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ACRONYMS

BLK	Blanket
CCWS	Component cooling water system
CHWS	Chilled water system
CV	Control volume
DIV	Divertor
FW	First wall
HS	Heat structure
HX	Heat exchanger
PHTS	Primary heat transfer system
VV	Vacuum vessel

ABSTRACT

This report describes the RELAP5 models that have been developed for the Vacuum Vessel (VV) Primary Heat Transfer System (PHTS). The models are intended to be used to examine the transient performance of the VV PHTS, and evaluate control schemes necessary to maintain parameters within acceptable limits during transients. Some preliminary results are presented to show the maturity of the models and to examine general VV PHTS transient behavior. The models can be used as a starting point to develop transient modeling capability in several directions including control system modeling, safety evaluations, etc, and are not intended to represent the final VV PHTS design.

Preliminary calculations using the models indicate that during normal pulsed operation, heat exchanger control may not be necessary, and that temperatures within the vacuum vessel during decay heat operation remain low.

1. INTRODUCTION

The Vacuum Vessel (VV) Primary Heat Transfer System (PHTS) consists of a single coolant loop supplying water flow to the 18 VV sectors (every 20 degrees around the torus). The 18 VV sectors are cooled in parallel, with the water inlets at the bottom and the water outlets at the top of each sector. The loop includes a main pump and a main shell and tube heat exchanger (HX). Another loop, with a low-flow pump and a small HX, is located in parallel to the main pump and main HX, and its purpose is to remove decay heat. The flow in the main loop is 950 kg/s, and the pressure at the VV inlet is 0.8 MPa. Figure 1 shows a schematic of the VV PHTS design. The average energy over time that must be removed from the VV under normal pulsed operation is 3.5 MW, with a constant coolant inlet temperature of 100°C and a coolant outlet temperature of 100.8°C. Under decay heat conditions, the low-flow pump is designed to provide a flow of 40 kg/s (taken from Ref. 1) and the heat exchanger is designed to remove 0.48 MW of power with a primary side temperature rise of 2.85°C (design values). This low-flow variable could be optimized. Table 1 shows some selected operating conditions.

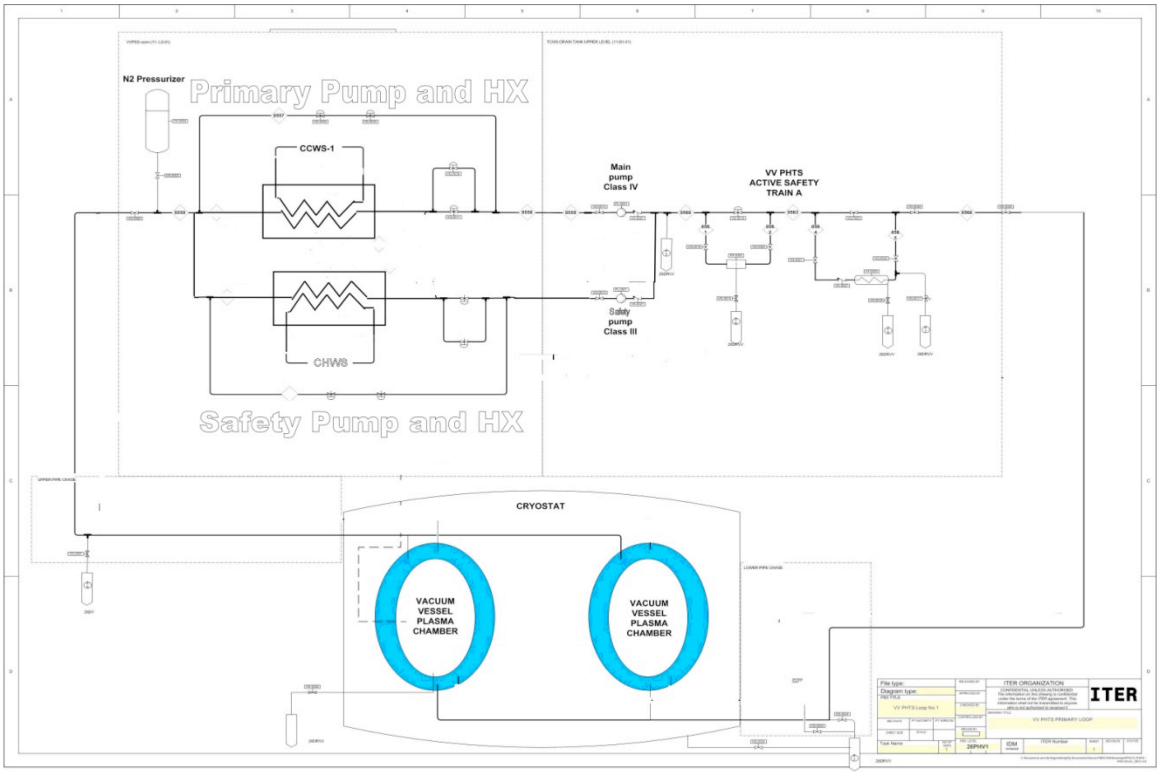


Fig. 1. Schematic of the selected alternative design of the VV PHTS.

Table 1. Operating conditions for the VV PHTS

Variable	Normal operation	Decay heat
Power of HX (MW)	3.5	0.48 (peak)
Flow rate (kg/s)	950	40
Pressure (MPa) VV inlet	0.8	0.7
Inlet temperature (°C)	100	Variable
Outlet temperature (°C)	100.8	Variable
Loop pressure drop (MPa)	0.8	0.025
Maximum coolant velocity in piping (m/s)	8.5	0.36
Piping size	DN 400 (16 in.)	DN 150 (6 in.)

2. RELAP5 MODELS

There are two different RELAP5 (Ref. 2) models: one models pulsed or normal power operation and the other models decay heat operation. The only difference between the two models is in the number of heat structures modeled: six and 17 in the normal and decay heat operation models, respectively. The code RELAP5-3D (Ref. 2) Version 2.4.2 was used for these models/calculations. This code has three-dimensional (3-D) capabilities that were not used in these models.

The RELAP5 models include the vacuum vessel, collector, distributor, pressurizer, main loop piping with the main pump and main heat exchanger, decay heat loop piping with the low-flow pump and the heat exchanger, filter loop, and the piping between the distributor and the collector through the VV. RELAP5 uses a number designation for each component. In the RELAP5 model discussed here, the 200 series components are for the hot leg and part of the cold leg up to the pump, the 100 series components are for the cold leg after the pump, the VV is component 1, the decay heat leg is 300–320 series components, the filter piping are 330 series components, and the pressurizer and associated piping are 340 series components. The secondary sides of the HXs are 400–410 components for the main loop and 420–430 components for the decay heat loop.

2.1 PIPING SYSTEM

Most of the dimensions (lengths, heights, elevations) for the RELAP5 model have been taken from CATIA drawings (Fig. 2). The main piping is DN400 Schedule 40S pipe (0.38734-m ID) selected in order to limit the maximum cooling water velocity inside the pipe to 8.5 m/s. This velocity was selected in order to keep piping pressure drops moderate. The piping water velocity and the piping size are variables that could be optimized.

The piping system shown in Fig. 2 has been used to develop the RELAP5 piping model. Details of the piping dimensions used including piping labels, the RELAP5 numbering scheme, and more detailed CATIA drawings are documented in Appendix C.

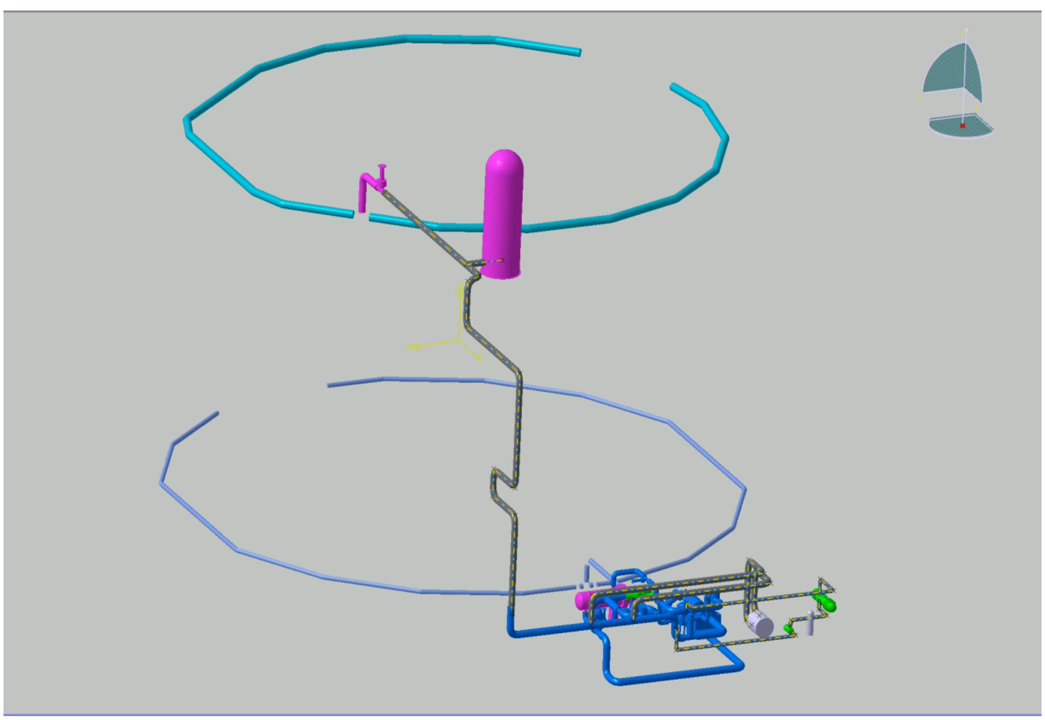


Fig. 2. CATIA view of the alternative design (VV not shown).

2.2 VACUUM VESSEL

The vacuum vessel parameters have been taken from a MELCOR model (Ref. 3), combining the open flow areas of the two half-vessels into a single vessel model (all 18 sectors combined into one single volume). The total flow area used for the VV is 15.92 m^2, total height is 12 m, and the hydraulic diameter is 0.1 m (taken from Ref. 3). The VV has been modeled as a vertical pipe with 12 horizontal levels; each level is 1 m high. The different parallel pipes between the distributor (at the bottom) and the VV sectors and between the VV and the collector (at the top) have been combined into a single pipe with the flow area of all the pipes added and with an equivalent hydraulic diameter. The total pipe length for these combined flow paths has also been conserved in order to correctly model the overall pressure drops. The collector and distributor have been modeled as pipes with twice the actual flow area, half the length, and the same hydraulic diameter of the actual piping. Both the collector and the distributor are connected to the main piping at about the middle point (see Fig. 2). When modeling either the collector or the distributor as a single pipe, the two half-sides are collapsed into a single pipe with <u>twice</u> the flow area (from the two sides combined) and <u>half</u> the total length but with the same hydraulic diameter of the original piping. The main pipe is connected at one end, and the collapsed branches to/from the VV at the other end.

