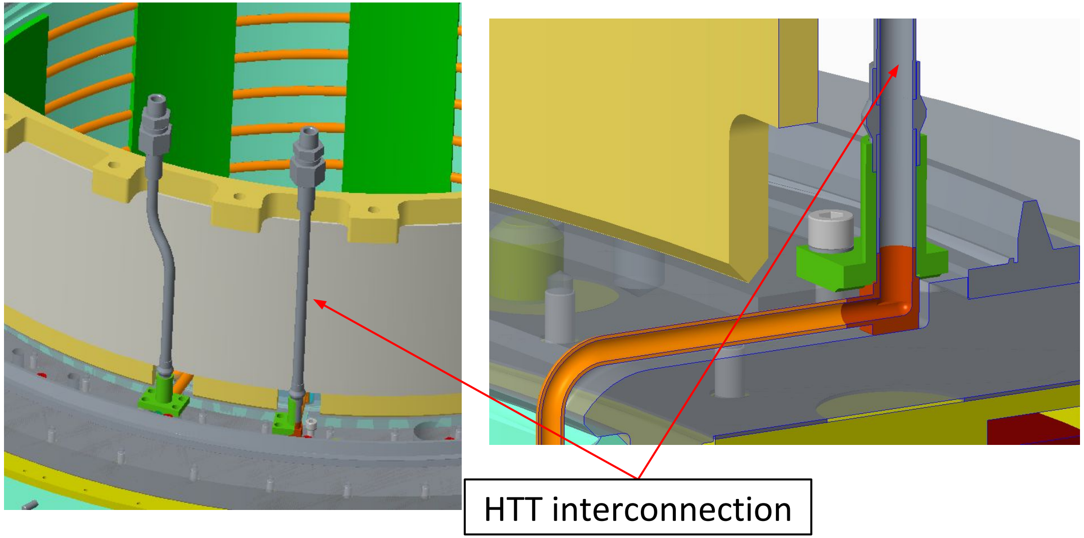


Interconnections Are Routed Through the Upper and Lower Umbrella

Heat Transfer Plate Interconnections - Example from Upper Plate



Heat Transfer Tube Interconnections



- HTT connects to the deionized water cooling system through upper and lower umbrella
- HTP connects to the pressurized helium heating and cooling system through upper and lower umbrella
- Thermal and electrical insulation for the interconnection lines protects nearby components in the umbrella

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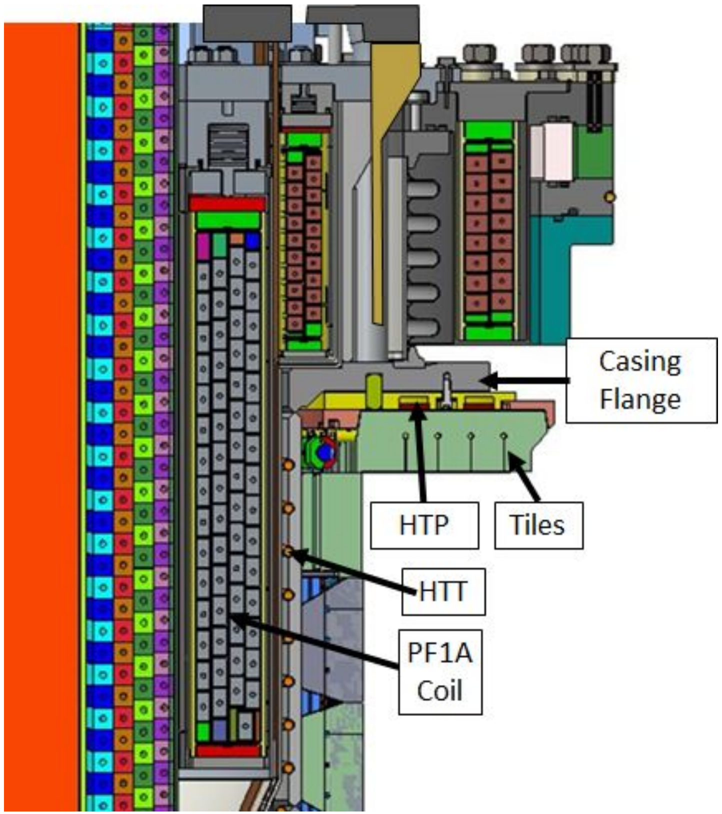
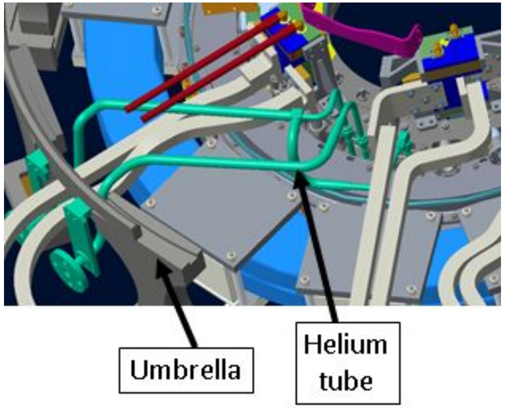
Requirements Defined and Met

