Thermal Analysis of the Divertor Primary Heat Transfer System Piping During the Gas Baking Process

December 2010

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Date Published: December 2010

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ABSTRACT

A preliminary analysis has been performed examining the temperature distribution in the Divertor Primary Heat Transfer System (PHTS) piping and the divertor itself during the gas baking process. During gas baking, it is required that the divertor reach a temperature of 350°C. Thermal losses in the piping and from the divertor itself require that the gas supply temperature be maintained above that temperature in order to ensure that all of the divertor components reach the required temperature. The analysis described in this report was conducted in order to estimate the required supply temperature from the gas heater.

BACKGROUND

Baking of vacuum-exposed components in ITER is required to prevent contamination of the plasma after surfaces have been exposed to air, steam, etc. Water baking is performed at elevated temperatures (~240°C) in order to drive these contaminants from the surfaces exposed to vacuum in preparation for renewed plasma operation. The baking technique is required because many exposed surfaces are hidden, and it is not possible to perform mechanical cleaning. In addition, during deuterium–tritium (D-T) operation, the divertor will trap tritium because beryllium eroded from the first wall will be carried to the divertor and co-deposited with incoming tritium. The ITER tritium operating limit is presently 700 g, and it has been estimated that only 1500–5000 pulses will be required to reach that limit. This means that the tritium inventory limit will be reached in only ~0.4–1.2 divertor lifetimes.[1] It is therefore very desirable to develop methods to remove the tritium before this limit is reached. Because many of the divertor surfaces are hidden, and will not allow mechanical cleaning, divertor baking is required to effect tritium removal. A baking temperature of 350°C is necessary to effectively "bake off" the tritium.[1] This temperature is high enough that it precludes the use of high-temperature water as the baking fluid since required operating pressures would be extremely high (saturation pressure at 350°C is over 16.5 MPa). Gas baking has therefore been selected as the preferred method of increasing divertor temperatures to the required 350°C (steam is not practical at this temperature because saturation pressure is over 16 MPa).

Compared to liquids, gases have a very low density, and a low capacity for transporting heat on a volumetric basis. The piping length between where the baking gas is introduced and the divertor is over 200 m in length. Since there are thermal losses from this piping as well as the divertor itself, a significant gas temperature decrease could occur just getting the gas to the divertor. It is therefore necessary to determine what the inlet gas temperature must be in order to ensure that the divertor achieves a 350°C temperature during the baking process.

BAKING SYSTEM PIPING CONFIGURATION

The baking gas supply piping assumed in this report starts at the gas heater system located on level 4 of the ITER Tritium building. The heater (shown in pink in Fig. 1) is assumed to be the hot gas supply point. Piping segments are numbered from this point. This numbering scheme is used in the remainder of this report to identify piping location within the gas baking pipe system. Piping dimensions were collected from CATIA drawings and used to estimate thermal losses.

Figure 2 shows the second group of piping as well as the overall gas baking piping layout in relation to the distribution system.

Fig. 1. Baking Gas Supply System—Heat Exchanger and Initial Piping.
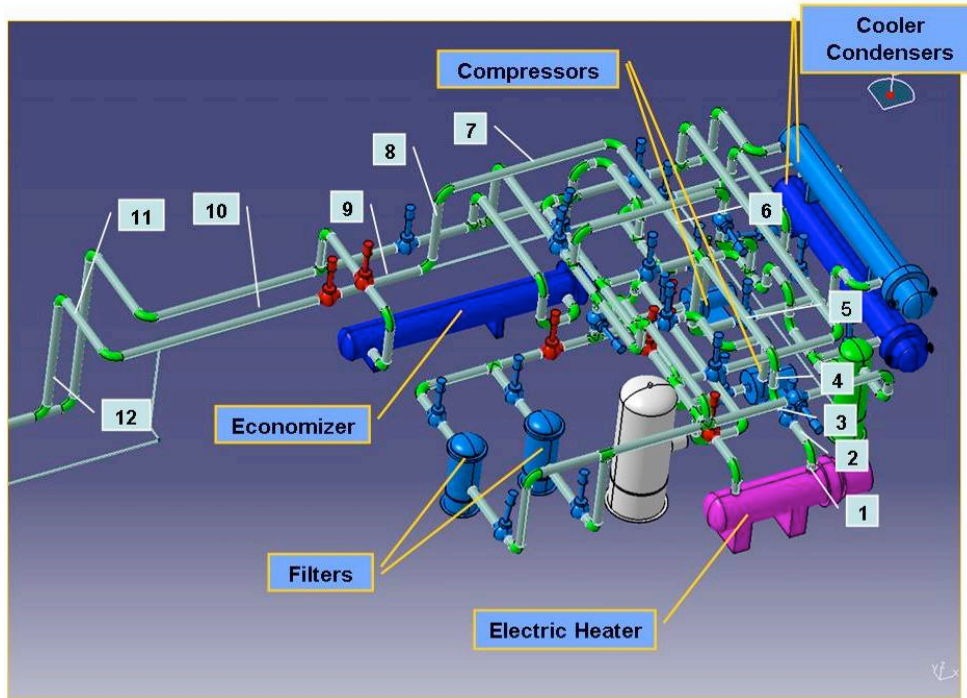