2.3 GENERAL LAYOUT

Figure 3 shows a view of the RELAP5 model, showing all the components of the VV PHTS during normal operation. The hot cooling water leaving the top of the VV is shown in orange/red; after it is cooled at the HX, its color changes to blue. Then it goes to the main pump and to the VV where it is heated again. The decay heat loop is shown in yellow and is inactive since flow does not circulate through it under normal operation. Figure 4 is a close-up view of the main HX, main pump, and the decay heat loop (in yellow). Figure 5 is an isometric view of the model, also generated by RELAP5-3D. The VV is at the left, the pressurizer is at the right top, and the pumps and HXs of both loops are at the bottom right. Finally, Fig. 6 shows the nodalization of the model. In addition to the primary system, the two secondary systems (one for each HX, main loop, and decay heat loop) are also shown. A total of 285 control volumes, 286 junctions, 6 heat structures (each structure is subdivided into 12 levels for the VV heat structures and into 10 levels for the HX structures), and 29 control functions were employed in the model.

Valves have also been incorporated into the model. The valves can be opened and closed at different times according to different trips, thus allowing the flow to circulate in the main loop or in the decay heat loop, or combined operation with the main loop active first switching to decay heat loop operation after a predetermined time. Table 2 describes the thermal hydraulic components of Fig. 6. The tables of Appendix C give more details of these components.

2.3.1 Decay Heat Cooling Loop

The decay heat loop consists of DN 150 40S Schedule pipe (0.154-m ID), a low-flow pump capable of providing 40 kg/s, and a heat exchanger capable of removing ~0.5 MW. Additional details for the HXs and the decay heat loop are in later sections.

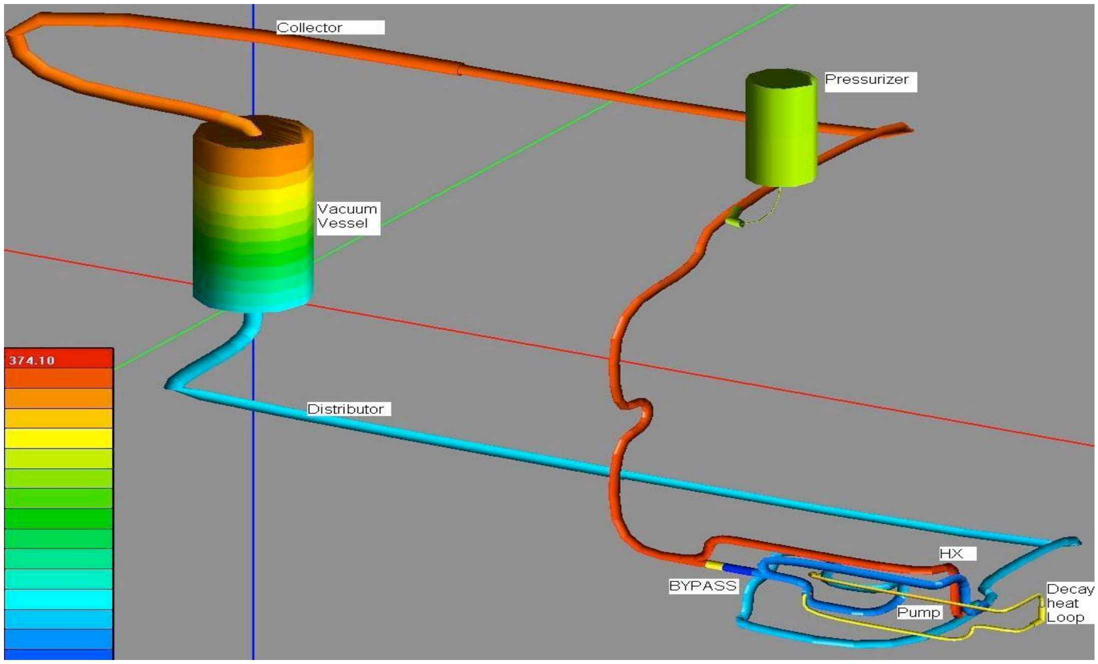


Fig. 3. View of the RELAP5-3D model of the VV PHTS.

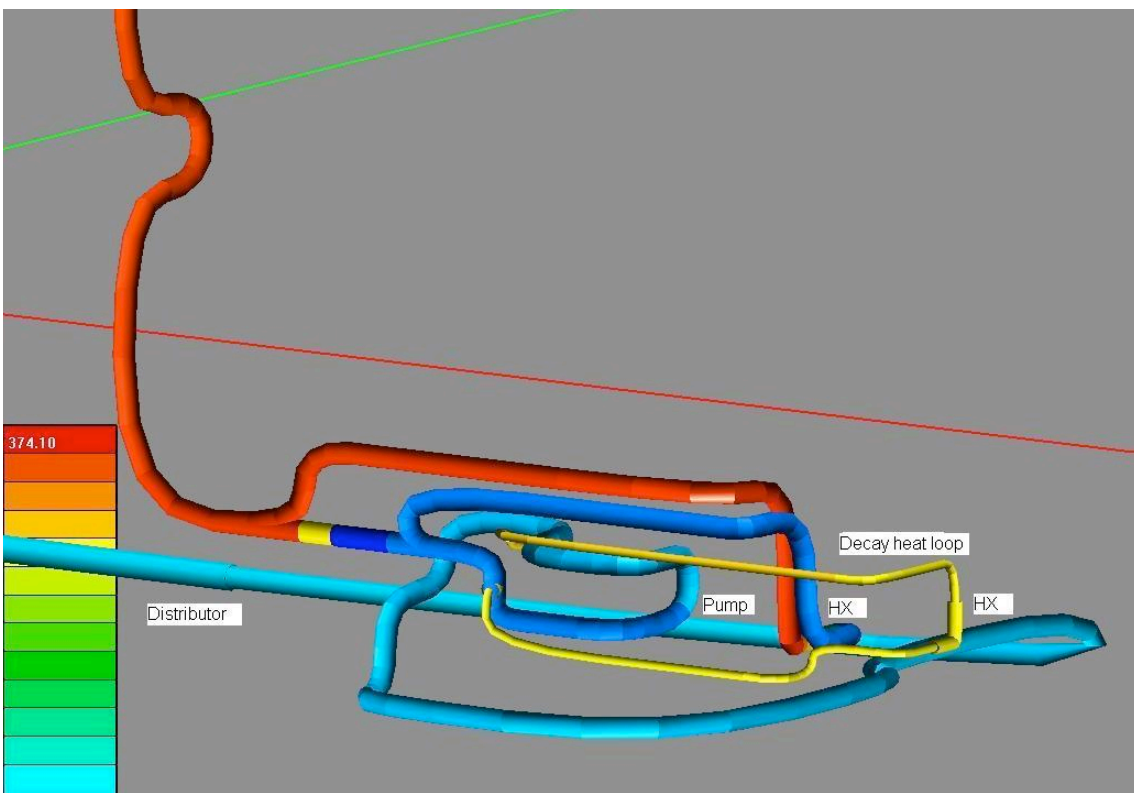


Fig. 4. Close view of the main HX and pump and the safety loop (in yellow).

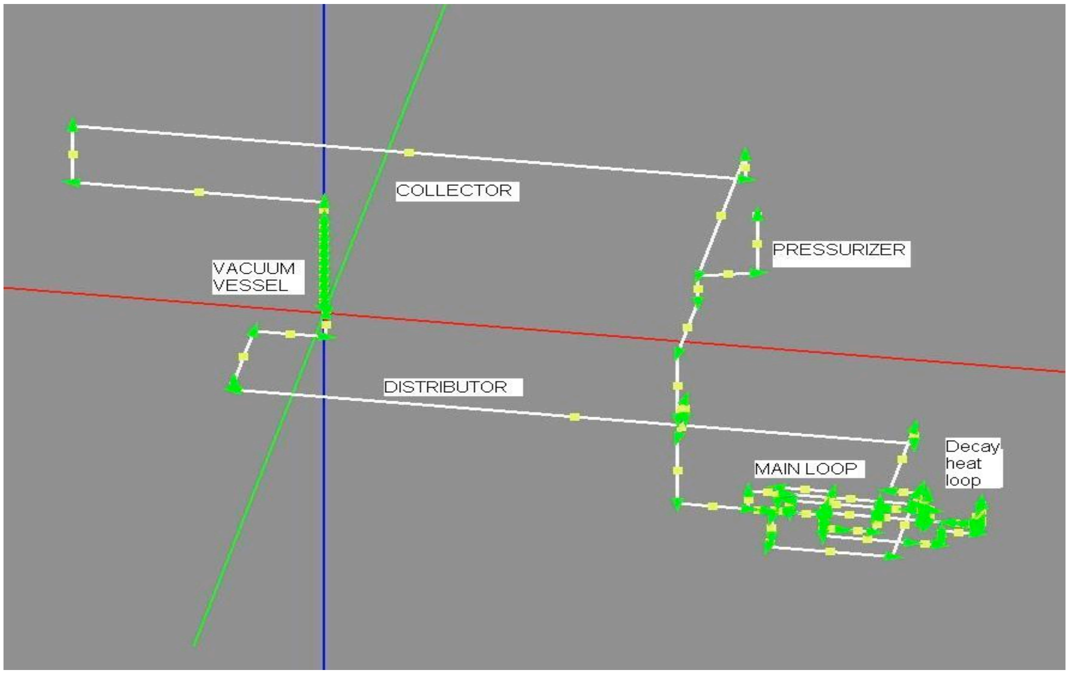


Fig. 5. RELAP5-3D isometric view of the VV PHTS.

