NCSX

Design Basis Analysis

Vacuum Vessel Heating/Cooling Distribution System Thermo-hydraulic Analysis

NCSX-CALC-12-002-001

11 April 2006

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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 hoses 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 mass balance analysis was performed to determine the steady state operating temperature of the vessel wall, i.e. the thermal ratcheting, as a check on the ANSYS analyses.

Performance Requirements and Criteria

The NCSX Vacuum Vessel Systems Requirements Document 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.
- The vacuum vessel must be capable of baking at 150 C before and after operational shots during MIE operation.
- 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.
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Reference Documents

DAC NCSX-CALC-12-001	VV Local Thermal Analysis
NCSX-BSPEC-12-00	NCSX Vacuum Vessel Systems Requirements Document
DAC NCSX-CALC-12-003	Heat Balance of the NCSX Vacuum Vessel During Operation and Bakeout

Assumptions

Heat input and output. These values were determined by DAC NCSX-CALC-12-003.

- The minimum heat input required by the tracing during steady state 350 C bakeout of the vessel is 8.17 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

The original baseline configuration assumed contoured tracing tubes attached on saddles and a maximum spacing of 8 inches on center. The inability to procure contoured tubing resulted in a new configuration which utilizes commercial flexible stainless steel hoses with braided jacket over a corrugated internal tube. A test program evaluated the hose performance to determine whether it was adequate for the vacuum vessel heating and cooling.

As a result, the baseline configuration utilizes pairs of hoses sharing common mounting brackets. The individual hoses in the pairs connect to separate supply and return headers. There are 16 pairs of hoses on each of the half-field periods, or a total of 192 parallel hoses 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, hosing diameter, coolant flow rate, and system pressure were input as variables. The outputs from the spreadsheet were, coolant temperature changes, film coefficients, friction coefficient, Reynolds numbers, hose wall temperatures, exit velocity, total heat transfer, and the net pressure drop. The hose pairs were assumed to be identical, centering on the same trajectory as original layouts 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

8 atmosphere nitrogen at 20 C	
spec ht(J/g-K)	1.047
density(g/cm^3)	0.0092
cond.(w/cm-K)	0.00033

dyn visc.(g/cm-s)	2.2E-04
diffusivity (cm^2/s)	3.48E-02
Prandtl	0.69
kin. visc. (cm^2/s)	2.4E-02

8 atmosphere nitrogen at 150 C

spec ht(J/g-K)	1.046
density(g/cm^3)	0.0064
cond.(w/cm-K)	0.00033
dyn visc.(g/cm-s)	2.2E-04
diffusivity (cm^2/s)	4.99E-02
Prandtl	0.69
kin. visc. (cm^2/s)	3.45E-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