Fig. 2. Layout of Baking System Piping.

Figure 3 shows the gas baking piping (in blue) as it parallels the divertor system distribution headers. From this point, the baking gas flows into and through the distribution header, and through the normal branch piping to the divertor assembly. The 54 divertor cassettes are baked from 18 branch circuits, such

that three divertor cassettes are baked in parallel, by one set of branch piping. The heat loss analysis in this report was performed for the branch piping that was at the end of the distribution header in order to pick the most conservative location for heat losses. Details of the distribution header-piping configuration are shown in Fig. 4. Branch piping that is not in use for baking is isolated from the remainder of the cooling water distribution headers during this process using the orange valves shown in Fig. 5. Also shown in Fig. 5 are the portions of the branch piping that attach to the distribution headers. Figure 6 shows the remainder of the branch piping leading to the divertor cassettes.

Fig. 3. Baking System Piping Connections to Divertor Distribution Header.

Fig. 4. Distribution Header Piping.

Fig. 5. Connection of Most Distant Branch Piping to Distribution Header (the brown colored piping in Fig. 5 and Fig. 6 [like pipe 75] were not included in the original CATIA model but were added for this analysis).
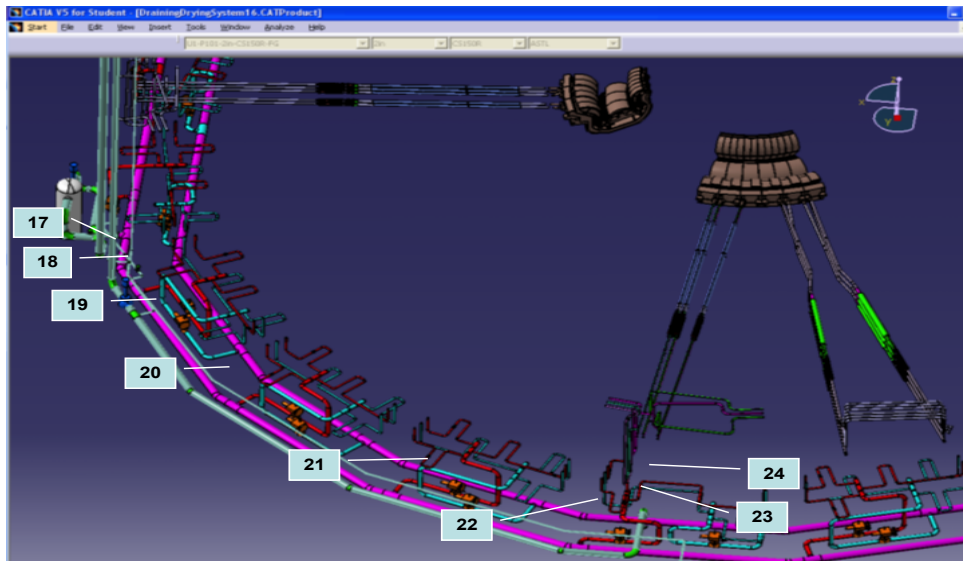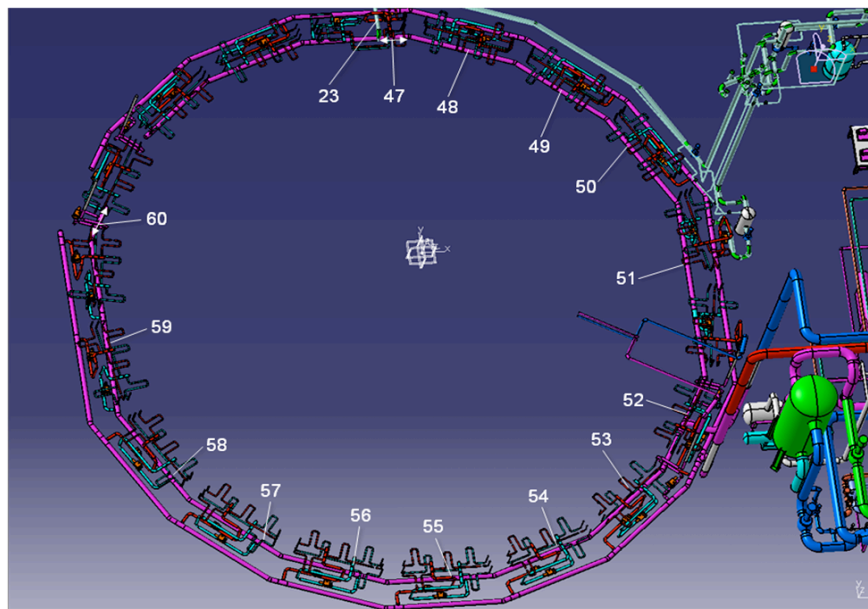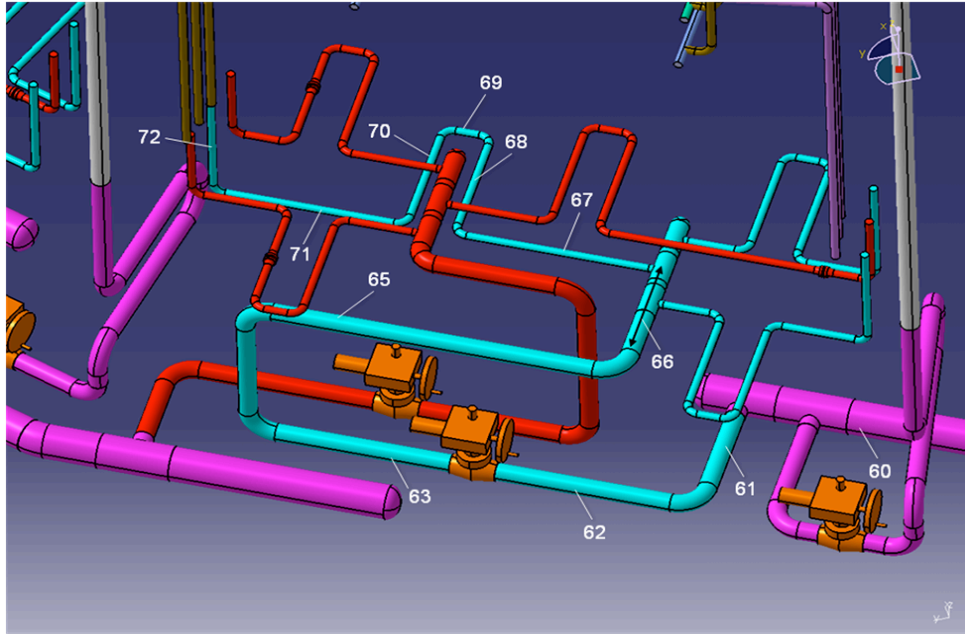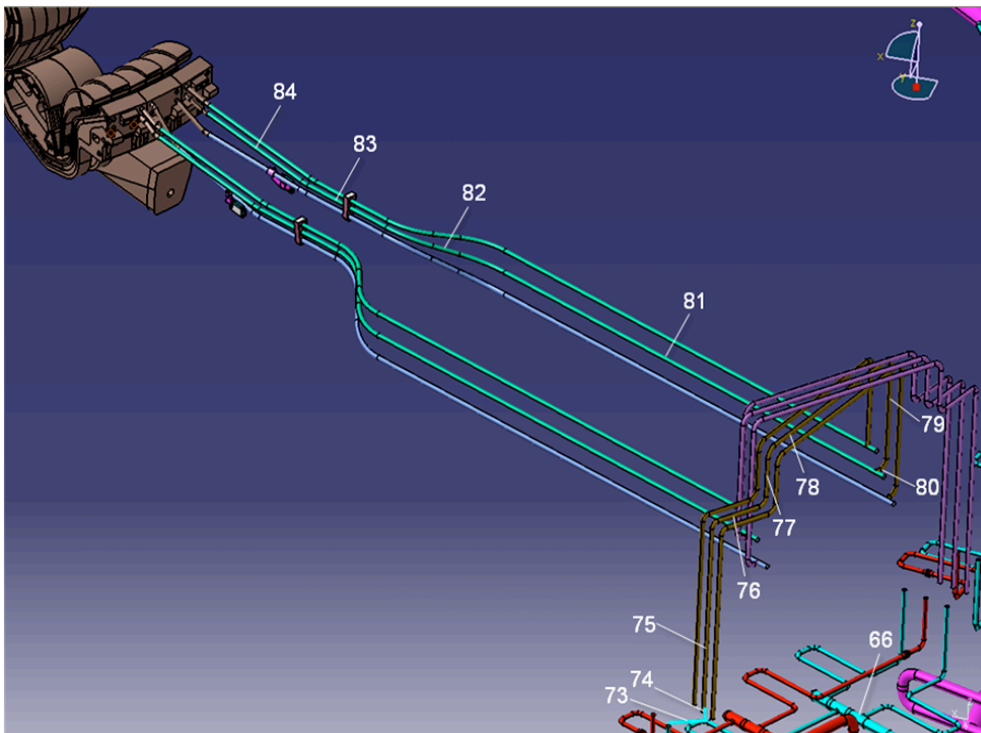