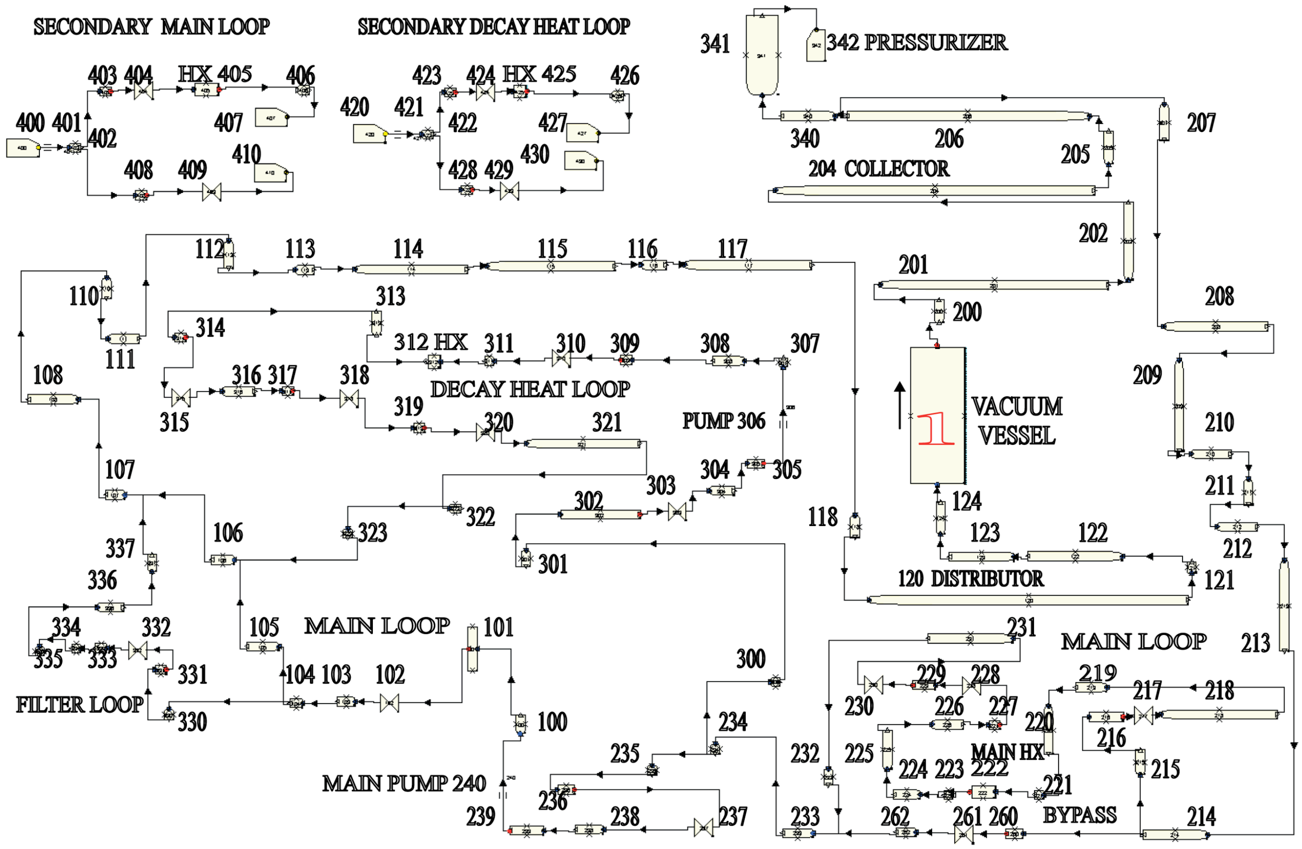


Fig. 6. RELAP5-3D Nodalization.

Table 2. RELAP5 hydraulic components of the VV PHTS

Component Number	Description
1	Vacuum vessel
100-118	Main pump discharge pipe
120	Distributor
121-124	Branches from distributor into VV
200-202	Branches from VV to Collector
204	Collector
205-221	Hot leg up to main heat exchanger
222	Main heat exchanger
223-239	Cold leg up to the main pump
240	Main pump
259-261	Bypass of the main heat exchanger
300-305	Decay heat loop, hot leg up to pump
306	Decay heat loop pump
307-311	Decay heat loop, hot leg from pump to heat exchanger
312	Decay heat exchanger
313-323	Decay heat loop, cold leg
330-337	Filter line
339-340	Pipe connecting the pressurizer to the loop
341-342	Pressurizer
400-410	Secondary loop for the main heat exchanger
420-430	Secondary loop for the decay heat exchanger

Operation of the decay heat loop at a nominal flow of 40 kg/s is provided by a pump Class III. This loop has a heat exchanger in series with the pump, designed for ~0.5 MW heat removal, a value that is above decay heat peak values and therefore more than sufficient for the removal of decay heat. The heat exchanger design is described in a later section. The secondary side is cooled by water from the chilled water system (CHWS-1), with a cold-water temperature of 6°C (279 K). A secondary flow of 18 kg/s was employed for a constant 0.5 MW heat load. Temperature controls were implemented like those in the main HX (to reduce secondary flow if the temperature of the primary coolant is too low). The CHWS-1 is a safety system, designed to operate like the pump (Class III) of this loop, under loss of main power conditions.

Pipe flow area for this loop is 186 cm^2. The total length of piping for this decay heat loop is 35.6 m, not counting the length of the HX tubes, which are 1 m long. With a flow of 40 kg/s flow, the water velocity inside the decay heat loop pipes is ~2.23 m/s, and 1.45 m/s inside the HX tubes. Flow at 40 kg/s will take 16.87 s to travel through the complete decay heat loop piping (just the 150-mm pipe from its connections from/to the main loop).

2.4 HEAT STRUCTURES

Only six structures have been considered in this model: four for the VV, and one for each wall of the two heat exchangers (main and decay heat loop). The dimensions of the VV heat structures have also been taken from the MELCOR model (Ref. 3, pp. 52–59). Two structures model the VV inner wall, one structure models the ribs inside the VV, and one structure models the outer wall. The VV heat structures were divided into 12 horizontal levels, following the same nodalization used for the VV itself. The HX heat structures were divided into 10 levels/nodes, which is the same nodalization used in the primary and secondary volumes of the HXs. The surface areas of the VV structures are as follows: 735 m^2 for the vertical inner wall, 135 m^2 for the horizontal inner wall, 7338 m^2 for the ribs, and 870 m^2 for the outer wall. The area of the outer wall (870 m^2) is equivalent to the areas of the two inner walls added. These areas consider the complete VV; they were split into two separate sets of four structures in the MELCOR model (Ref. 3). Power distribution is as follows: vertical inner wall, 42%; horizontal inner wall, 8%; and the remaining 50% for the ribs. The outer wall does not get any power. Table 3 shows the heat structure parameters. The RELAP5 model that is used for decay heat calculations has additional heat structures incorporated, namely, the first wall and blanket, the divertor, and the thermal shield. These additional structures will be described later.

Table 3. Heat structures

Name	Area (m^2)	Levels	Power (%)
Vertical VV inner wall	735	12	42
Horizontal VV inner wall	135	12	8
Ribs	7338	12	50
VV outer wall	870	12	0
Main HX	26	10	–
Decay heat HX	4.3654	10	–

2.5 FILTER LOOP

A small loop with a filter/screen in parallel with the main loop has also been modeled. The piping for this loop is DN 150 pipe (0.154-m ID), and the total pipe length is 7.8 m. Pipe flow area is 186 cm^2. This filter is located in the cold leg, downstream of the main pump exit, as shown in Figs. 7 and 8. Under normal operating conditions (950 kg/s flow in the main loop), the flow through this loop is 63.4 kg/s (6.7% of the total flow), which corresponds to a water velocity inside the filter loop piping of 3 m/s. The pressure drop through this line has been calculated by RELAP5 to be 28.5 kPa when the flow is 63.4 kg/s.

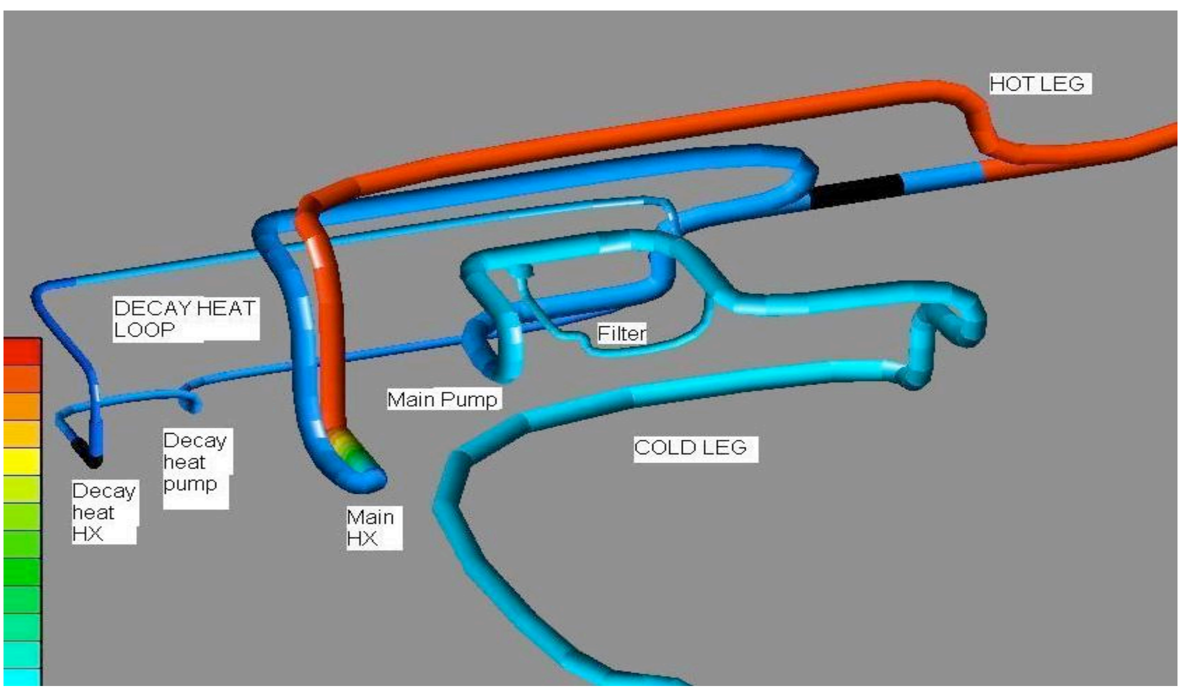


Fig. 7. Filter loop downstream of the main pump.