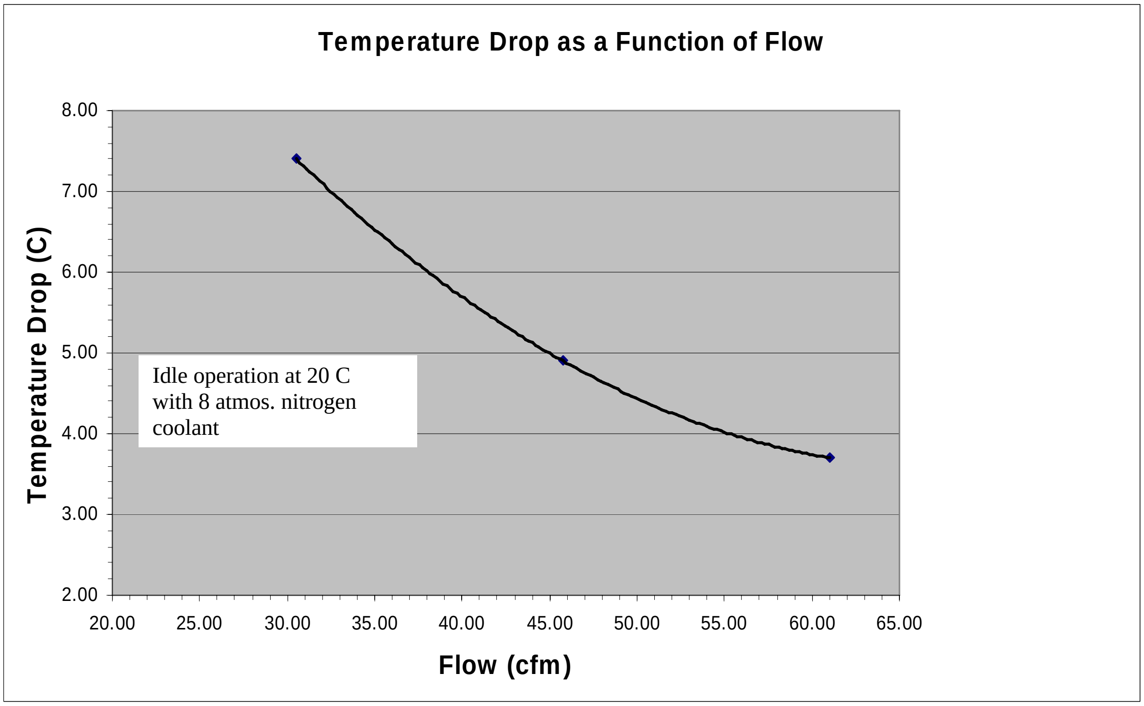
Results

The mass flow requirements are driven by the requirements to operate the vessel with a fifteen minute rep rate, not by bakeout. The baseline attachment scheme and helium system operated at 20 atmospheres pressure, with 1/4 inch diameter hose, is adequate for bakeout but when the intermittent nature of the mounting and net heat transfer coefficient of the mount geometry is taken into account, it is found that the wall temperature must ratchet up significantly above the coolant media before energy balance is achieved. This is confirmed in the referenced DAC NCSX-CALC-12-001.
The bulk temperature rise during cooling is based on simple mass balance.