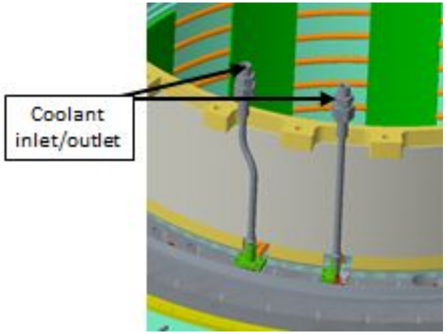
Source	Requirements	Comment	met
GRD	General requirements	Heating and energy input, materials, bakeout temperatures, field and current	✓
NSTX-CRIT-0001	Design criteria	Provides the project definition of margin for loads vs. allowables	✓
NSTX-U-RQMT-SRD-004	Bakeout temperatures	Requirements determined by physics goals	✓
NSTX-U-RQMT-RD-010	Magnetic permeability requirement	Base material, machining and welding	✓
NSTX-U-RQMT-RD-003	Disruptions	Provides guidance on computation of halo and eddy currents, including fatigue considerations, as an input to analysis	✓
NSTX-RQMT-U-SRD-005	The internal vacuum vessel heating paths and DC current heating system	carbon tiles to be baked out at a temperature of >300 deg C within 48 hrs.	✓
NSTX-U-RQMT-RD-015	Updated bakeout parameters	Updated parameters affect heat transfer plate performance during bakeout	✓
NSTX-U-RQMT-RD-013	Thermal Scenarios	Heat deposition on plasma facing tiles during operations	✓

Interfaces Defined in the SRD and Accommodated by Design



- Plasma Facing Components
  - IBD-H tile interface
- Bakeout
- PF1A magnet
- Coolant systems
- Top and bottom umbrellas
- HTT/HTP part of Center stack
  - Intra-Center stack Interfaces





Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Center Stack Structure	Bakeout system	link	Defines interfaces between the HTP and the helium bakeout system
Center Stack Structure	PFC	link	Defines interfaces between the HTP and the passive plates
Center Stack Structure	Cooling Systems	link	Defines interfaces between the HTT and the cooling water system