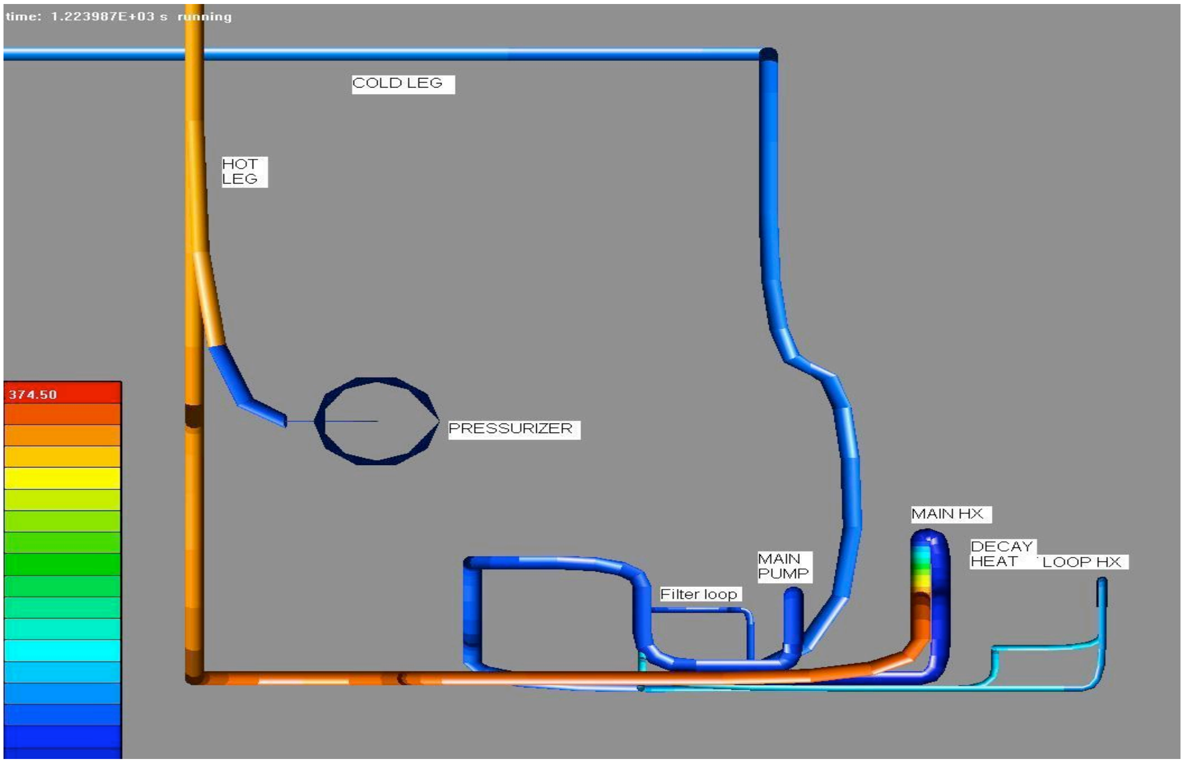


Fig. 8. Top view of the loop with the filter loop shown at center, bottom.

2.6 PRESSURIZER MODEL

A gas pressurizer is presently modeled. The pressurizer model uses the pressurizer component of RELAP5, which is a pipe component called PRIZER. In this model, a closed volume contains water at the bottom and non-condensible gas (nitrogen) at the top. The size (volume) of the pressurizer was calculated by examining the necessary volume expansion of the VV PHTS.

At 100°C the total mass of water in the system is 214,000 kg or 223.8 m^3. This volume gets reduced to 214.8 m^3 (difference 9 m^3) when the temperature drops to 20°C (ambient temperature), and it increases to 247.95 m^3 when the temperature increases to 200ºC for baking (difference 24.15 m^3). Therefore the pressurizer needs to accommodate a volume change of 9 + 24.15 = 33.15 m^3. The minimum pressurizer volume can be 35 m^3.

If a pressurizer volume of 35 m^3 is chosen, and starting with an only-gas pressurizer at 20°C, 26 m^3 of gas space will be left at 100°C, and only 1.85 m^3 of gas space will remain at 200°C, which is less than 10% of the pressurizer total volume. A volume of 40 m^3 was therefore chosen for the pressurizer design. At 100°C, the gas volume will be 31 m^3. Table 4 shows the pressurizer design values. At normal operating conditions (950-kg/s system flow and pulsed power), the pressure in the gas space is set at ~0.4 MPa in order to have a pressure of 0.8 MPa at the VV inlet.

Table 4. Pressurizer design values

Temperature (°C)	Total loop volume (m^3)	Pressurizer free volume m^3 (%)
20	214.8	40 (100%)
100	223.8	31 (77.5%)
200	247.95	7 (17%)

2.7 HEAT EXCHANGERS

A preliminary thermal hydraulic design for the heat exchangers was developed using the heat exchanger design code, *Shell and Tube Heat Exchanger Design* (Ref. 4). The primary heat exchanger design placed the VV PHTS water on the tube side, and the Component Cooling Water System (CCWS) water on the shell side at a temperature of 28°C (301K). Both flows were once through. The primary heat exchanger was designed to accommodate a power level of 3.47 MW with a primary side temperature drop of 0.788°C, and a secondary side temperature rise of 10°C. It consists of 260 tubes, 31.75-mm (1.5-in) OD. A summary of the design is given in Appendix A, along with a sketch. Table 5 shows the design values.

Table 5. Heat exchangers

HX	Power (MW)	Flow primary (kg/s)	ΔT primary (°C)	Flow secondary (Kg/s)	ΔT secondary (°C)	No. tubes	Tube diameter mm (in.)	Tube length (m)
Main	3.47	950	0.788	75	10	260	31.75 (1.5)	1
Decay heat	0.48	40	2.85	11.4	10	146	19.05 (0.75)	0.5

The secondary coolant flow of 25.6 kg/s does not require any controls during pulsed power operation. During other transients, some controls implemented in the secondary side will be active—if the temperature of the coolant leaving the primary side drops below 372.8 K, the secondary coolant flow is reduced. This temperature is only 0.2 K below the desired minimum temperature of 373 K. When the temperature increases to 373 K again, full secondary flow is reestablished.

The power level of 3.47 MW is the total of the time-averaged pulsed power (2.472 MW) plus the pump power (~1 MW). The time-averaged pulsed power (for 10 MW pulses during 400 s with 30-s ramp up and 60-s ramp down) is

$$\bar{P} = \frac{0.5\,(30+60) + 400}{1800}\,10 = 2.472\ \text{MW} .$$

The decay heat exchanger is a U-Tube design with VV PHTS water flowing on the tube side, and Chilled Water System (CHWS) water flowing on the shell side. The secondary side flow is once through, and the primary side used one pass through the U-Tubes. The heat exchanger consists of 146 tubes of 19.05-mm (0.75-in) OD. The decay heat exchanger was designed to accommodate 0.48 MW of power at a primary-side water temperature difference of 2.85°C. The power value was taken from the peak of the decay heat curves generated by RELAP5, which will be discussed later. A summary of the decay heat exchanger design is given in Appendix B, along with a sketch.

2.8 PUMPS

Both the main and decay heat pumps in the RELAP5 model use the RELAP5 pump component. Both pumps use the single-phase homologous curves existing in RELAP5 and based on a Westinghouse pump. Pump parameters assumed are given in Table 6.

Table 6. Pump parameters

Pump	Rated flow kg/s (m^3/s)	Rated head (m)	Rated torque (N·m)	Moment of inertia ($kg·m^2$)
Main	950 (0.99)	86	1.9×10^4	420
Decay heat	40 (0.042)	2.7	25	8

2.9 MODEL OF THE ADDITIONAL STRUCTURES USED FOR DECAY HEAT CALCULATIONS

A separate RELAP5 model has been developed to model decay heat rejection using the VV PHTS. It includes the piping and structures described previously but adds additional heat structures to account for decay heat in the plasma-facing components.

During abnormal conditions (like loss of off-site electric power), the main pump will not be available, and the decay heat cooling loop will remove the nuclear decay heat of the complete VV and its internal components (first wall, blanket and divertor) using the pump flow of 40 kg/s and the decay heat HX with a capacity of 0.5 MW. The decay heat of the VV itself is small (26.5 kW peak value at time zero, decaying after that); however, the decay heat of the internal components is much larger. The first wall (FW) and blanket (BLK) have a combined decay heat of 11.265 MW at time zero, and the divertor (DIV) has a decay heat of 1.716 MW at time zero. After a loss of power transient occurs, the power to the main cooling systems is lost and coolant stops circulating. Coolant in the FW, BLK, and DIV stays inside their respective cooling systems; however, for conservatism, it is assumed that the coolant in the cooling systems of the internal components (FW, BLK, and DIV) is lost, and the internal components transfer heat to the VV by radiation. Their radiation contributions take many hours to reach their peak values as their temperatures increase due to the decay heat generated.

Table 7 shows the decay heat of the VV and its internal components (FW/BLK, DIV) as a function of time after shutdown. These values are also taken from Ref. 3. The combined decay heat at time zero after shutdown (which is time 1 s in the table) is over 13 MW.

In order to calculate the decay heat contributions from the FW, BLK, and DIV to the VV walls, these component structures were modeled in RELAP5 (without their cooling systems). The radiation contributions between these structures and between the structures and the VV walls were modeled as well.

The models of the structures were taken from the MELCOR input of Ref. 3. The FW was modeled with three structures, the BLK with four structures, and the divertor with four structures (pp. 18–21 of Ref. 3). Figure 9 shows the FW/BLK MELCOR structures that have been used in this model. It is further assumed that all of the coolant channels inside these structures are empty (water is lost) and heat is transferred from one structure to another only by radiation through the gaps between them. The first structure on the left (HS10) transfers heat to the next one (HS11), this one (HS11) transfers heat to HS12, HS12 to HS13, HS13 to HS14, HS14 to HS15, HS15 to HS16, and finally, HS16 transfers heat to the VV inner wall (HS21 in Fig. 9). The structures have been modeled as vertical flat slabs, with an area of 680 m^2 each. The inner vertical wall of the VV has an area of 735 m^2, which is a little larger than the FW/BLK area. The decay heat used for each structure is given in Table 8, also taken from Ref. 3.