Fig. 6. Remainder to Divertor Branch Piping.

A table of geometry was developed for each pipe segment in the previous schematics. Piping dimensions were taken from the CATIA representation of the gas baking system. Table 1 shows the geometry used in the analysis. Also shown in this table is the insulation thickness assumed in the analysis. This thickness was taken from a table developed for the ITER PHTS using the NAIMA 3E Plus computer program. The table provided the required insulation thickness necessary to keep the insulation outside surface temperature at 60°C (or lower) if the pipe were operating at 350°C. All the CATIA models were taken from the configuration management models of the 2004 design.[2]

Table 1. Piping geometry for gas baking

Pipe number	Length (mm)	Diameter (mm)	Schedule	Insulation thickness (mm)
1	224	250	80S	82.5
2	1785	250	80S	82.5
3	260	250	80S	82.5
4	631	250	80S	82.5
5	4055	250	80S	82.5
6	4641	250	80S	82.5
7	4884	250	80S	82.5
8	2134	250	80S	82.5
9	2587	250	80S	82.5
10	6330	250	80S	82.5
11	2238	250	80S	82.5
12	3838	250	80S	82.5
13	6438	250	80S	82.5
14	2203	250	80S	82.5
15	803	250	80S	82.5
16	21838	250	80S	82.5
17	573	250	80S	82.5
18	332	250	80S	82.5
19	4946	250	80S	82.5
20	8276	250	80S	82.5
21	8503	250	80S	82.5
22	2250	250	80S	82.5
23	2338	250	80S	82.5
24	255	250	80S	82.5
47	2005	300	80S	82.5
48	7208	300	80S	77.5
49	7208	300	80S	77.5
50	7686	300	80S	77.5
51	13399	300	80S	77.5
52	7682	300	80S	77.5
53	7217	300	80S	77.5
54	7218	300	80S	77.5
55	7208	300	80S	77.5
56	7225	300	80S	77.5
57	7208	300	80S	77.5
58	7683	300	80S	77.5
59	13399	300	80S	77.5

Table 1 (continued)

Pipe number	Length (mm)	Diameter (mm)	Schedule	Insulation thickness (mm)
60	2387	300	80S	82.5
61	987	150	80S	82.5
62	1564	150	80S	77.5
63	1564	150	80S	77.5
64	1203	150	80S	77.5
65	2875	150	80S	77.5
66	1028	150	80S	77.5
67	1662	65	80S	77.5
68	1009	65	80S	60
69	209	65	80S	60
70	1009	65	80S	60
71	1509	65	80S	60
72	1123	65	80S	60
73	658	65	80S	60
74	500	65	80S	60
75	3199	65	80S	60
76	805	65	80S	60
77	656	65	80S	60
78	3292	65	80S	60
79	1619	65	80S	60
80	100	65	80S	60
81	8176	65	80S	60
82	446	65	80S	60
83	1732	65	80S	60
84	2119	65	80S	60