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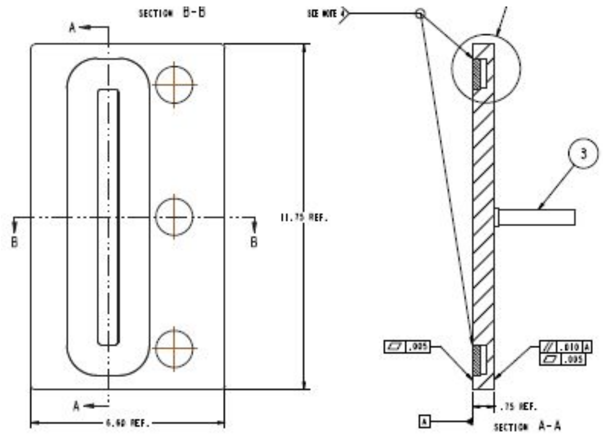
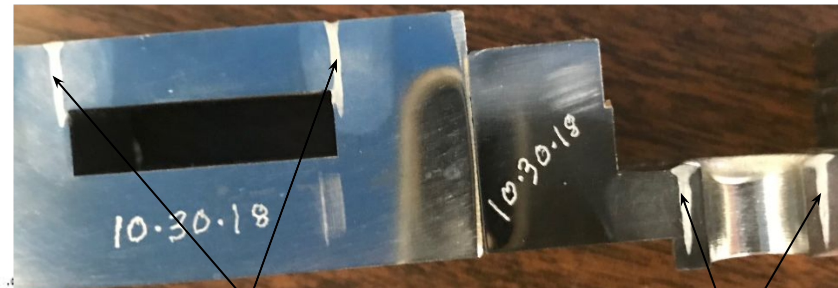
Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Peak EM field for HTT. Peak field for IBDH	NSTXU-CALC-11-08-00	Provides peak electromagnetic field for HTT structural analysis. Provides peak field to IBDH
Peak eddy current density at IBDH/V casing, and HTP	NSTXU-CALC-10-07-00	Provides peak eddy current density for inboard divertor horizontal and vertical casing, as well as heat transfer plate
Worst case temperature difference between HTT and IBDV casing, and between HTP and IBDH casing	NSTXU-CALC-10-06-00	NSTX-U global thermal model provides temperature distribution for HTT, HTP and center stack casing
HTP Design Calculation, Halo Loads	NSTXU-CALC-12-25-00	Calculate the halo load on the HTP. Ensure bolts and pins are sufficient to take on the halo load
Integrated HTT stress analysis	NSTXU-CALC-12-23-00	Provides structural analysis result for HTT with all loads combined
Integrated HTP stress analysis	NSTXU-CALC-12-26-00	Provides structural analysis result for HTP with all loads combined
Integrated helium connection line calculation	NSTXU_1-1-3-3-9_CALC_100	Provides structural analysis result for helium inter-connection lines with all loads combined

Prototyping - HTP

First Machining and EB Welded



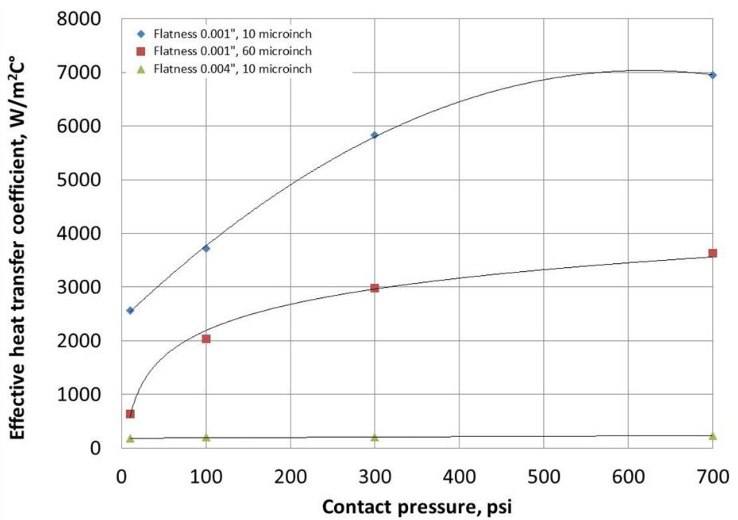


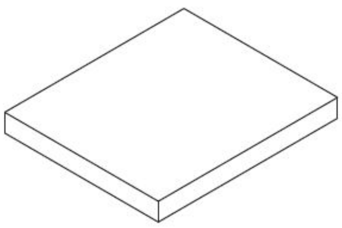
Full penetration EB welds for cooling channel