Table 7. Decay heat of the vacuum vessel and internal components

Time	Time (s)	VV (W)	FW/BLK (W)	DIV (W)	Total (W)
1 s	1	26500	11265000	1716000	13007500
5 min	300	24400	9133000	1342000	10499400
30 min	1800	21000	5350000	780000	6151000
1 h	3600	18400	4324000	640000	4982400
3 h	10800	11500	2961000	430000	3402500
5 h	18000	7540	2259000	312000	2578540
10h	36000	3430	1399000	172000	1574430
1 day	86400	1920	723000	94000	818920
3 days	259200	1670	324000	42100	367770
7 days	604800	1490	276000	48400	325890
1 month	2592000	1270	244000	42100	287370
3 months	7776000	1030	205000	34300	240330
1 year	31536000	681	146000	13600	160281

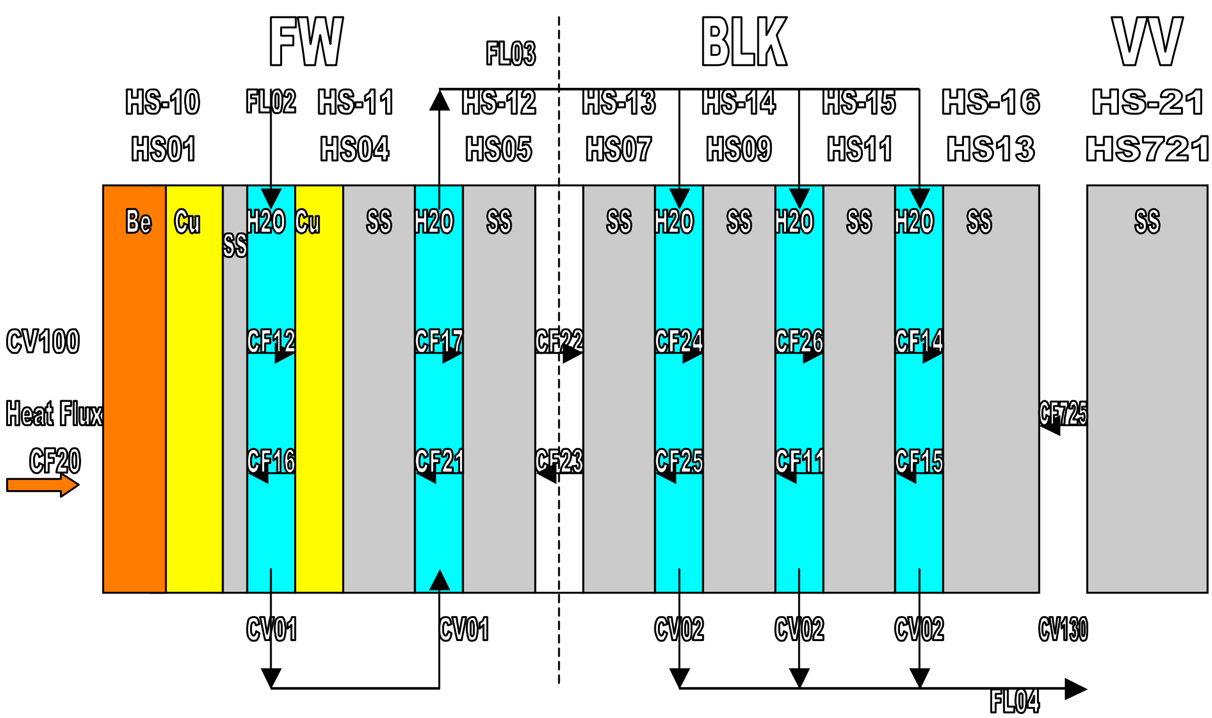


Fig. 9. MELCOR structures for the first wall (FW) and blanket (BLK). Top heat structure numbers are the RELAP5 numbers; MELCOR numbers are below RELAP5 numbers. The control volumes (CV), flows (FL), and control functions (CF), are for the MELCOR model.

Table 8. Decay heat for each structure of the FW/BLK (in W)

Time (s)	HS10	HS11	HS12	FW-total	HS13	HS14	HS15	HS16	BLK-total	Grand total
1	3049000	4482000	850000	**8381000**	642000	1623000	431000	188000	**2884000**	11265000
300	1995000	3836000	661000	**6492000**	580000	1481000	403000	177000	**2641000**	9133000
1800	626000	1838000	620000	**3084000**	494000	1265000	349000	158000	**2266000**	5350000
3600	416000	1347000	565000	**2328000**	445000	1108000	305000	138000	**1996000**	4324000
10800	350000	1022000	356000	**1728000**	271000	688000	189000	85000	**1233000**	2961000
18000	314000	916000	235000	**1465000**	175000	442000	123000	54000	**794000**	2259000
36000	243000	709000	110000	**1062000**	76000	186000	53000	22000	**337000**	1399000
86400	124000	361000	65000	**550000**	40000	94000	28000	11000	**173000**	723000
259200	28000	82000	59000	**169000**	36000	84000	25000	10000	**155000**	324000
604800	21000	59000	54000	**134000**	33000	78000	22000	9000	**142000**	276000
2592000	20000	58000	46000	**124000**	28000	66000	19000	7000	**120000**	244000
7776000	19000	57000	35000	**111000**	22000	51000	15000	6000	**94000**	205000

The divertor was modeled with four structures as described in pages 46 and 47 of Ref. 3. An area of 135 m^2 was used for each heat structure, the same as the VV horizontal inner wall. Figure 10 shows these four structures. The total decay heat of the divertor (Table 7) is split into the four structures of Fig. 10 by the fractions of 0.617, 0.086, 0.222, and 0.075, going from left to right (next to the VV) of Fig. 10.

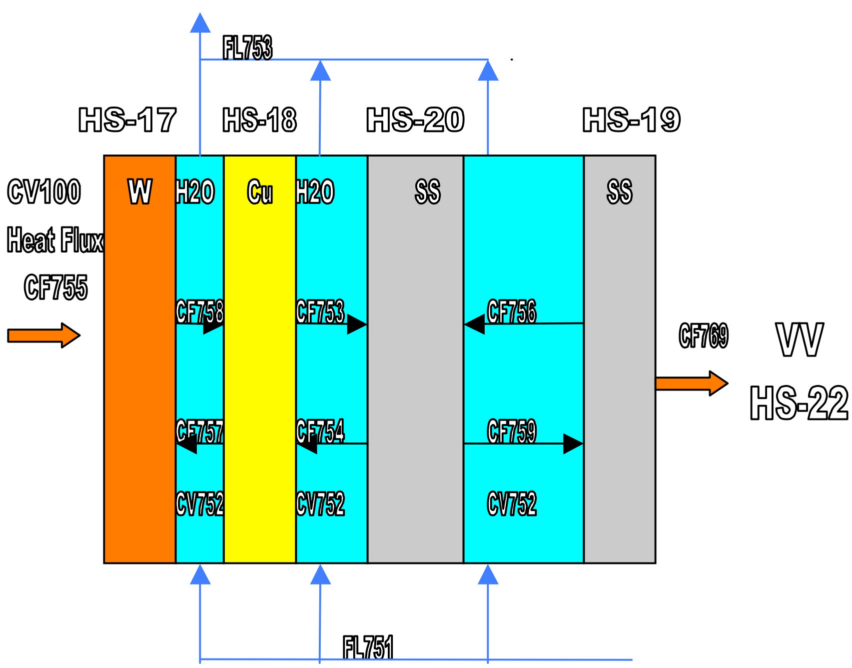


Fig. 10. Divertor model with four structures. Heat structure numbers are the RELAP5 numbers.

The thermal shield between the VV and cryostat was also modeled as in Ref. 3. It has a total area of 1908 m^2, and it is assumed to be at a constant temperature of 180 K.

An additional volume has been added, CV-2, which models the vacuum region inside the vacuum vessel. The FW/BLK and DIV structures are located inside this volume for radiation purposes. Its initial conditions are 660 K and 5-kPa pressure.

Emissivities of 0.3 between the seven FW/BLK structures and of 0.25 between the last BLK structure and the VV structures were used. Emissivities of 0.3 were employed between the four divertor structures, and an emissivity of 0.25 was assumed between the last divertor structure and the VV. Finally, an emissivity of 0.05 was employed for the thermal shield together with an emissivity of 0.2 for the VV outer wall facing the thermal shield. These emissivities are the same values used in the MELCOR model (Ref. 3) employed in safety calculations.

RELAP5 is only capable of modeling either radiative exchange between structures or conduction between structures; radiative exchange was selected as the only mode of heat exchange between structures. Therefore, any connections between these structures which might allow a thermal conduction path are not considered in the RELAP5 model. MELCOR, on the other hand, can account for both radiation and conduction. Since RELAP5 does not model heat conduction between structures, MELCOR heat transfer calculations modeling both conduction and radiation are expected to be higher than the RELAP5 calculations. Actual heat transfer values are expected to be also higher than the RELAP5 calculated values.

3. CALCULATIONS USING THE MODEL

3.1 NORMAL OPERATION AT PULSED POWER

The results presented in this report has been calculated at various times during development of the RELAP model and are therefore based on models which may not be consistent from one set of results to another. The intent of this section is to show that the model works as intended, and that the general behavior of the VV PHTS is reasonable. For repetitive pulsed power operation, the power is assumed to deposit volumetrically in the VV structures (outer walls and ribs), and is assumed to be removed from the structures by the VV PHTS coolant. Each pulse is assumed to have a maximum power of 10 MW with a rise time of 30 s (linear), and a decay time of 60 s (also linear). The flat portion of the pulse (at 10 MW) is assumed to last 400 s. A zero power dwell time of 1310 s after each pulse makes each repetitive pulse sequence 1800 s total. A plot of a single power pulse is shown in Fig. 11 (the fact that the pulse rise does not appear linear is due to the plotting frequency, and not the actual power input shape).

The calculations assumed that this pulse was repetitive (infinitely repeated) and examined the fluid temperature response of the PHTS with a constant flow of water on the secondary side of the main heat exchanger, assuming a secondary-side water inlet temperature of 301 K.

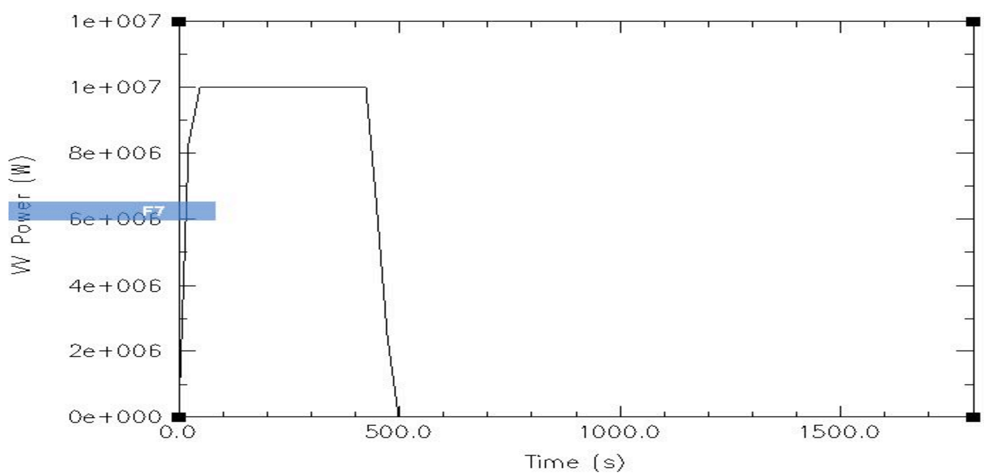


Fig. 11. Single power pulse shape assumed in the calculations.

Multiple transient runs varying the HX secondary flows were made with this model until a quasi-steady-state condition was reached. In this context, quasi steady state implies that the temperature variations in the VV PHTS system were repeated at every pulse without the average temperature (or the maximum or minimum temperature) of the system varying over a long time period. The secondary side flow of the heat exchanger was the parameter changed in each run until a quasi-steady-state condition was achieved.