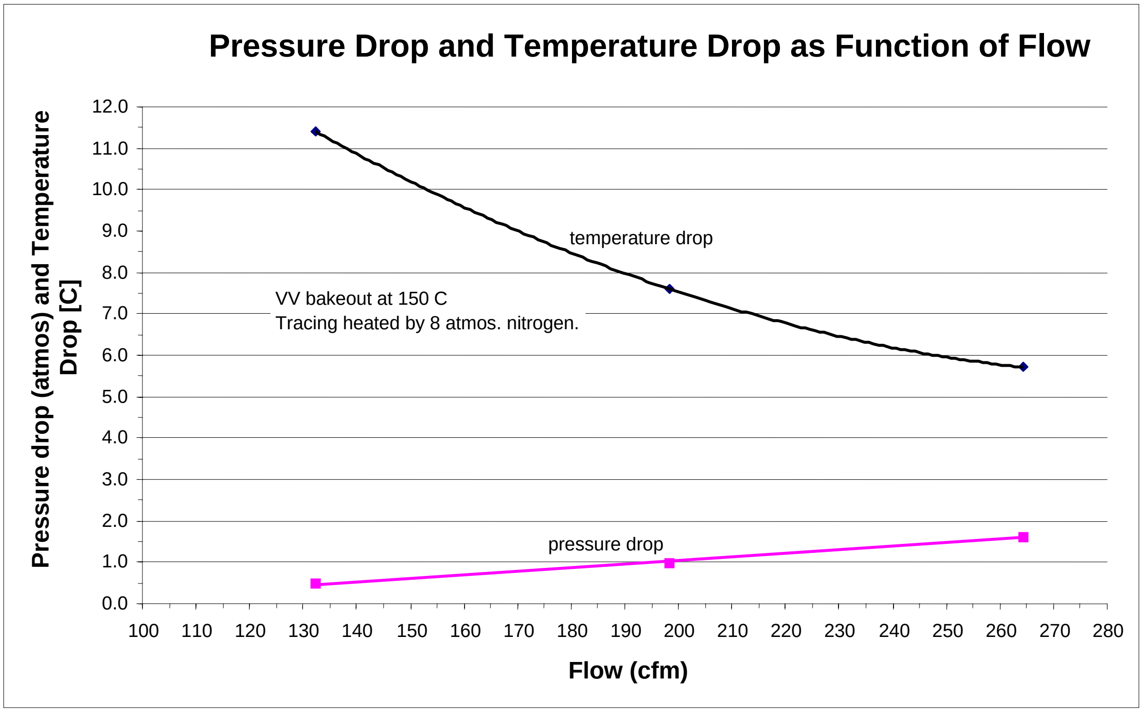
MIE Operation

During initial operation of the VV air or nitrogen gas will be used, in lieu of helium. Calculations were performed to determine the requirements for heat input during standby operation and 150 C bakeout but not for cooldown; the heat input during MIE will be very small and bakeout needs will predominate. The calculations shown assume nitrogen but the results are essentially the same for air. Pressure is assumed to be 8 atmospheres, the available system pressure for shop air in the NCSX facility. Use of shop air would require conditioning of the supply to remove moisture and oil before it is circulated through the VV coolant system.

Flow during idle operation



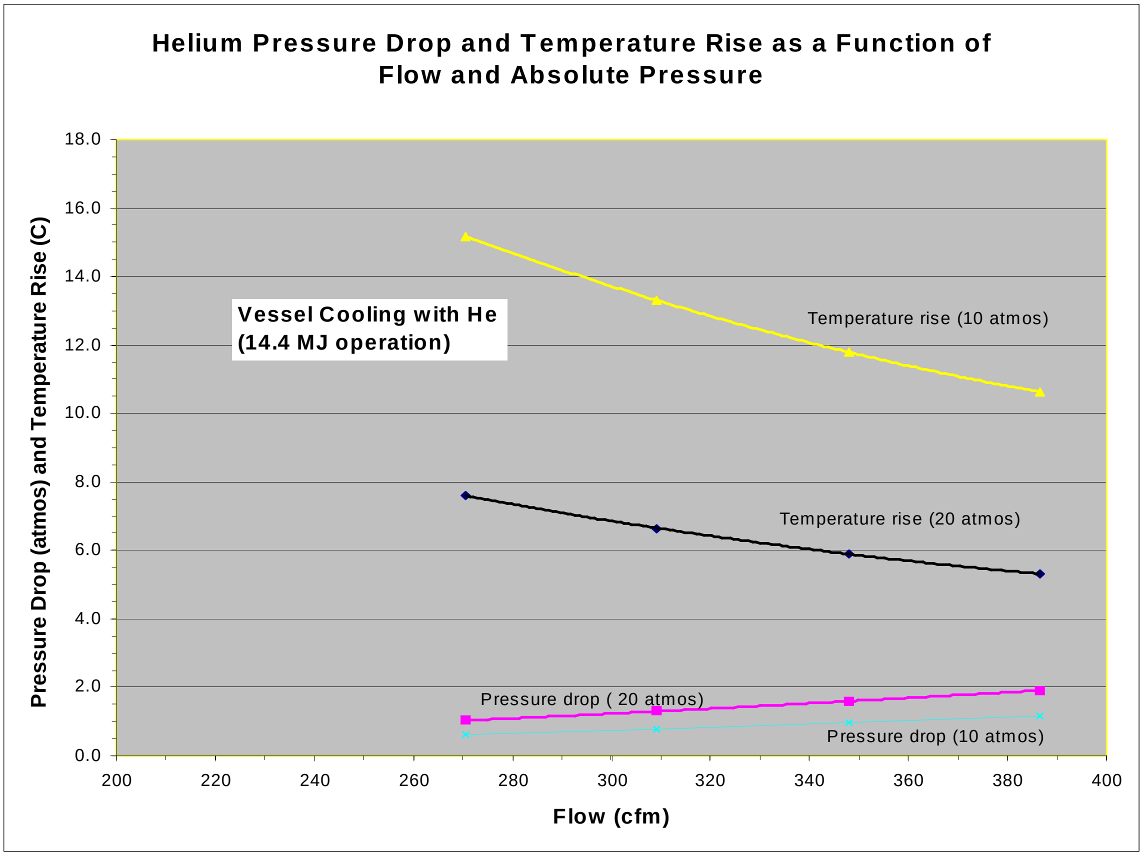
Nitrogen flow during 150 C bakeout



Upgrade 14.4 MJ operation

There is no single operating regime for the helium supply during bakeout and cooling, therefore, a family of parameters was developed which will give the operators an envelope in which to operate, i.e. a choice of pressures, flow, and delta temperature. The only hard requirement is for the VV to stay below 80 C between and during operational shots. To do this the parameters must be matched with the requirements in the referenced DAC NCSX-CALC-12-001 to assure that the delta temperature chosen does not exceed the limits set forth in that document.