Full penetration EB welds for inlet/outlet tube

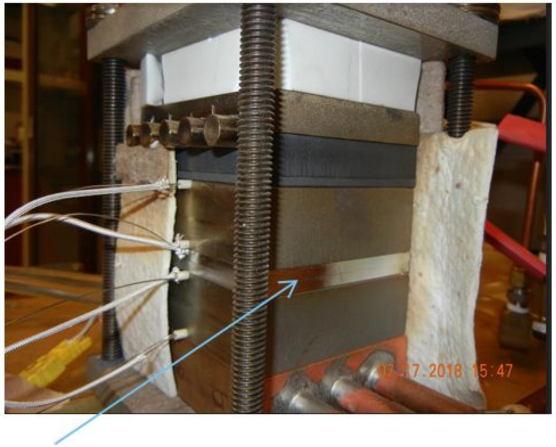
- Heat Transfer Plate Prototyping was successfully completed to test vacuum EB welding with full penetration weld and minimum heat affected zone
- ¾” thick plate for first machining. After post weld machining the plate thickness is about 0.69” with a flatness of 0.003” on both top and bottom sides
- Specifications for the full penetration welds and the final plate flatness were met

Prototyping - Thermal Contact Resistance

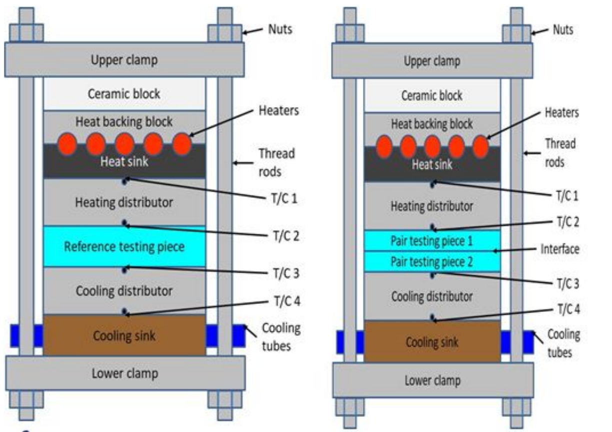




Inconel 625 samples,
3.5”X3”X(0.35”/0.175”)



Inconel samples



- Test thermal contact resistance between inconel 625 surfaces with surface gap, surface finish and contact pressure
- Gap from 0.001” to 0.004”
- Surface finish from 10 microinch to 60 microinch tested
- Pressure from 0 to 700 psi
- 300w/m^{2}K has been used for effective thermal contact conductance

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All Casing Related Chits have been Closed

Chits closed after FDR for all the Center Stack Casing related HTT/HTP components

Chits for interconnection lines (FDR 12/17/2019) are expected to be closed in a few weeks. These chits were addressed and currently going through the review and approval process.

National Spherical Torus eXperiment Upgrade

Chit Resolution Report
for
Center Stack Heating/Cooling Transfer Tubes (HTT) & Plates (HTP)

NSTX-U-REC-093-01

Prepared By: Christopher Pagano — Digitally signed by Christopher Pagano Date: 2019.02.19 14:52:47 -05'00'
C. Pagano, Engineer

Reviewed By: Dang Cai
D. Cai, Cognizant Engineer

Approved By: G Douglas Loesser
D. Loesser, Responsible Engineer

Approved By: Yuhu Zhai
Y. Zhai, Project Engineer

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Chit Resolution Report: link

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Procurement, Fabrication, Installation, and Test

All Center Stack Casing related components have been fabricated

Leak checking and hydraulic pressure testing have been performed

These components will be installed onto Center Stack Casing by the casing vendor, Holtec

Leak checking after Center Stack Casing completion will be performed by Holtec

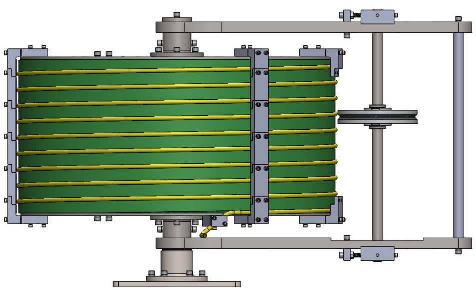
Water and helium interconnection components will be fabricated, installed and tested in house after 3B approval

HTT Fabrication: Completed

PPPL Design → HandyTube → GJ Oliver → PPPL C-MG → HollisLine → Complete

Princeton Plasma Physics Laboratory Procedure		
Procedure Title: Winding and Bending of the HTT		
Number: C-NSTXU-FP-VVHW-011	Revision: 00	Effective Date: 10/16/2019 Expiration Date: (3yr. unless otherwise stipulated)
CAT: ☒A1 ☐A2 ☐A3	Justification: (If required) CE and/or ES&H Head:	
Author: S. Sheckman		Date
Responsible Engineer: D. Loesser		Date