Calculation Results

The parametric runs discussed above indicated that a mass flow rate of approximately 128 kg/s was needed on the secondary side of the heat exchanger to maintain a quasi-steady-state condition while maintaining VV inlet coolant temperatures between 372 K and 374 K. (This model was an early version with an older heat exchanger design so it has a higher secondary flow than presently used.) All of the results presented in this section used that value for the secondary-side flow rate.

Figure 12 shows the heat exchanger outlet temperature over a time period of 35,000 s, or approximately 20 pulses. The initial portion of this plot (maybe up to about 10,000 s) might be considered a long-term “transient,” as the overall system temperature is stabilizing somewhat. Beyond ~10,000 s, the average HX coolant outlet temperature changes <0.1 K (slightly decreasing), and the overall temperature variation is only about 1.2 K or ± 0.6 K. In this case, the maximum temperature is approximately 374 K, and the minimum temperature is approximately 232.8 K, so some additional tuning could be performed to establish the mean temperature at 373 K, if that is desirable. However, because the temperatures were within the limits established for the VV inlet temperature using this secondary-side coolant flow rate, additional tuning was not done for this calculation.

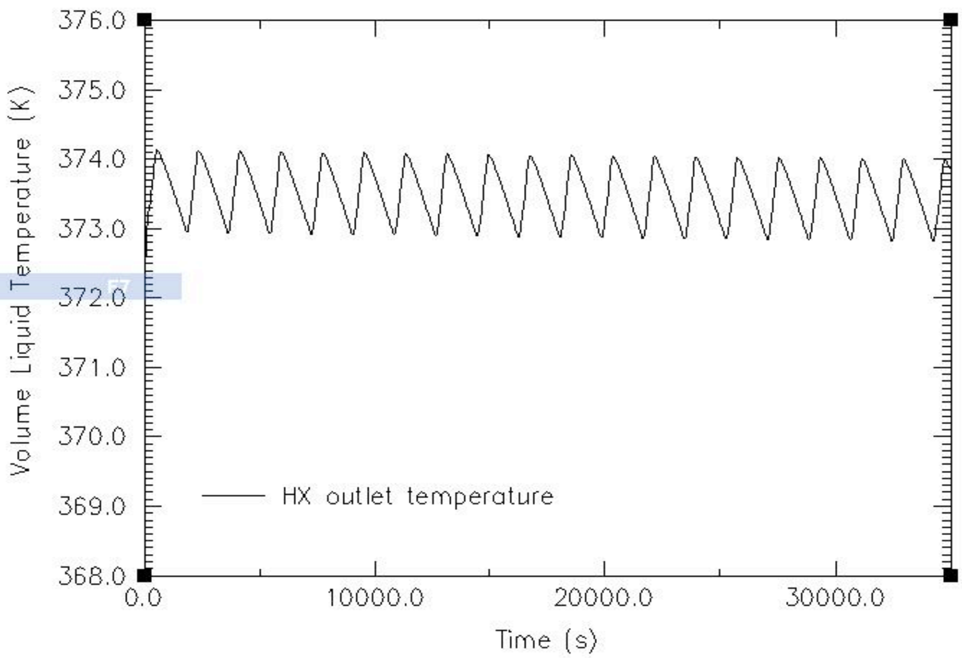


Fig. 12. Heat exchanger coolant outlet temperature (primary side).

Figure 13 shows the VV coolant inlet and outlet temperatures. The inlet temperature, which is shown in red, follows the HX outlet temperature, while the outlet temperature (black curve) is essentially in phase with the inlet temperature and less than 1 K higher. Figure 14 shows the VV structural temperatures at two different radial locations within the stainless steel. These temperatures represent the axial center at the vertical elevation of the VV model. The black curve is the cell closest to the coolant, while the red curve represents temperature response of the calculational cell most distant from the coolant. The results indicate a temperature variation within this portion of the vacuum vessel of about 10 K, with the structure approaching a uniform temperature of approximately 374 K at the end of each zero power dwell period. Also noted is that the two portions of the structure are just slightly out of phase.

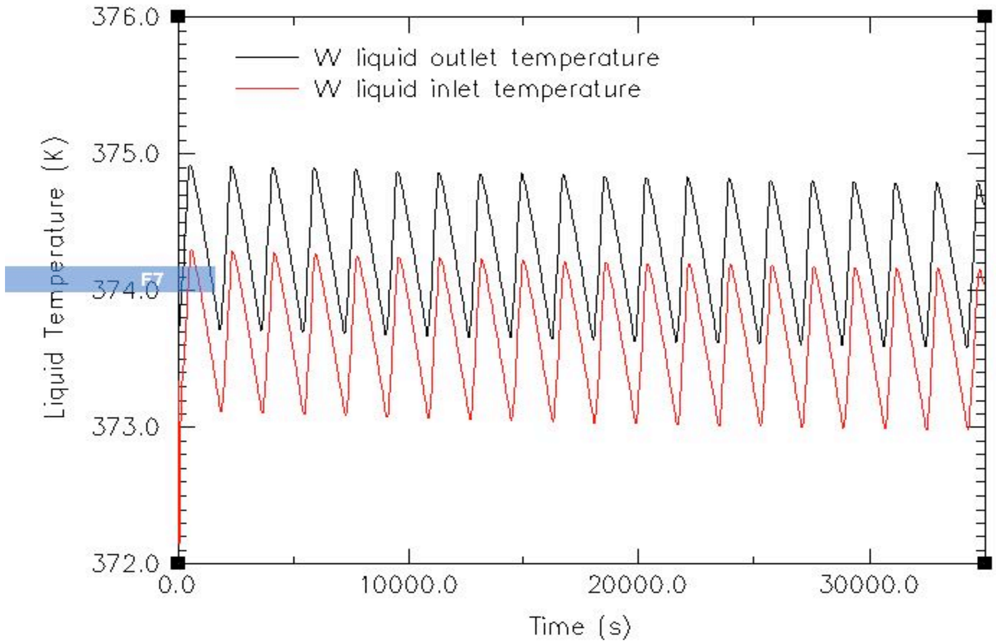


Fig. 13. Vacuum vessel coolant inlet and outlet temperatures.

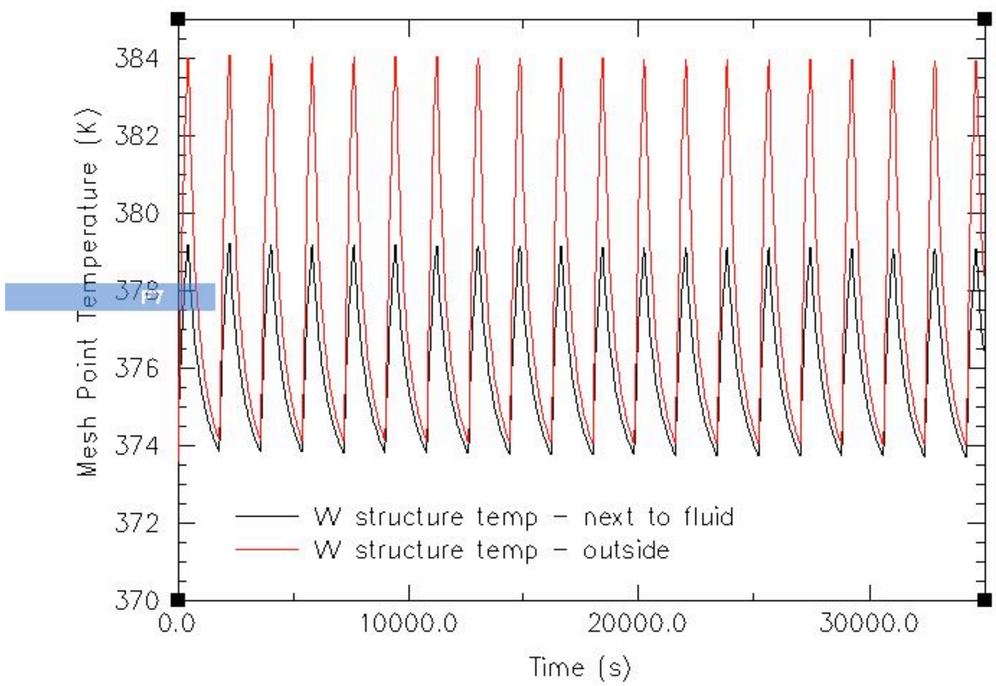


Fig. 14. Vacuum vessel structure temperatures.

The green curve in Fig. 15 shows the time-dependent power input by nuclear heating in the VV. These are the same profiles as shown in Fig. 11 above. The black curve is the power removed by the VV coolant, and it shows some peaking during a pulse cycle but never goes to zero as does the nuclear power. The straight blue line is the pumping power (ultimately deposited in the coolant due to frictional and form losses), while the red line is the power removed by the HX that includes both pump heat and nuclear heat. This curve does not show much peaking in the power rejection profile. This is because the temperature difference between the primary and secondary coolants is so high (~345 K) and the fluid temperature increase through the vacuum vessel is so small (~0.8 K). Since both secondary and primary flows are held constant, the variation in temperature difference between primary and secondary reflects directly the power rejected by the HX. From Fig. 13, the primary fluid temperature varies by 1.2 K during pulse operation, from 373.6 K to 374.8 K, and the temperature difference from primary to secondary in the heat exchanger then varies from approximately 305.6 K to 306.8 K. This means that the variation in power rejected through the heat exchanger only varies by about 4%.

The reasonableness of Fig. 15 can be evaluated by looking at the time integral of each of these curves, since the total amount energy rejected through the heat exchanger must eventually equal that put into the coolant through nuclear heating and pump heat. Figure 16 shows the energy input by nuclear heating into the VV structure as a red curve. This curve is stepped because of the 490-s "powered" pulse followed by a 1310-s zero power dwell time. The blue curve is the energy being input into the coolant flowing through the VV (using liquid temperature rise and mass flow through the VV). These two curves must be equal at the end of each pulse to maintain a quasi-steady-state condition within the VV PHTS system. The green curve is energy deposited in the coolant due to pump power. Finally, the black curve reflects the total energy removed by the HX, which includes the nuclear heating as well as the pump heat. The integral values all are consistent with a quasi-steady-state condition.