Flow characteristics during cooling with VV at 48 C ratchet temperature Average heat transfer is 16 kW.



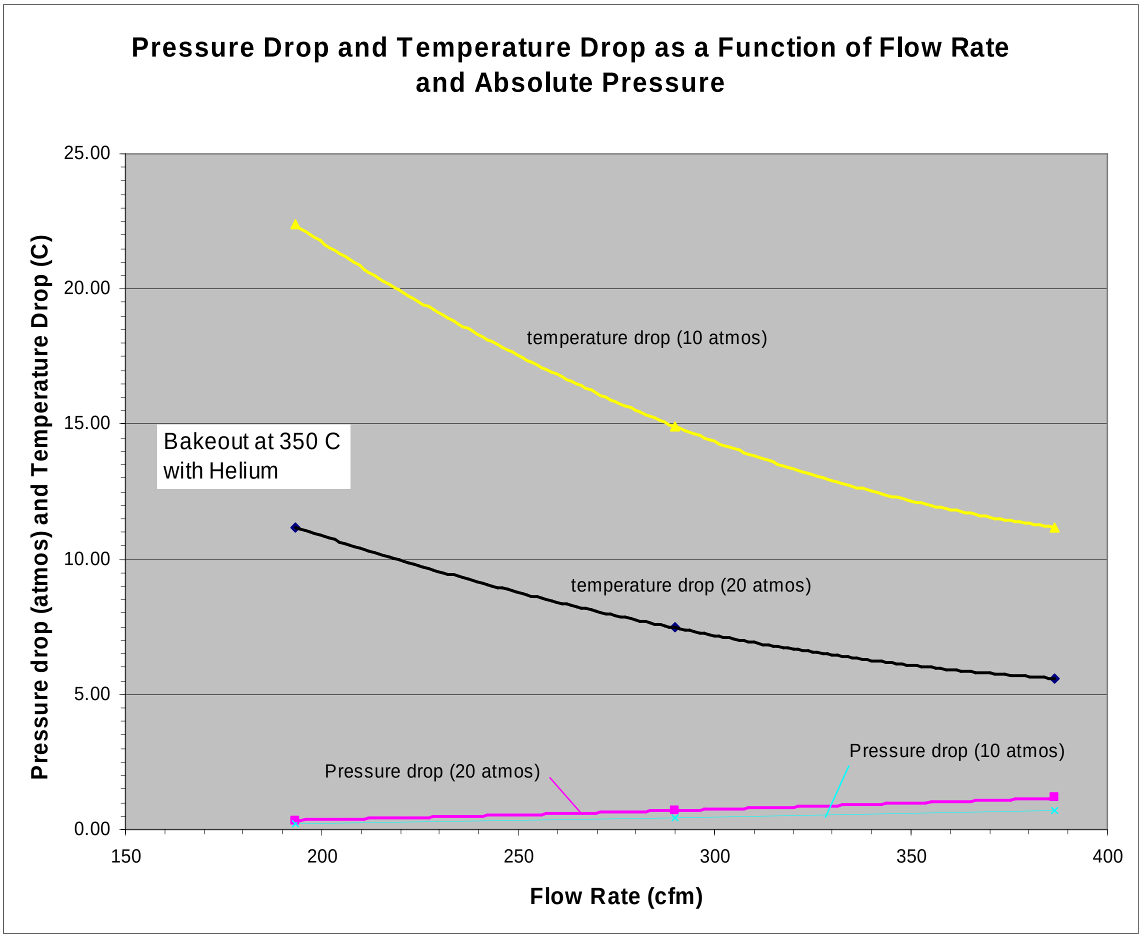
Flow characteristics during cool down operation

