National Spherical Torus eXperiment Upgrade

Thermal Analysis Requirements

NSTX-U-RQMT-RD-013-01

11/11/19

Stefan Gerhardt Digitally signed by Stefan Gerhardt Date: 2019.11.11 07:29:20 -05'00'

Prepared By: Stefan Gerhardt, Systems Integration

Han Zhang Digitally signed by Han Zhang Date: 2019.11.12 14:53:05 -05'00'

Prepared By: Han Zhang, Bakeout Analysis

Joseph R_ Petrella Jr_ Digitally signed by Joseph R_ Petrella Jr_ DN: C=US, O=PPPL, CN=Joseph R_ Petrella Jr_, E=jpetrell@pppl.gov Reason: I have reviewed this document Location: Date: 2019-11-12 15:20:09

Reviewed By: Joe Petrella, Bakeout RE

Timothy N. Stevenson Digitally signed by Timothy N. Stevenson Date: 2019.11.13 09:20:33 -05'00'

Reviewed By: Tim Stevenson, Operations and Safety Systems RE

Peter H. Titus Digitally signed by Peter H. Titus Date: 2019.11.13 19:33:53 -05'00'

Reviewed By: Pete Titus, Analysis Technical Authority

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2019.11.14 07:52:45 -05'00'

Approved By: Yuhu Zhai, Project Engineer

Change Record

Revision	Date	Description of Change
0	12/13/17	Initial Release
1	11/11/19	Updated signature list and titles
		Updated the helium skid outlet temperature
		Placed legacy material from Section 3 in Section 3.1
		Added the thermal transient scenarios (LoH, LoHC, RSU) as a new Section 3.2
		Added the requirement to define recommended controlled startup and shutdown scenarios in new Section 3.2
		Added Table 2.6 regarding normal operations failure LoV scenarios.

References:

[1] NSTX-U-RQMT-GRD-001, *NSTX-U General Requirements Document*

1. Background

The GRD [1] in tables 4.1.5-2 and 4.1.5-3 provides guidance on power partitioning during plasma discharges. This memo provides additional guidance on how the power should be distributed for the purposes of global thermal analysis, including global ratcheting analysis. It is not intended to be used for detailed PFC studies.

This memo also provides information for the bakeout assessment.

2. Plasma Scenarios to Model

There are five plasma scenarios to assess, as given in Table 2-1 with quantitative description given in Tables 2-2 through 2-4. Note that these are not expected to be consistent with those given in the PFC System Requirements Document, and represent slightly elevated power/energy input into various PFC regions.

Table 2-1*: Description of the five plasma scenarios.*

Scenario #	Scenario Description
1	Conducted power to near-midplane portion of IBDV and IBDH, 10.5 MW, 5 Seconds, H-mode
2	Conducted power to mid-height portion of IBDV and IBDH, 10.5 MW, 5 Seconds, H-mode
3	Conducted power to near-midplane portion of IBDV and Row 1/2 OBD, 10.5 MW, 5 Seconds, H-mode
4	100% radiated power, 10.5 MW, 5 seconds, H-mode
5	Conducted power to CSAS and Far OBD, 2 seconds, 3 MW, L-mode

The power or energy applied to each surface is composed of a direct conducted power, and radiated power. The conducted power represents the power in the form of plasma directed by the magnetic field to the surface of the PFC. The radiated power is that which is radiated by the plasma, and distributed over the full inner surface of the vessel.

The energy conducted to specific PFC surfaces for the 5 scenarios is indicated in Table 2-2. This power is deposited over finite regions of specific PFC surfaces. Note that the dR and dZ are full widths, i.e., the extent of heating is dR/2 on either side of central radius, dZ/2 on either size of the central height. Note also that for the vertical target, the central heating location is given negative, corresponding to the lower target. The upper target heating should use the same coordinates, reflected over the midplane.