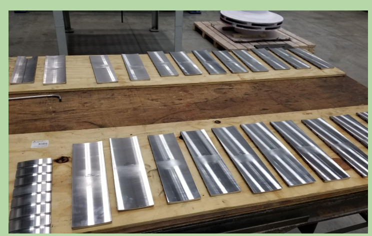
HTT Bending Procedure



HTT Bending Fixture CAD

At GJ Oliver: Mandrel Fabrication

At GJ Oliver: Completed Mandrel



At GJ Oliver: Diced Clamps

At PPPL C-MG:Preparing HTT for Heat Treatment

At PPPL C-MG: HTT after Bending Procedure

Completed HTT at Hollisline

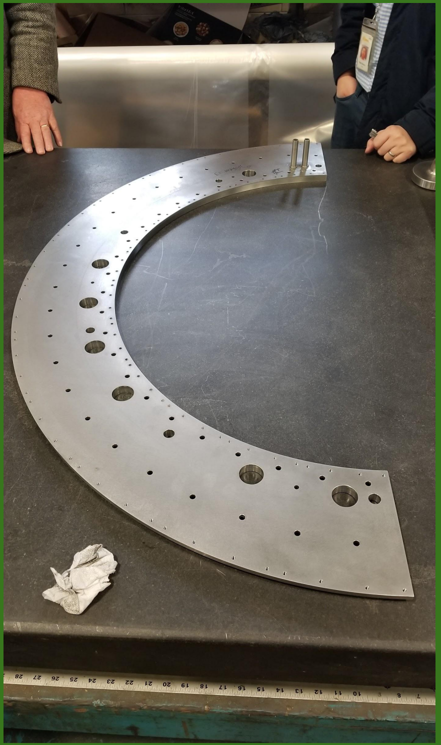
HTP Fabrication: Completed

PPPL Design → Corrosion Metals → HollisLine → PTR E-Beam → HollisLine → Complete

HTP Inconel 625 Plates after Water-Jetting

Final Machining Processes

PTR: E-Beam Welds



Completed HTP

Title-III Engineering of the HTT/HTP are Fully Supported - NCRs

NCR Item	NCR Number	Description of the Issue
Vendor NCR	NCR1978-1	Mandrel Nonconforming, used to test A3 bending methods. E-DC11074
Vendor NCR	NCR-Princeton #002	Welds made convex instead of concave, welds ground flush with surface. E-DC11174-01, E-DC11174-02, E-DC11174-03, E-DC11174-04
PPPL NCR	NCR4049	A-1 Procurement without Supplier Qualification for HTP
PPPL NCR	NCR4094	Dimension out of tolerance on E-DC11074
PPPL NCR	NCR4088	E-DC11225-1, HTT Outerform rework after heat treatment deformation
Vendor NCR	NCR#002	Dimension out of tolerance on E-EB1089-3

All NCR’s resolved without issue.

Title-III Engineering of the HTT/HTP are Fully Supported - ECNs

Drawing Number	ECN Number	Description of the Change
E-DC11073	ECN8201	Material Change to Inconel 625, Bend radius increased
E-DC11074	ECN8201	Tolerance increased, Notes added
E-DC11074	ECN8214	Add zero orientation, Notes added, Manufacturing details added
E-DC11198	ECN8201	Bolts and corresponding Tap changed to 1”-8 thread
E-EB1089	ECN8201	Material Changed to Inconel 625
E-DC11124	ECN8201	Change GD&T requirement, Add inspection to EB weld
E-DC11124	ECN8290	Dimension change
E-DC11125	ECN8201	Change GD&T requirement, Add inspection to EB weld
E-DC11125	ECN8290	Dimension change
E-DC11225	ECN8201	Tolerance increased, Weld Note added

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Project Risks are Actively Being Managed

HTT / HTP control account initially had five Level II and three Level III retired risks

- All risks now retired or rolled up:
  - Two of the LII and three of the LIII risks were retired with the successful FDR
  - One risk was retired because it was a standard test used in construction
  - The final two risks for potential leaks and fit-up issues have been rolled into Project risks with similar issues

Prototype program improves confidence in component design and vendor capabilities, as well as projected cost and schedule performance.

