NCSX

Design Basis Analysis

Vacuum Vessel Heating/Cooling Distribution System Thermo-hydraulic Analysis

NCSX-CALC-12-002

02 November 2004

Prepared by:

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct. I concur with analysis methodology and inputs and with the reasonableness of the results and their interpretation.

Reviewed by:

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Introduction

The NCSX vacuum vessel utilizes external tracing tubes and gaseous helium to provide heating during bakeout and standby operation of the vessel and cooling of the vessel after operational shots. An analysis was performed to determine the size and number of coolant lines required to deliver the prescribed quantity of heating/cooling and to determine the thermo-hydraulic parameters of the system. A 1-D analysis was performed to determine the steady state operating temperature of the vessel wall, i.e. the degree of thermal ratcheting that may be expected.

Performance Requirements and Criteria

The NCSX Vacuum Vessel Systems Requirements Document, NCSX-BSPEC-12-00 requires that:

- The vacuum vessel and interior components must be capable of baking at 350 C and maintained at 40-80 C before and after operational shots.
- Upgrade operation will use 12 MW of heating for 1.2 seconds duration.
- The vessel must be operated with a rep rate of fifteen minutes at maximum heat operation.

Assumptions

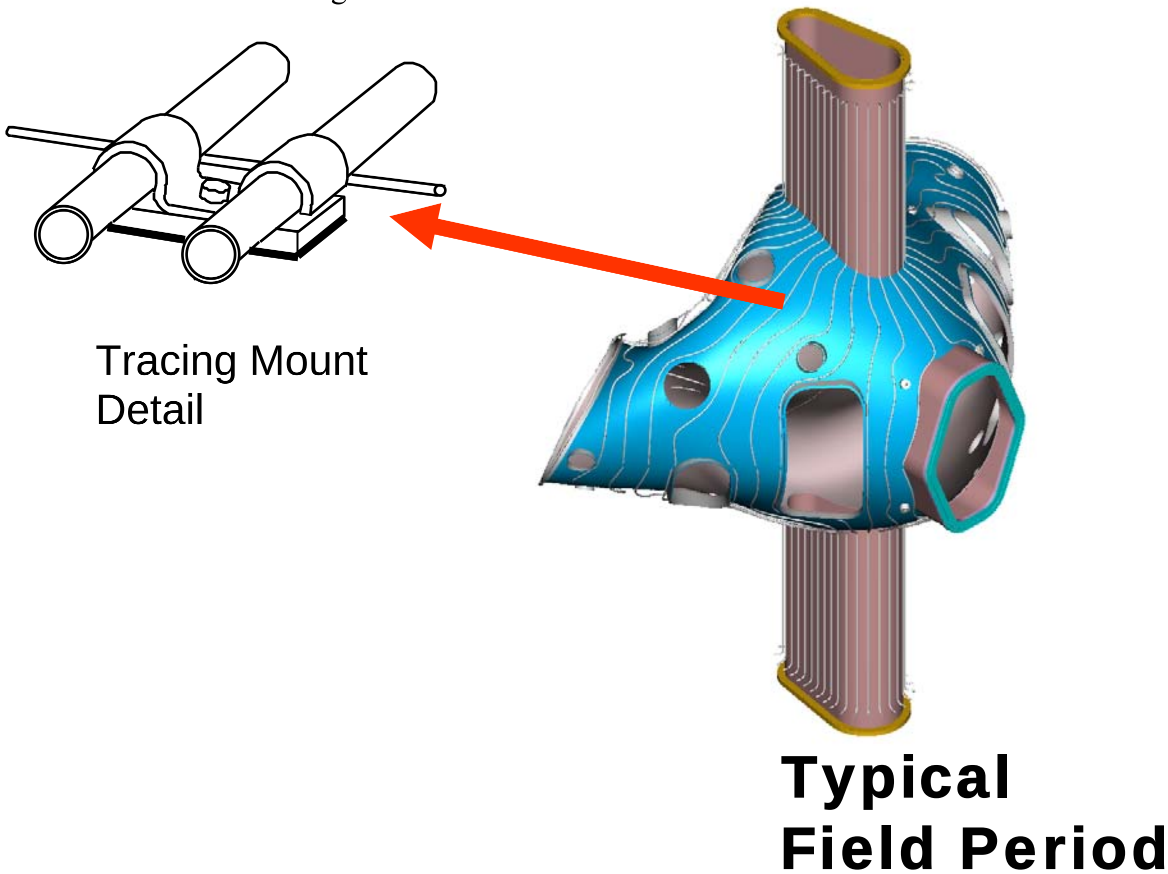
Heat input and output. These values were determined by DAC NCSX-CALC-12-003-00, Heat Balance of the NCSX Vacuum Vessel During Operation and Bakeout.