Flow at 309 cfm total

20 C helium

20 atmos

Iterative soln:				PRESSURE	av	Mass flow									pressure	pressure
ITEM	MODEL	LENGTH	LENGTH	DROP(trial)	velocity	(g/s)				surface temp	temp Rise	bulk	exit vel	inlet vel	drop	drop total
NO	NO	(in)	(cm)	atmos	m/s		Re	f	h	rise(K)	bulk dT	temp(C)	m/s		atmos/m	atmos
1	SE123-011.PRT	180.62	458.77	1.301	27.36	2.73	27,768	0.147	0.018	41.15	5.9	28.9	27.64	27.10	0.272	1.25
2	SE123-012.PRT	173.80	441.45	1.301	27.90	2.78	28,307	0.146	0.018	42.77	5.8	28.8	28.17	27.63	0.281	1.24
3	SE123-013.PRT	171.55	435.73	1.301	28.08	2.80	28,492	0.146	0.018	43.33	5.7	28.7	28.35	27.81	0.285	1.24
4	SE123-014.PRT	191.64	486.75	1.301	26.57	2.65	26,958	0.148	0.018	38.79	6.1	29.1	26.84	26.30	0.258	1.26
5	SE123-015.PRT	190.61	484.16	1.301	26.64	2.66	27,030	0.148	0.018	39.00	6.0	29.0	26.91	26.37	0.260	1.26
6	SE123-016.PRT	194.75	494.66	1.301	26.35	2.63	26,741	0.148	0.018	38.17	6.1	29.1	26.63	26.09	0.255	1.26
7	SE123-017.PRT	207.52	527.11	1.301	25.53	2.55	25,905	0.149	0.018	35.82	6.3	29.3	25.80	25.26	0.241	1.27
8	SE123-018.PRT	215.94	548.48	1.301	25.03	2.50	25,396	0.150	0.018	34.42	6.4	29.4	25.30	24.76	0.233	1.28
9	SE123-019.PRT	245.26	622.97	1.301	23.48	2.34	23,829	0.153	0.018	30.31	6.9	29.9	23.75	23.22	0.208	1.30
10	SE123-020.PRT	246.16	625.25	1.301	23.44	2.34	23,785	0.153	0.018	30.20	6.9	29.9	23.71	23.17	0.208	1.30
11	SE123-021.PRT	256.12	650.53	1.301	22.98	2.29	23,319	0.153	0.018	29.02	7.0	30.0	23.25	22.71	0.200	1.30
12	SE123-022.PRT	232.11	589.57	1.301	24.14	2.41	24,495	0.152	0.018	32.02	6.7	29.7	24.41	23.87	0.218	1.29
13	SE123-023.PRT	215.55	547.51	1.301	25.05	2.50	25,418	0.150	0.018	34.48	6.4	29.4	25.32	24.78	0.233	1.28
14	SE123-024.PRT	251.69	639.29	1.301	23.18	2.31	23,523	0.153	0.018	29.53	6.9	29.9	23.45	22.92	0.204	1.30
15	SE123-025.PRT	262.24	666.09	1.301	22.71	2.27	23,045	0.154	0.018	28.35	7.1	30.1	22.98	22.44	0.196	1.31
16	SE123-026.PRT	236.22	600.00	1.301	23.93	2.39	24,281	0.152	0.018	31.47	6.7	29.7	24.20	23.66	0.215	1.29
		av. length(m)	5.51		total(g)	40.16		av	0.018	34.93	6.43					
		total length(m)	1058.20		av=	2.51										



Flow characteristics during 350 C bakeout Net heat transfer is 8.17 kW.