***Table 2-2**: Energy partitioning of the five plasma scenarios.*

			Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5
		DN ->	1	1	1	1	0
		Power [MW] ->	10.5	10.5	10.5	10.5	3
		Duration [s] ->	5	5	5	5	2
Conducted Power, Vertical Target	Conducted power to tile surface during shot	MW	0.735	0.735	0.735	0.000	0.000
	Center of Power	m	-1.320	-1.450	-1.320	-1.350	-1.350
	dZ of Power	m	0.050	0.050	0.050	0.100	0.100
	Upper Target Conducted Power Density	MW/m^2	5.441	5.441	5.441	0.000	0.000
	Upper Target Conducted Energy	MJ	3.675	3.675	3.675	0.000	0.000
	Lower Target Conducted Power Density	MW/m^2	5.441	5.441	5.441	0.000	0.000
	Lower Target Conducted Energy	MJ	3.675	3.675	3.675	0.000	0.000
Conducted Power, Horizontal Target	Conducted power to tile surface during shot	MW	2.940	2.940	0.000	0.000	0.000
	Center of Power	m	0.540	0.540	0.580	0.580	0.580
	dR of Power	m	0.120	0.120	0.100	0.100	0.100
	Upper Target Conducted Power Density	MW/m^2	7.221	7.221	0.000	0.000	0.000
	Upper Target Conducted Energy	MJ	14.700	14.700	0.000	0.000	0.000
	Lower Target Conducted Power Density	MW/m^2	7.221	7.221	0.000	0.000	0.000
	Lower Target Conducted Energy	MJ	14.700	14.700	0.000	0.000	0.000
Conducted Power, Outer Target	Conducted power to tile surface during shot	MW	0.000	0.000	2.940	0.000	1.470
	Center of Power	m	0.650	0.650	0.650	0.800	0.970
	dR of Power	m	0.100	0.100	0.100	0.100	0.052
	Upper Target Conducted Power Density	MW/m^2	0.000	0.000	6.649	0.000	0.000
	Upper Target Conducted Energy	MJ	0.000	0.000	14.700	0.000	0.000
	Lower Target Conducted Power Density	MW/m^2	0.000	0.000	6.649	0.000	4.284
	Lower Target Conducted Energy	MJ	0.000	0.000	14.700	0.000	2.940
Conducted Power, CS Angled Section	Conducted power to tile surface during shot	MW	0.000	0.000	0.000	0.000	0.630
	Center of Power, Radial	m	0.400	0.400	0.400	0.400	0.425
	dR of Power	m	0.050	0.050	0.050	0.050	0.020
	Density	MW/m^2	0.000	0.000	0.000	0.000	0.000
	Upper Target Conducted Energy	MJ	0.000	0.000	0.000	0.000	0.000
	Lower Target Conducted Power Density	MW/m^2	0.000	0.000	0.000	0.000	5.531
	Lower Target Conducted Energy	MJ	0.000	0.000	0.000	0.000	1.260

The radiated power flux to components associated with each scenario is provided in table 2-3. The radiated power fraction is assumed to be 30%, except for the 100% radiated power in Scenario #4. This power is radiated uniformly from the plasma, resulting in energy deposition on the various surfaces as in the table. These energies should be distributed uniformly over the surfaces, i.e. the 4.379 MJ on the CSFW from Scenario #1 should be distributed uniformly on the CS.

***Table 2-3**: Radiated power assumptions for the five scenarios*

			Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5
		DN ->	1	1	1	1	0
		Power [MW] ->	10.5	10.5	10.5	10.5	3
		Duration [s] ->	5	5	5	5	2
Radiated Power	Uniformly Radiated Power	MW	3.150	3.150	3.150	10.500	0.900
	Uniformly Radiated Energy	MJ	15.750	15.750	15.750	52.500	1.800
	CSFW, Energy	MJ	4.379	4.379	4.379	14.595	0.500
	CSA, Upper, Energy	MJ	0.457	0.457	0.457	1.523	0.052
	IBDV, Upper, Energy	MJ	0.410	0.410	0.410	1.365	0.047
	IBDH, Upper, Energy	MJ	0.221	0.221	0.221	0.735	0.025
	OBD, Upper, Energy	MJ	1.103	1.103	1.103	3.675	0.126
	SPP, Upper, Energy	MJ	1.071	1.071	1.071	3.570	0.122
	PPP, Upper, Energy	MJ	1.276	1.276	1.276	4.253	0.146
	FW, Energy	MJ	2.300	2.300	2.300	7.665	0.263
	PPP, Lower, Energy	MJ	1.276	1.276	1.276	4.253	0.146
	SPP, Lower, Energy	MJ	1.071	1.071	1.071	3.570	0.122
	OBD, Lower, Energy	MJ	1.103	1.103	1.103	3.675	0.126
	IBDH, Lower, Energy	MJ	0.221	0.221	0.221	0.735	0.025
	IBDV, Lower, Energy	MJ	0.410	0.410	0.410	1.365	0.047
	CSA, Lower, Energy	MJ	0.457	0.457	0.457	1.523	0.052

Specific rules used in these computations are given in Table 2.4.

***Table 2-4**: Specific rules used to construct the information in Tables 2-2 & 2-3*

Radiated Power Fraction	30% (except Scenario 4)
Double Null In-Out Split of Conducted Power	80% Out, 20% In, and 50% up, 50% down
Lower Single Null Split of Conducted Power	70% Out, 30% In, and 100% toward dominant X-point
Poloidal Distribution of Radiated Power	scaled from estimation of power fluxes to regions during 10.4 MW scenario[1]

For these scenarios, three cooling schemes shall be assumed, as in Table 2-5.

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[1] If desired, the following values may be used (all in MW/m^2): CSFW: 0.70, CSAS: 0.50, IBDV: 0.30, IBDH: 0.30, OBD: 0.30, SPP: 020, PPP: 0.20, FW: 0.15. These numbers are estimates only and depend on plasma shape and operational scenario.

***Table 2-5**: Cooling schemes*

Cooling Scheme	Baseline	Upgraded 1	Upgraded 2
OH & PF Water	15 C Water	15 C Water	15 C Water
IBDV	15 C Water	15 C Water	15 C Water
IBDH	He Cooling Plate, 280 PSI	He Cooling Plate, 280 PSI	He Cooling Plate, 280 PSI
Vessel	Radiation to Atmosphere	Radiation to Atmosphere	15 C Water
OBD/PPP Cooling Loops	inert	He Cooling, 280 PSI	inert

Consistent with the GRD repetition rate assertions (4.1.4a), the internal components of the system shall operate with a 2400 second repetition rate under the baseline cooling, and a 1200 second repetition rate on one of the Upgraded cooling schemes.