- The minimum heat input required by the tracing during steady state bakeout of the vessel is 17 kW.
  The analysis assumes even heat distribution to the VV vessel wall during bakeout with the ports maintained at 150 C at the flange ends and 350 C at the vessel ends. The port temperatures are maintained by resistance heaters and their input is taken into account by the above referenced DAC.

- The average heat removal during operation is 16 kW.
  The maximum temperature rise of the vessel after a shot is 11.7 C, determined by assuming the heat is evenly distributed. This is essentially correct if it assumed that there will be PFC tiles which intersect the heat and redistribute it to the vessel wall.

- Tracing Configuration
  Preliminary design work assumed 150 C bakeout, tracing tubes continuously attached to the vessel by welding and/or grouting, and a maximum spacing of 8 inches on center. This spacing resulted in a configuration using 16 parallel tubes on each of the vessel half-periods; a total of 96 for the entire vessel. The change to 350 C bakeout resulted in a new configuration which attaches the tubes with individual brackets. It also increases the heating requirements for the tubes. The old configuration will not supply the required mass flow unless the tubing diameter is a minimum of 3/8”

diameter, a size which may prove difficult to bend and fit into the envelope reserved for insulation and heating components. It is also marginal from the standpoint of heat transfer area unless a great number of brackets are used.



As a result, the configuration chosen utilizes pairs of smaller diameter tubes sharing common mounting brackets. The individual tubes in the pairs connect to separate supply and return headers. There are 16 pairs of tubes on each of the half-field periods, or a total of 192 parallel tubes on the vessel.

Thermo-Hydraulics

Methodology
The analysis was performed on MICROSOFT EXCEL using standard fluid flow equations and iterating to find the net pressure drop across the parallel flow circuits.
The vessel temperature, tubing diameter, helium flow rate, and system pressure were input as variables. The outputs from the spreadsheet were, helium temperature changes, film coefficients, friction coefficient, Reynolds numbers, tube wall temperatures, exit velocity, total heat transfer, and the net pressure drop. The tubing pairs were assumed to be identical, centering on the same trajectory as the original layout using a single larger tube.

Material Properties

20 atmosphere Helium at 20 C	
spec ht(J/g-K)	5.19
density(g/cm^3)	0.0032
cond.(w/cm-K)	0.00154
dyn visc.(g/cm-s)	1.99E-04
diffusivity (cm^2/s)	9.27E-02
Prandtl	0.67
He kin. visc. (cm^2/s)	6.22E-02

20 atmosphere Helium at 350 C	
spec ht(J/g-K)	5.20
density(g/cm^3)	0.0020
cond.(w/cm-K)	0.0034
dyn visc.(g/cm-s)	3.96E-04
diffusivity (cm^2/s)	1.52E-01
Prandtl	0.65
He kin. visc. (cm^2/s)	9.83E-02

Inconel	
spec ht(J/g-K)	0.42
density(g/cm^3)	8.03
cond.(w/cm-K)	0.121
diffusivity (cm^2/s)	0.036

Results

The mass flow requirements are driven by the requirements to operate the vessel with a fifteen minute rep rate, not by bakeout. A Helium system operated at 20 atmospheres pressure with 1/4 inch diameter tubing is adequate for bakeout but unacceptable for cool down. 5/16 inch diameter tubing (0.28 inch wall) meets the requirements of both with a comfortable margin.
The bulk temperature rise during cooling is based on simple mass balance with continuous heat transfer from the tubing. When the intermittent nature of the mounting is taken into account, it is found that the wall temperature must ratchet up above the coolant media before energy balance is achieved. This is confirmed in the referenced DAC NCSX-CALC-12-001-00.

The following results assume 5/16” tubing.
Flow characteristics at room temperature operation.