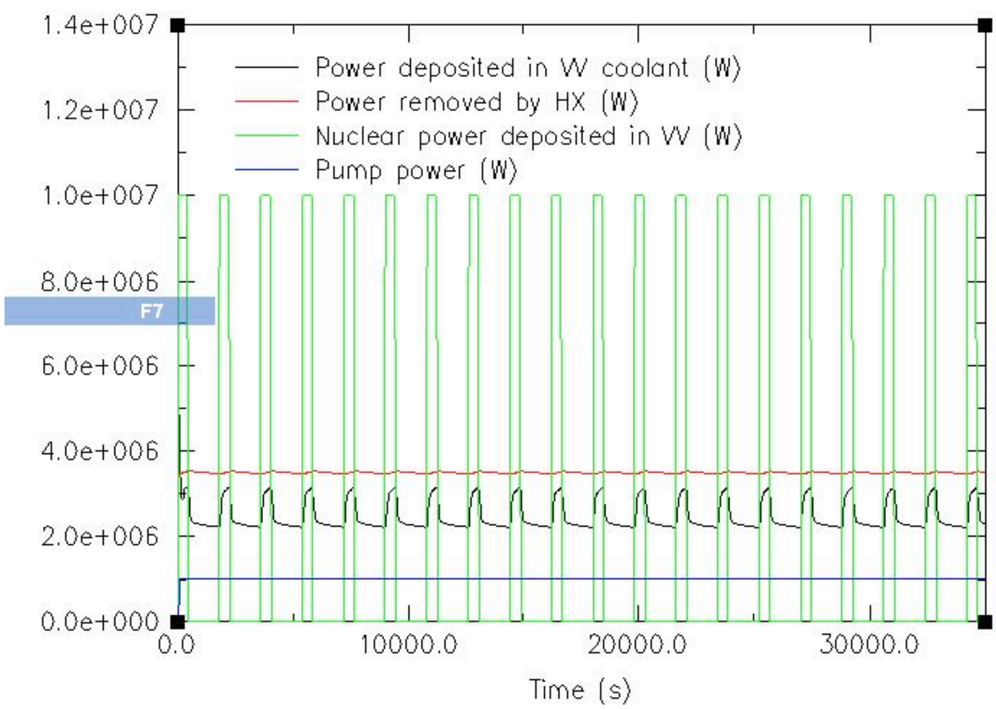


Fig. 15. Time-dependent power deposition in various parts of the VV PHTS.

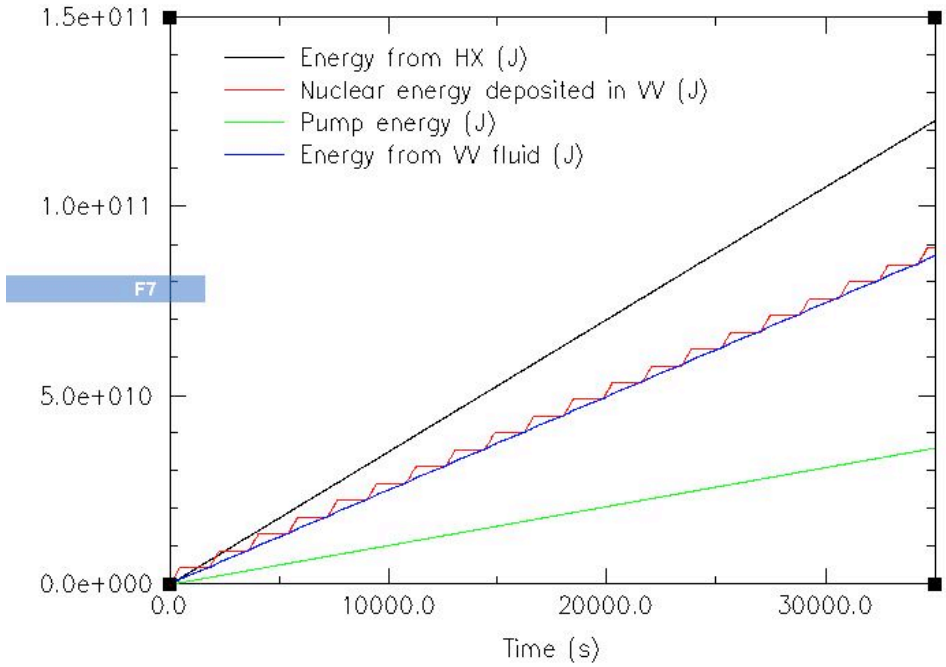


Fig. 16. Energy inventory around the VV PHTS.

Conclusions of continuous pulsed power operation

The calculations indicate that for repetitive pulse operation, it would not be necessary to control the HX in order to meet the inlet temperature requirements of the vacuum vessel. It may however be necessary to apply some controls to accommodate long-term power variations, but it seems as though the response time for this control could be much slower than the pulse length. Additionally, some type of control will be needed to accommodate transients, to keep the entire system from cooling down during a loss of plasma event for instance, or perhaps heating up if there were continuous power excursions. This may only need flow control on the secondary side of the heat exchanger, depending on the transient that needs to be accommodated, and the thermal limits established for the vacuum vessel.

The pump heat for this system is significant (approximately one-third of the nuclear heat). Measures need to be taken to minimize pressure drop where possible to minimize both pump input power requirements as well as heat rejection requirements.

3.2 NORMAL OPERATION FOLLOWED BY A LOSS OF POWER

The model was exercised to establish normal pulsed power operation (main loop on, decay heat loop off) followed by operation of the decay heat loop with the main loop off.

Figure 17 shows calculated coolant temperatures during plasma pulsed power operation for six cycles (pulse described as before), followed by operation of the decay heat loop at a constant heat load of 0.5 MW. Figure 18 shows the power input during the six pulses. Decay heat operation follows after 10,800 s at a constant value of 0.5 MW. Decay heat values are very small at time zero, reaching a peak value of less than 0.5 MW, so a constant heat load of 0.5 MW is very conservative. Temperatures of the coolant leaving and entering the VV are shown. During the pulsed power operation (six 1800 s cycles for a total of 10,800 s), the temperature of the cold coolant entering the VV oscillates between 373.1 K and 374.3 K, and the temperature of the hot coolant leaving the VV oscillates between 373.7 K and 374.9 K. The coolant flow is constant at 950 kg/s during the pulsed power operation. Decay heat loop operation starts at 10,800 s with a coolant flow of 40 kg/s. The main pump and the main HX are isolated during this operation. The cold coolant temperature leaving the decay heat HX and entering the VV decreases to 368.5 K due to the low temperature of the secondary water (CHWS at 279 K) in the decay heat loop HX. The main loop had a secondary water temperature of 301 K (from the CCWS system). The hot coolant temperature leaving the VV does not go over 374.6 K. The temperature rise across the vacuum vessel is well below the 10ºC requirement, and the maximum temperature is still well below the baking temperature for both normal and decay heat conditions.

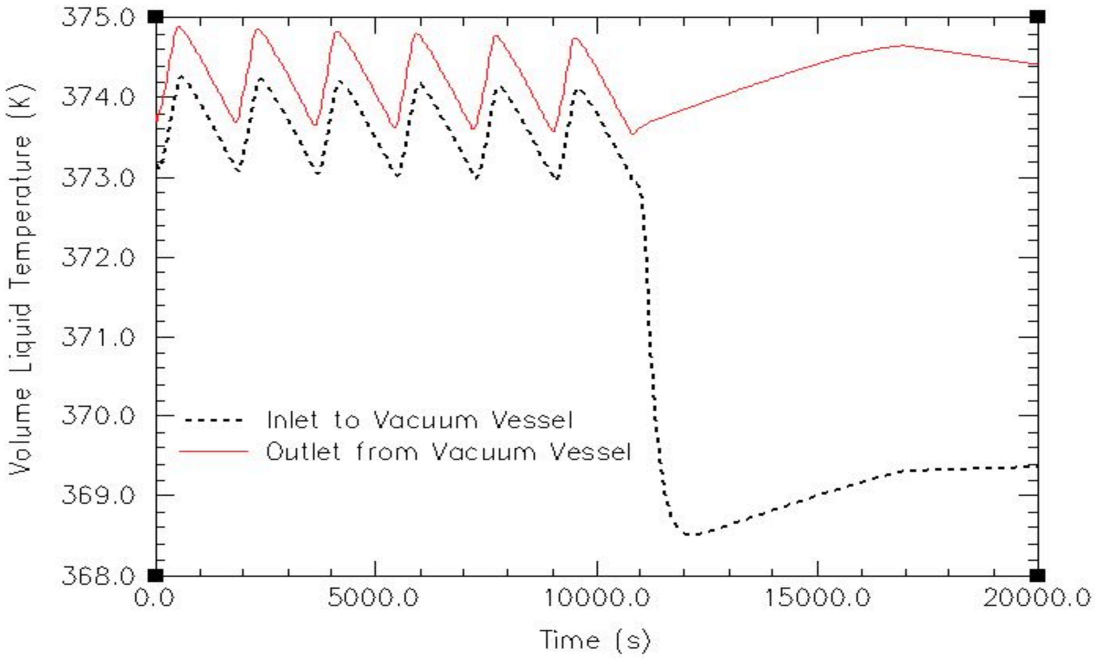


Fig. 17. Inlet and outlet temperatures to the vacuum vessel.

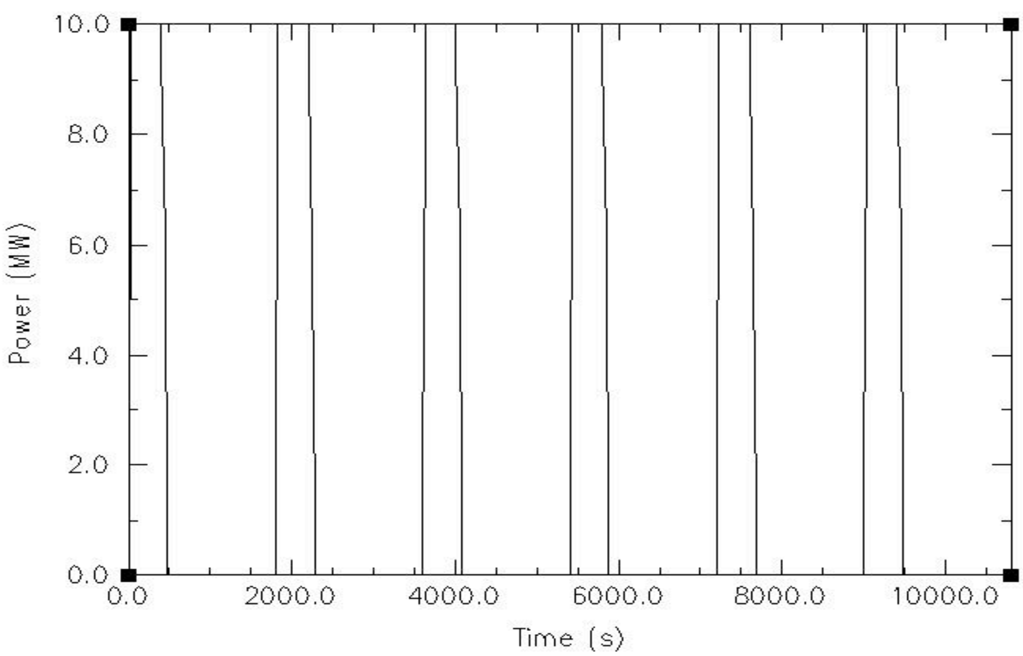


Fig. 18. Power profile during pulsed power operation (six pulses).