Flow characteristics during 350 C bakeout
290 cfm
20 atmos

Iterative soln:				PRESSURE	av	Mass flow								pressure	pressure
ITEM	MODEL	LENGTH	LENGTH	DROP(trial)	velocity	(g/s)		*		temp drop	bulk	exit vel	inlet vel	drop	drop total
NO	NO	(in)	(cm)	atmos	m/s		Re	f	h	bulk dT	temp(C)	m/s		atmos/m	atmos
1	SE123-011.PRT	180.62	458.77	0.705	25.12	1.23	8,216	0.212	0.018	6.7	366.4	24.73	24.99	0.157	0.722
2	SE123-012.PRT	173.80	441.45	0.705	25.61	1.25	8,376	0.211	0.018	6.6	366.5	25.22	25.48	0.163	0.719
3	SE123-013.PRT	171.55	435.73	0.705	25.77	1.26	8,431	0.211	0.018	6.5	366.6	25.38	25.64	0.165	0.717
4	SE123-014.PRT	191.64	486.75	0.705	24.39	1.19	7,977	0.214	0.018	6.9	366.2	24.00	24.25	0.149	0.727
5	SE123-015.PRT	190.61	484.16	0.705	24.45	1.19	7,998	0.214	0.018	6.9	366.2	24.06	24.32	0.150	0.726
6	SE123-016.PRT	194.75	494.66	0.705	24.19	1.18	7,912	0.214	0.018	6.9	366.1	23.80	24.06	0.147	0.728
7	SE123-017.PRT	207.52	527.11	0.705	23.43	1.14	7,665	0.216	0.018	7.2	365.9	23.04	23.30	0.139	0.733
8	SE123-018.PRT	215.94	548.48	0.705	22.97	1.12	7,514	0.217	0.018	7.3	365.8	22.58	22.84	0.134	0.737
9	SE123-019.PRT	245.26	622.97	0.705	21.56	1.05	7,051	0.221	0.018	7.8	365.3	21.17	21.42	0.120	0.747
10	SE123-020.PRT	246.16	625.25	0.705	21.52	1.05	7,038	0.221	0.018	7.8	365.3	21.13	21.38	0.120	0.748
11	SE123-021.PRT	256.12	650.53	0.705	21.09	1.03	6,900	0.222	0.018	8.0	365.1	20.70	20.96	0.115	0.751
12	SE123-022.PRT	232.11	589.57	0.705	22.16	1.08	7,248	0.219	0.018	7.6	365.5	21.77	22.03	0.126	0.743
13	SE123-023.PRT	215.55	547.51	0.705	22.99	1.12	7,521	0.217	0.018	7.3	365.8	22.60	22.86	0.134	0.736
14	SE123-024.PRT	251.69	639.29	0.705	21.28	1.04	6,960	0.221	0.018	7.9	365.2	20.89	21.15	0.117	0.749
15	SE123-025.PRT	262.24	666.09	0.705	20.85	1.02	6,819	0.223	0.018	8.0	365.0	20.46	20.71	0.113	0.753
16	SE123-026.PRT	236.22	600.00	0.705	21.96	1.07	7,184	0.220	0.018	7.6	365.4	21.57	21.83	0.124	0.744
		av. length(m)	5.51		total(g)	18.02		av	0.018	7.30				0.1359	0.736
		total length(m)	1058.2		av=	1.13									

It is anticipated that the bakeout may be augmented by other means such as inductive heating and the full capacity of the system, as calculated, may not be necessary.

All of the cooling analysis assumed that the helium will be supplied at room temperature. Use of chilled helium would greatly increase the efficiency and result in quicker cool down times. This is a fall back that could be utilized if needed in later high power operation.

Losses in tubing and ring headers

The pressure losses listed are across the braided hose only; there will be additional pressure losses in the 5/16 inch rigid tubing. Pressure drop in the ring headers is insignificant due to the low flow velocity (15 m/s).

Total loss in ring headers during bakeout/cooling	0.01 atmos
Tubing loss during cooling	0.18 atmos.
Tubing loss during bakeout	0.11 atmos.

These are values for the maximum flow condition in the Upgrade operation using helium and include entrance and exit losses.

Conclusions

1/4 inch ID braided hoses and 8 atmosphere nitrogen/air can meet the operational requirements during MIE and 10-20 atmosphere Helium can meet the operational and bakeout requirements during upgrade operation. Some small changes in hose length have been made since this analysis but not enough to significantly alter the overall flow conditions or enough to change the conclusions. The nominal pressure drop in the hosing is modest, 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, indicates that the intermittent mounting brackets configuration, calling for 5 inch vertical spacing and 6 inch 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

The thermo-hydraulic calculations in these analyses assume a constant heat transfer coefficient at the coolant hosing, as measured by experimentation, and a lumped one dimensional effective heat transfer area to determine the net temperature rises in the wall and coolant media. These are limit analyses and give 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 NCSX-CALC-12-001-00, where the effects of the gasket and 3-D geometry are accounted for. Both analyses assume even heat distribution and neither takes into account any thermal peaking. The design and installation of the cooling system will be completed before the plasma thermal distribution is characterized, however, upgrade operation will utilize internal limiters and wall armor to protect high flux regions and will tend to even out the heat distribution. There is also excess capacity built into the coolant system so that compensation may be made for conditions beyond those analyzed.