Item No	Model No	Length (in)	Length (cm)	Pressure Drop atmos	Mass flow (g/s)	Re	f	w/cm^2-K h	Temp Rise bulk dT(K)	Bulk temp(C)	Exit vel m/s	Inlet vel m/s
1	SE123-011.PRT	180.6	458.8	0.291	3.51	34777	0.02	0.20	4.04	24.04	33.42	32.97
2	SE123-012.PRT	173.8	441.4	0.291	3.58	35452	0.02	0.20	3.87	23.87	34.06	33.62
3	SE123-013.PRT	171.5	435.7	0.291	3.60	35684	0.02	0.20	3.81	23.81	34.28	33.84
4	SE123-014.PRT	191.6	486.8	0.291	3.41	33762	0.02	0.19	4.31	24.31	32.46	31.99
5	SE123-015.PRT	190.6	484.2	0.291	3.42	33853	0.02	0.19	4.28	24.28	32.55	32.08
6	SE123-016.PRT	194.7	494.7	0.291	3.38	33491	0.02	0.19	4.38	24.38	32.21	31.73
7	SE123-017.PRT	207.5	527.1	0.291	3.28	32444	0.02	0.19	4.70	24.70	31.22	30.72
8	SE123-018.PRT	215.9	548.5	0.291	3.21	31806	0.02	0.19	4.91	24.91	30.61	30.11
9	SE123-019.PRT	245.3	623.0	0.291	3.01	29844	0.02	0.18	5.65	25.65	28.76	28.22
10	SE123-020.PRT	246.2	625.2	0.291	3.01	29789	0.02	0.18	5.67	25.67	28.71	28.16
11	SE123-021.PRT	256.1	650.5	0.291	2.95	29205	0.02	0.17	5.93	25.93	28.16	27.60
12	SE123-022.PRT	232.1	589.6	0.291	3.10	30677	0.02	0.18	5.32	25.32	29.55	29.02
13	SE123-023.PRT	215.6	547.5	0.291	3.21	31834	0.02	0.19	4.90	24.90	30.64	30.14
14	SE123-024.PRT	251.7	639.3	0.291	2.97	29460	0.02	0.17	5.81	25.81	28.40	27.85
15	SE123-025.PRT	262.2	666.1	0.291	2.91	28861	0.02	0.17	6.08	26.08	27.83	27.27
16	SE123-026.PRT	236.2	600.0	0.291	3.07	30410	0.02	0.18	5.42	25.42	29.29	28.76
		av.(m)	5.5		51.63		av	0.19	4.94			
		total(m)	1058.2	av.	3.23							

Average heat transfer is 15.9 kW.

Flow characteristics at 350 C.

Item No	Model No	Length (in)	Length (cm)	Pressure Drop (atmos)	Mass flow (g/s)	Re	f	Film coef (w/cm^2-K) h	Temp drop bulk dT(K)	Bulk temp(C)	Exit vel (m/s)	Inlet vel (m/s)
1	SE123-011.PRT	180.6	458.8	0.099	1.3	6588	0.035	0.117	15.9	351.1	19.1	19.5
2	SE123-012.PRT	173.8	441.4	0.099	1.4	6716	0.035	0.119	15.2	351.8	19.5	19.9
3	SE123-013.PRT	171.5	435.7	0.099	1.4	6760	0.035	0.120	15.0	352.0	19.6	20.1
4	SE123-014.PRT	191.6	486.8	0.099	1.3	6395	0.035	0.114	16.9	350.1	18.5	19.0
5	SE123-015.PRT	190.6	484.2	0.099	1.3	6413	0.035	0.115	16.8	350.2	18.5	19.0
6	SE123-016.PRT	194.7	494.7	0.099	1.3	6344	0.035	0.114	17.2	349.8	18.3	18.8
7	SE123-017.PRT	207.5	527.1	0.099	1.2	6146	0.036	0.111	18.5	348.5	17.7	18.2
8	SE123-018.PRT	215.9	548.5	0.099	1.2	6025	0.036	0.109	19.3	347.7	17.3	17.8
9	SE123-019.PRT	245.3	623.0	0.099	1.1	5653	0.036	0.104	22.2	344.8	16.1	16.7
10	SE123-020.PRT	246.2	625.2	0.099	1.1	5643	0.036	0.104	22.3	344.7	16.1	16.6
11	SE123-021.PRT	256.1	650.5	0.099	1.1	5532	0.037	0.102	23.3	343.7	15.7	16.3
12	SE123-022.PRT	232.1	589.6	0.099	1.2	5811	0.036	0.106	20.9	346.1	16.6	17.2
13	SE123-023.PRT	215.6	547.5	0.099	1.2	6030	0.036	0.109	19.3	347.7	17.3	17.8
14	SE123-024.PRT	251.7	639.3	0.099	1.1	5581	0.037	0.103	22.9	344.1	15.9	16.5
15	SE123-025.PRT	262.2	666.1	0.099	1.1	5467	0.037	0.101	23.9	343.1	15.5	16.1
16	SE123-026.PRT	236.2	600.0	0.099	1.2	5760	0.036	0.105	21.3	345.7	16.4	17.0
		total (m)	1058.2	total	19.6		av	0.110	19.4			
		av.(m)	5.51	av.	1.23							

Net heat transfer is 23.7 kW.