A CATIA representation of a single divertor cassette is shown in Fig. 7. The nitrogen flow from the branch piping splits to supply each of the three divertors on that branch circuit. Three parallel flow paths are also used to supply the surface of each divertor. Flow is split between each of the three divertor surfaces. Surface 1 is points 2 through 6 in Fig. 8, surface 2 is points 6 to 7, 8 to 9, and 10 to 11, and surface 3 is points 11 through 14. The body of the divertor itself acts as the manifold to supply each surface. Baking gas is supplied at the outer region of the divertor and is assumed to flow from point 2 to point 6 (Fig. 8), to the inner region of the diverter with flow from point 11 to point 14, and to the dome region from surfaces 6 to 7, then 8 to 9, and then 10 to 11. The flow streams both within a single divertor and between the three divertors are then assumed to recombine and exit to the outlet branch piping.
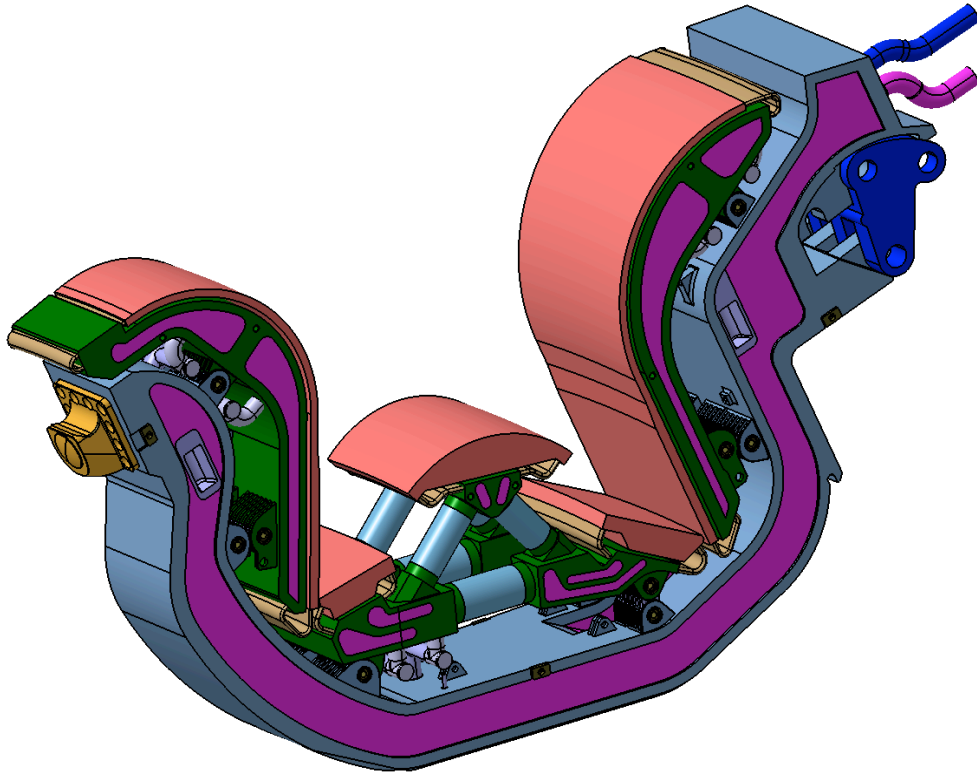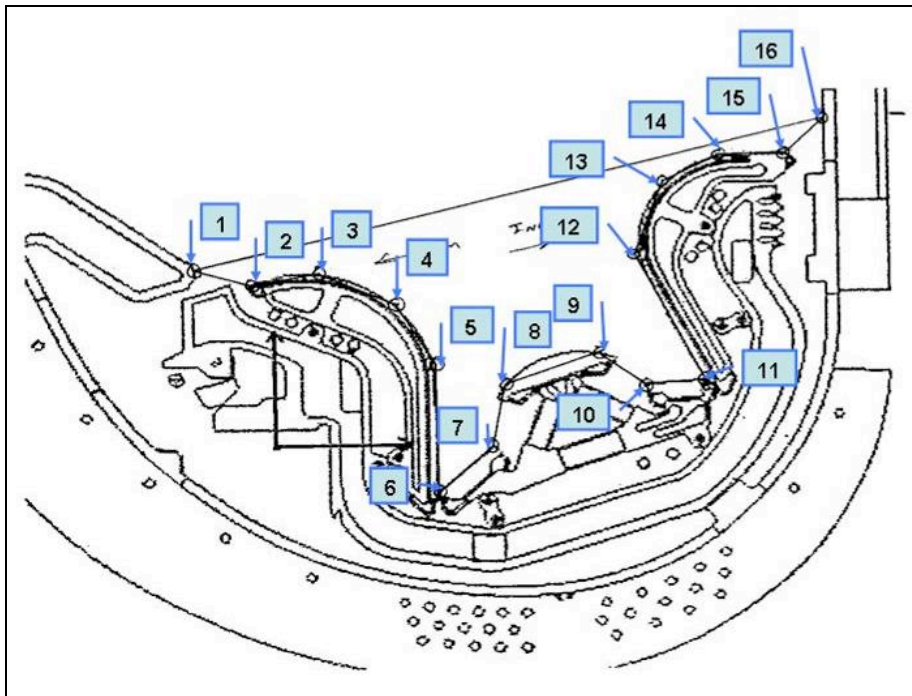
Fig. 7. Divertor from CATIA.