For analysis, graphite plasma facing component surfaces shall be assumed to have an emissivity of 0.7.

In addition, the Normal Operations Loss of Vacuum Scenarios in Table 2-6 shall be assessed to provide assurance of safe operations, in particular rapid thermal contraction resulting in component collision or large thermal stresses. These may be assessed by FEA or simple limit analysis.

***Table 2-6**: Time dependent scenarios - normal operations*

	Description	Scenario	Starting Condition	Vacuum Condition	Inner-PF and OH Coil Cooling Scenario	Ceramic Break Cooling Loop	Outer Vessel Forced Cooling (Fans)
NOLoV -1	Normal Operations Loss of Vacuum	At the end of the run day, with fully ratched thermal conditions, vacuum is lost. Can be either air or Ar from the argon purge system. All cooling retained.	Fully ratcheted thermal conditions at the end of the run day	Atmospheric pressure of either Ar or air	On	On	Off
NOLoV -2	Normal Operations Loss of Vacuum	At the end of the run day, with fully ratched thermal conditions, vacuum is lost. Can be either air or Ar from the argon purge system. Cooling lost as well	Fully ratcheted thermal conditions at the end of the run day	Atmospheric pressure of either Ar or air	Off	Off	Off

3. Bakeout Scenarios to Model

3.1 Static Assumptions

The bakeout simulations shall be done under the following assumptions:

Table 3.1-1*: Assumptions for bakeout*

He Pressure @ skid	PSI	280
He Temperature @ skid	°C	440
OH, TF, and PF Cooling Water[2]	°C	15
CS Casing Current	kA	<=8

The air side vacuum vessel water system shall add or subtract heat in order to maintain an average vessel temperature of 150 C.

It can be assumed that hot He is utilized on the following components:

- Neutral beam armor
- Upper and lower secondary and primary passive plates
- Upper and lower outboard divertors
- Upper and lower horizontal target cooling plate

[2] Flow rate is limited by the coil design and the NTC supply pressure, listed in the cooling water SRD.

The distribution of He flow amongst the various paths shall be based on the relative conductance of the paths.

For analysis, graphite plasma facing component surfaces shall be assumed to have a nominal emissivity of 0.7; sensitivity analysis may be performed for other values of emissivity.

3.2 Transient Scenarios

The time dependent analysis scenarios shall be considered for bakeout:

***Table 3.2-1**: Time dependent scenarios - Bakeout*

	Description	Scenario	Starting Condition	Heating Scenario	Vacuum Condition	Inner-PF and OH Cooling Scenario	Ceramic Break Cooling Loop	Outer Vessel Forced Cooling (Fans)
LoH	Bakeout System Trip	Any number of system faults (breaker trips, He leaks, blower trips) shuts down all heating systems, while water cooling remains	Equilibrated full bakeout temperature (unless otherwise specified)	Ex-vessel water heater- off Hot He - off DC Current - off	Vacuum maintained throughout	Full cooling flow retained	Full cooling flow retained	On
LoHC	D-Site power outage	Complete power loss to D-site	Equilibrated full bakeout temperature (unless otherwise specified)	Ex-vessel water heater- off Hot He - off DC Current - off	Vacuum maintained throughout	Potable water flow applied after 60 minute delay (60 PSIG Head Pressure)	Off	Off
BLoV	Bakeout Loss of Vacuum	Failure of vacuum window during bakeout brings causes NSTX-U internal pressure to equilibrate with atmosphere	Equilibrated full bakeout temperature (unless otherwise specified)	Ex-vessel water heater- off Hot He - off DC Current - off	Vacuum lost; vessel fill with air	Full cooling flow retained	Full cooling flow retained	On
BRSU	Rapid Start up	Heating systems turned on with full energy	All PFCs and vessel components at room temperature	Ex-vessel water- full on Hot He - full on DC Current - full on	Vacuum maintained throughout	Full cooling flow retained	Full cooling flow retained	On

Here, the scenarios mean the following:
LoH - Loss of Heating (always for bakeout)
LoHC - Loss of Heating and Cooling (always for bakeout)
BLoV - Bakeout Loss of Vacuum
BRSU - Bakeout Rapid Start Up

Recommended evolutions for controlled start-up and controlled shut-down of the bakeout system shall be provided. These scenarios shall be shown to tolerate the LoH, LoHC & LoV scenarios at any point during the ramp-up or ramp-down. Alternatively, the allowed range of in-out temperature differentials[3] shall be provided which allow projection of the safe trajectory to and from the high-temperature operating point (here, safe implies that the LoH, LoHC, and LoV scenarios may safely occur at any allowed temperature differential).

[3] Here, the in-out temperature differential is defined as the difference in temperatures between the inboard structures (CS casing, or CS tiles as a surrogate) and the outer vessel.