Thermal Response Time During Operation

Methodology

A 1-D hand analysis was performed using MICROSOFT EXCEL, assuming a plate of fixed width with cooling at each edge. The inverse Biot number and Fourier moduli were determined to extract the corresponding temperature functions from the Heisler chart for the centerline temperatures of a finite slab. The computation was repeated for 15 minute cycles until the temperature reached steady state. The results may be seen on the following graph.

Geometry

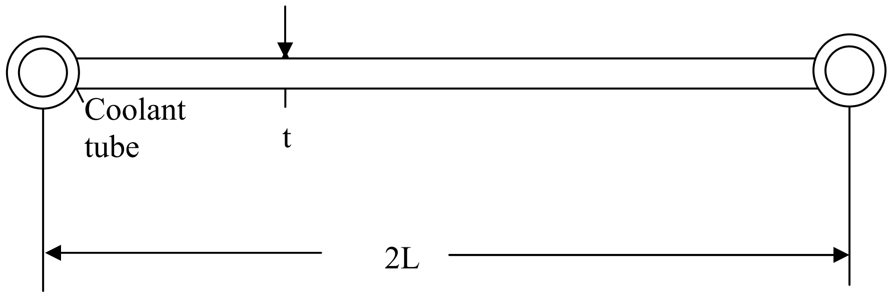
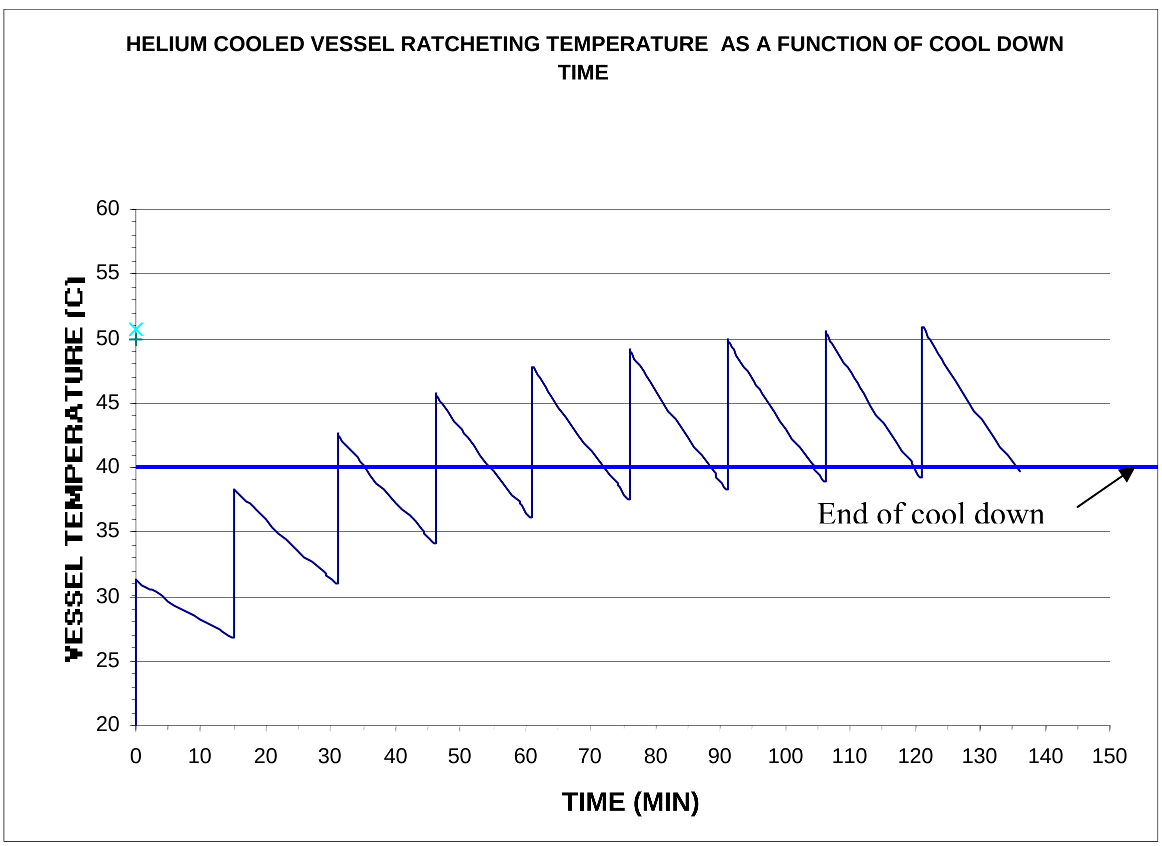