Fig. 8. Cross Section of a Divertor Cassette.

ANALYSIS

In order to calculate losses in the piping, a lumped parameter energy balance was applied to the gas flow in each piping section. For the analysis presented here, the baking gas was assumed to be nitrogen with a flow rate of 4.9 kg/s and a pressure of 1MPa.[3] Losses were determined using one-dimensional radial heat transfer through the pipe and insulation. Constant properties were assumed for all calculations. Property values used in the calculations are presented in Table 2.

Table 2. Properties used in the heat loss calculations

Component	Property	Value
Stainless steel	Thermal conductivity	19.5 w/m/K
Insulation (fiberglass@260°C)	Thermal conductivity	0.082 w/m/K
Nitrogen (350°C, 1MPa)	Thermal conductivity	0.04539 w/m/K
	Density	5.3839 kg/m^3
	Viscosity	3.0446e–5 Ns/m^2
	Specific heat	1.0828 J/g/K
	Pr (Prandt number)	0.7263
Air (21°C, 0.1MPa)	Thermal conductivity	0.025961 w/m/K
	Density	1.2222 kg/m^3
	Viscosity	1.78e–5 Ns/m^2
	Specific heat	1.00483 J/g/K
	Pr	0.687
	Expansion coefficient	3.38e–3/K

The heat transfer coefficient from the gas to the pipe wall was calculated using the Dittus-Boelter correlation.[4]

$$Nu_d = 0.023\ Re_d^{0.4}Pr^{0.3} \, ,$$

where

Nu_d – Nusselt number ($h_n d_{pi}/k_n$),
Re_d – Reynolds number ($\rho_n d_{pi}/m$),
h_n – heat transfer coefficient (W/m^2/K),
d_{pi} – pipe inner diameter (m),
k_n – nitrogen thermal conductivity (W/m/K),
Pr – nitrogen Prandtl number ($\mu_n C_p/k_n$),
μ_n – nitrogen dynamic viscosity (Ns/m^2),
C_p – specific heat (J/g/K), and
ρ_a – nitrogen density (kg/m^3).

The natural circulation heat transfer coefficient on the outside surface of the insulation is calculated using one of two correlations, depending on the pipe orientation.

For a horizontal pipe orientation, a correlation presented in Bird, Stewart, and Lightfoot[5] is used.

$Nu_h = 0.525\ (GrPr)^{1/4}$,

where

Nu_h – Nusselt number ($h_h d_{io}/k_a$),
h_h – heat transfer coefficient in horizontal direction (W/m^2/K),
Gr – Grashof number ($d_{io}^3\rho a^2 g\beta\Delta T/\mu^2$),
d_{io} – insulation outer diameter (m),
k_a – air thermal conductivity (W/m/K),
ρ_a – air density (kg/m^3),
g – acceleration of gravity (m/s^2),
β – air expansion coefficient (1/K),
ΔT – air-to-insulation temperature difference (K), and
μ_a – air dynamic viscosity (Ns/m^2).

For a vertical pipe orientation, a correlation by Popiel[6] is used.