- QA/QC observations of their process,
- Leak checking
- Pressure testing
- Flatness demonstrated to be achievable

FMECA for HTT and HTP (1)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Horizontal Target Cooling System (HTP)	Failure of welded interface of HTP He feedthrough to CS casing	Excessive disruption loads; thermal stresses	Vacuum leak	12	DCPS Software	None	Vacuum Gauges and Residual Gas Analyzers	4
Horizontal Target Cooling System (HTP)	Failure of welded interface of feedthrough tubes to plates themselves	Excessive disruption loads	He leak into vacuum chamber; must pumpt down HTP, unable to use it for heating/cooling; repair next outage	12	DCPS Software	None	Vacuum Gauges and Residual Gas Analyzers	4
Horizontal Target Cooling System (HTP)	Failure of bolts which hold the HTP in place	excessive disruption loads	He may become loose, creating leaks in fittings	12	None	DCPS Software	None	4
Horizontal Target Cooling System (HTP)	Failure of e-beam weld on main cooling channel of the HTP	excessive disruption loads	He leak into vacuum chamber; must pumpt down HTP, unable to use it for heating/cooling; repair next outage	12	DCPS Software	None	Vacuum Gauges and Residual Gas Analyzers	4
Vertical Target Cooling System (HTT)	Water leak at interface of HTT to hose	Vibration works the joints loose, damage to hose fitting during maintenance or nearby work.	Water leaks into the casing resulting microtherm damage, insulators being compromised, water on leads of inactive coils	9	FCPC Ground Fault Detection	Vessel and Diagnostic Grounds	Shorted Turn Protection System	6

FMECA for HTT and HTP (2)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Horizontal Target Cooling System (HTP)	Failure of pins that provide alignment	excessive disruption loads overcome centering/alignment features	heat flux asymmetries	9	Plasma TV	DCPS Software	None	4
Horizontal Target Cooling System (HTP)	Failure of fittings in ex-vessel tubing	Excessive disruption loads	He leak to air; may attempt to pump down; HTP not usable; must repair next outage	6	None	None	None	6
Vertical Target Cooling System (HTT)	Water leak at joint between 1/4" and 3/8" sections of pipe	Vibration works the joints loose	Water leaks into the casing resulting microtherm damage, insulators being compromised, water on leads of various coils	4	FCPC Ground Fault Detection	Vessel and Diagnostic Grounds	Shorted Turn Protection System	4
Vertical Target Cooling System (HTT)	Water leak at right-angle connection under the casing flange	Vibration works the joints loose	Water leaks into the casing resulting microtherm damage, insulators being compromised, water on leads of various coils	4	FCPC Ground Fault Detection	Vessel and Diagnostic Grounds	Shorted Turn Protection System	4

15 total FMs identified, all those with unacceptable risk have been mitigated
Primary Mitigation - DCPS ensures that loads are limited to those in the design basis

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Quality, Environment, Safety, and Health

- The design meets the GRD requirement to not have water in the vessel
- Maximum helium operation pressure 300 PSIG
- Helium burst disc set at 315 PSIG
- HTT and HTP will be pressure tested to 1.5 times of maximum operation pressure
- Tubing and VCR fitting are rated over 3000 PSIG at room temperature
- 316L SS VCR fitting and gasket are rated at 517C
- No potential radiological impact of item/activity failure

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- Requirements have been met via a combination of analysis, test and prototyping.
- Interfaces are considered in the design and documented in the ICDs
- All chits related to the center stack casing related HTT/HTP components are closed. Chits for water and helium interconnection lines were addressed and under review/approval
- All the center stack casing related HTT/HTP components have been fabricated
- Risks are mitigated through:
  - Thermal contact resistance test
  - HTP prototype
- Hazards are typical industrial hazards, mitigated by the PPPL worker safety and health program (ES&H 5008 "Safety Manual")