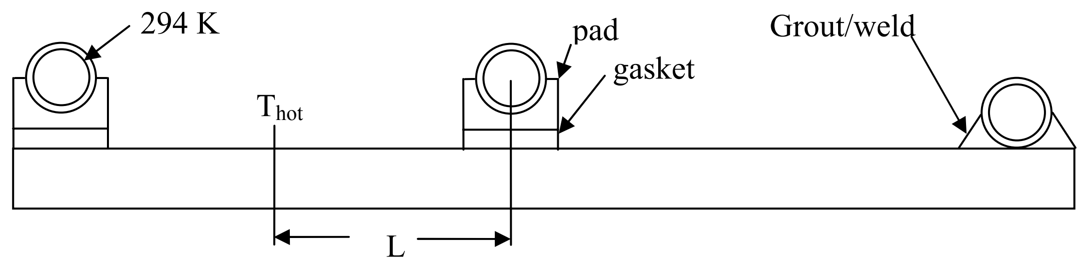
Plate half width L	4 inches
Tube ID	0.257 inches (0.65 cm)
Inconel thickness t	0.375 inches
Losses to cryostat are included.

Results
The vessel wall temperature ratchets up until it reaches 40 C at the end of the cool down periods and stays constant from there on.



RESULTS SUMMARY

A comparison of the temperature gradients in the vessel wall using different geometry is shown below. The temperatures are after cool down and steady state ratcheting is achieved. The values for the cases using pads and gaskets were obtained from DAC NCSX-CALC-12-001-00.



	WELD/GROUT	GRAFOIL PAD GRID		
	8” CENTERS	8” X 10”	6” X 6”	4” X 4”
ΔT He BULK(K)	5	5	5	5
ΔT FILM (ASSUME h=1800 w/m^2-K)	<1	4.3	4.3	4.3
ΔT TUBE TO PLATE(K)	~0	2	2	2
ΔT GRADIENT IN PLATE(K)	15	39	20	7
TOTAL ΔT(at T_{hot})	21	55.3	31.3	18.3

Conclusions

5/16” diameter tubes and 20 atmosphere Helium can meet the operational and bakeout requirements. The pressure drop in the tubing is very modest, 0.29 atmospheres during cool down, and flow is sufficiently balanced not to require any active control or valving.

It will require a single in-line valve in each return header to limit flow. Velocities are well within the incompressible flow regime.
DAC NCSX-CALC-12-001-00, VV Local Thermal Analysis indicates that the original intermittent mounting brackets configuration, calling for 10 inch vertical spacing and 8 inch staggered horizontal spacing with a 15 minute cool down, will ratchet the vessel wall well within the 80^{o} C maximum steady state temperature requirement.

Caveats
Since this work was completed, additional ports were added to the vacuum vessel. This will require reconfiguring some of the tubing and will change some lengths. The changes are expected to be small and should have little overall effect.
The thermal cycling calculations in this analysis assume a constant heat transfer coefficient at the coolant tube and perfect conduction from a continuous welded tube. This is a limit analysis and gives only an approximate solution for design purposes. Determining the required spacing of intermittent clamps and gaskets is beyond the scope of this document. A more complete analysis is contained in DAC NCSX-CALC-12-001-00, where the effects of the gasket and 3-D geometry are accounted for. The results of this analysis were used to compile the values in the chart tabulating the delta temperatures in the plate. The tube spacing analyses assume even heat distribution and do not take into account any thermal peaking. The 8 inch spacing may not be adequate for some portions of the VV and additional tubing or lengthened tubing with more surface coverage may be required in suspect areas. The design of the cooling system will be completed before the plasma thermal distribution and heating factors are fully characterized, therefore, a conservative approach may be to space all tubing closer than required for normal operation. Later upgrade operation will utilize internal limiters and wall armor to protect high flux regions.