$Nu_H = A\ Ra_H^{\ n}$,

where

$A = 0.519 + 0.03454(H/d_{io}) + 0.0008772(H/d_{io})^2 + 8.855e{-}6(H/d_{io})^3$,

$n = 0.25 - 0.00253\ (H/d_{io}) + 1.152e{-}5\ (H/d_{io})^2$,

Nu_v – Nusselt number ($h_v H/k_a$),
h_v – heat transfer coefficient in vertical direction (W/m^2/K),
H – height of pipe (m),
k_a – thermal conductivity (W/(Km)
Ra – Rayleigh number ($Gr_H Pr$), and
Gr_H – Grashof number ($H^3\rho_a^2 g\beta\Delta T/\mu_a^2$).

Radiation from the outer insulation surface to the ambient is also assumed to occur. The radiation heat transfer, Q_{rad}, is added to that from natural convection:

$Q_{rad} = A_i\varepsilon_i\sigma(T_{io}^4 - T_a^4)$,

where

ε_i – emissivity of the outer insulation surface,
A_i – insulation outer surface area (m^2),
σ – Stefan-Boltzmann constant (W/m^2/k^4),
T_{io} – insulation outer surface temperature, (°C), and
T_a – ambient air temperature (°C).

The piping heat loss calculation incorporates conduction through the stainless steel piping and insulation and uses the following equation:

$Q = U\, A_{pi}\, (T_{io} - T_a),$

where

$U = 1/(1/h_n + d_{pi}/2/k_{ss}\, \ln(d_{po}/d_{pi}) + d_{pi}/2k_i\, \ln(d_{io}/d_{ii}) + d_{pi}/d_{io}/h^*),$

Q – energy loss through pipe and pipe insulation (W),
A_{pi} – pipe inside area (m^2),
h^* – either h_v or h_h depending on the pipe orientation, and
k_{ss} – stainless steel thermal conductivity (W/m^2/K).

The outlet temperature of one piping segment is used as the inlet temperature for the next piping segment as the nitrogen progresses toward the divertor.

Losses through piping supports were also considered. A simplified piping support was modeled. A support was envisioned that is welded directly to the piping in a cross geometry with one leg of the cross oriented axially along the pipe and the other leg oriented circumferentially around the pipe. Each leg of the cross was assumed to be made up of 25.4 mm thick stainless steel. The length of each leg was assumed to be one-third the circumference of the pipe. The cross was assumed to extend 25.4 mm beyond the insulation thickness at which point the temperature of the support was assumed to be 21°C. Because the support was assumed to be surrounded by insulation, the only heat losses were assumed to occur from the pipe surface to the point assumed to be 21°C. Piping supports were arbitrarily assumed to be placed every 6.1 m along the piping length. Support losses per meter of pipe were then calculated and added to the other piping losses. A schematic of the support is shown in Fig. 9.

ORNL 2009-G01233A/chj

21°C Surface

Fig. 9. Representation of a Generic Pipe Support.

During the baking process, the plasma chamber is assumed to be under vacuum, and the heat loss from the divertor is assumed to all be from radiation. In order to perform the radiation calculations, radiation from the divertor was assumed to be two-dimensional. View factors from the divertor top surface to the vacuum vessel (and between components) were calculated by dividing the divertor surfaces into flat segments as indicated in Fig. 8. The points at the ends of each of the segments were digitized. View

factors for each segment were then calculated using Hottel's crossed string method[7] (see Fig. 10 for reference).

$$F_{ik} = (L_{ik} + L_{jl} - L_{il} - L_{jk})/(2A_i),$$

where

F_{ik} – view factor between surface A_i and A_k,
A_i – area of surface i (m^2), and
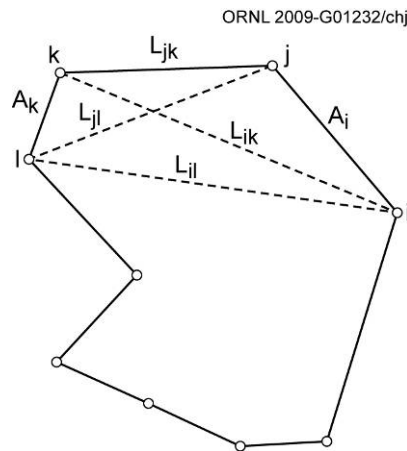L_{ij} – length of line from point i to point j (m).

Fig. 10. Cross Strings Method.

Divertor surface area values were taken from CATIA drawings. The line lengths for each divertor segment (from the digitization process discussed above) were summed, and a value for line length per surface area was calculated. This value was then used to determine the effective surface area for each segment used in the radiation calculations. The divertor surface areas facing the vacuum vessel (upward) that were assumed in the analysis are shown in Table 3. The calculations assumed that three divertors were serviced at one time by the baking system, and that the blanket surfaces surrounding the divertor in the plasma chamber were at 240°C, and that the vacuum vessel was at 200°C; that is, that the vacuum vessel and other components within the plasma chamber were also at their baking temperatures. The blanket emissivity was assumed to be 1, the divertor surface emissivity was assumed to be 0.7,[3] and the emissivity of steel was assumed to be 0.3.

Table 3. Assumed divertor surface areas

Divertor section	Area (m^2)
Inner divertor	3.04
Divertor dome	5.06
Outer divertor	4.33

RESULTS

Calculations were performed using the above assumptions to determine the nitrogen inlet temperature necessary to meet the 350°C divertor baking requirement. Table 4 shows the nitrogen exit temperature for each of the piping segments of Table 1. In addition, the outlet temperature for each part of the divertor is shown. As implied by the calculations, in order to get a gas temperature in the divertor of 350°C, a nitrogen inlet temperature to the gas baking piping of 380°C is required.

Table 4. Pipe segment outlet temperature

Pipe number	Outlet temperature (°C)
Inlet temperature	380.0
1	379.9785
2	379.8079
3	379.783
4	379.7228
5	379.3354
6	378.8925
7	378.427
8	378.2252
9	377.9791
10	377.3773
11	377.1649
12	376.8041
13	376.1941
14	375.9871
15	375.9112
16	373.8895
17	373.8356
18	373.8045
19	373.3398
20	372.5633
21	371.7673
22	371.5572
23	371.3389
24	371.3151
47	371.0985
48	370.3018
49	369.5068
50	368.6624
51	367.2078
52	366.3508
53	365.564
54	364.7789
55	363.9967
56	363.2144
57	362.4358
58	361.609
59	360.1659

Table 4 (continued)

Pipe number	Outlet temperature (°C)
60	359.9163
61	359.8541
62	359.7554
63	359.6568
64	359.5814
65	359.4003
66	359.3355
67	359.2709
68	359.2317
69	359.2236
70	359.1844
71	359.1257
72	359.0825
73	359.0569
74	359.0376
75	358.9152
76	358.884
77	358.8587
78	358.7309
79	358.6688
80	358.6649
81	358.3477
82	358.3304
83	358.2633
84	358.1812
Divertor section 2-3	356.3171
Divertor section 3-4	354.3696
Divertor section 4-5	353.0389
Divertor section 5-6	350.8839
Divertor section 6-7	355.5322
Divertor section 8-9	353.437
Divertor section 10-11	352.6808
Divertor section 11-12	354.1329
Divertor section 12-13	351.6652
Divertor section 13-14	350.7944

CONCLUSIONS

These simplified calculations have shown that in order to have a minimum gas temperature in the divertor of 350°C, the gas baking system heater must supply 380°C nitrogen at the entrance of the gas baking system piping. These calculations have assumed that the system is at steady state. The radiation heat transfer in the vacuum vessel has been greatly simplified, and in order to develop a more accurate estimate, more detailed calculations in that region need to be performed. The back side of the plasma facing surfaces of the divertor that face downward were not considered in the present analysis, because it was thought that there were several surfaces between the divertor and the vacuum vessel would act as radiation shields (mounting structure, flow channels, etc.), and would significantly reduce the radiation

losses in that direction. However this assumption needs to be checked. Conduction through the divertor support systems also needs to be considered but was not included in this analysis, no hand calculations have been made of the losses through the supports. Additionally, more detailed calculations of losses through piping supports need to be undertaken, using actual support geometry and spacings. These calculations were all steady state, and if it is of interest to determine how long it takes to get to the desired baking temperatures, it will be necessary to perform transient analysis accounting for the heat capacity of the structures. This could be accomplished using a RELAP calculation or other such system analysis code as well as an adiabatic calculation to see what the minimum temperature rise time would be versus flow rate and temperature.

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