Figure 19 shows the flow through the VV (950 kg/s during the first 10,800 s, main loop operation, followed by 40 kg/s during the operation of the decay heat loop).

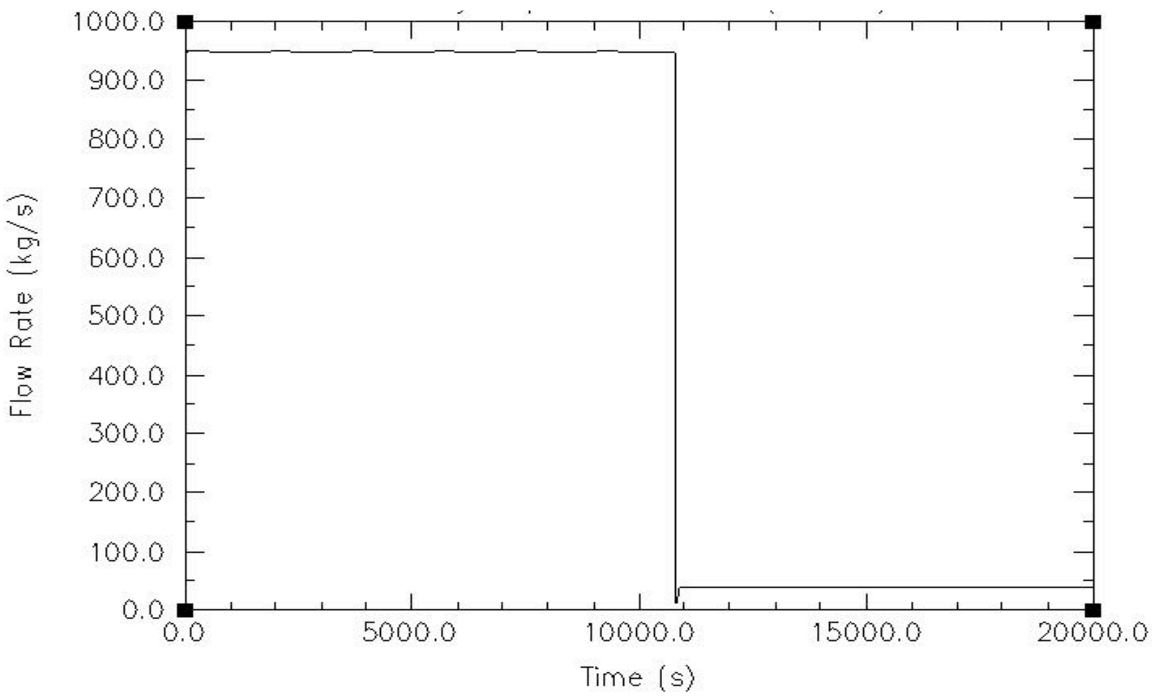


Fig. 19. Flow through the vacuum vessel (950 kg/s main—40 kg/s decay heat).

Figure 20 shows the power deposited into the coolant inside the VV, the power removed by the main HX, and the power removed by the safety HX after 10,800 s. The power into the VV follows the power profile of the power pulses (Fig. 12) with six peaks. While the peak power deposited into the VV structures is 10 MW, the coolant only reaches a peak value of 3.2 MW; however, the minimum power into the coolant is 2.2 MW, while the corresponding pulsed power at that time is zero. The VV walls act as a buffer between the pulsed power deposited into the walls and the coolant removing the heat from the vacuum vessel.

Figure 21 shows the pressure in five different locations of the system during this transient operation. The pressurizer pressure is kept constant at 0.4 MPa. The inlet to the VV is at 0.8 MPa (a design value) during full flow operation of the main loop; it decreases to 0.7 MPa during the operation of the decay heat loop. The VV outlet is at 0.7 MPa during main loop operation and at 0.58 MPa during decay heat loop operation. The highest pressure in the main loop is at the outlet of the main pump with a value of 1.06 MPa. The lowest pressure is at the inlet to the main pump with a value of 0.25 MPa. The main pump is isolated during decay heat loop operation; thus, the main pump pressures shown in Fig. 21 after 10,800 s do not have any meaning. The pressure differential (inlet to outlet) of 0.1 MPa in the VV during full flow (950 kg/s) operation includes the static head contribution. Friction pressure drop through the VV is 50 kPa after the static head is removed (the latest model uses loss coefficients to force the pressure drop through the VV to be 50 kPa under normal flow conditions). The flow takes 225 s (3.75 min) to travel the complete loop (at 950-kg/s flow). The flow takes 167 s (2.8 min) to travel through the VV only—the calculated velocity in the VV is 0.072 m/s, and the total VV length (height) is 12 m. The maximum velocity in the complete system is 8.43 m/s for the hot coolant in the main pipes (400-mm pipe).

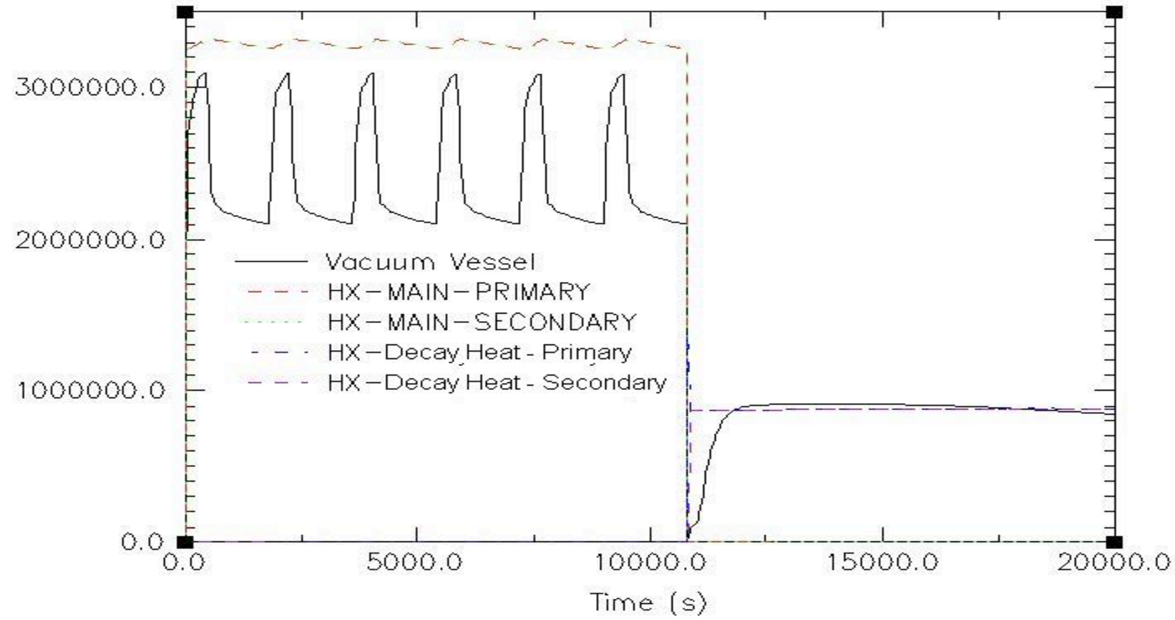


Fig. 20. Power (in W) deposited into the coolant (VV) and removed by the heat exchangers.

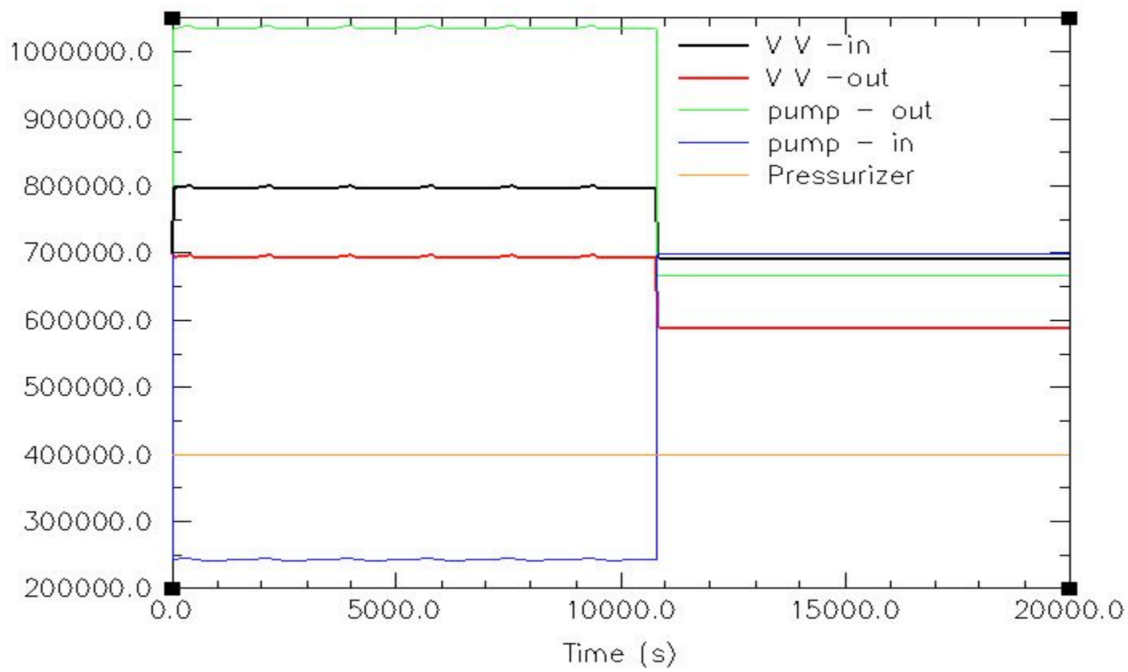


Fig. 21. Calculated pressures in the system in pascals.

The following figures show temperature distribution inside the structures (walls) of the VV. Figure 22 is for the inner wall; it is colder at the bottom as the cold coolant enters the bottom of the VV. The left side is in contact with the coolant, and the right side is insulated. The temperatures at the left side are lower than at the right side because the coolant is on the left side. Figure 23 shows the temperature of the ribs located inside the vessel. This structure is in contact with the coolant on both sides; therefore, there are insignificant radial (horizontal) temperature gradients and only vertical gradients as the coolant heats up on its way out to the top.

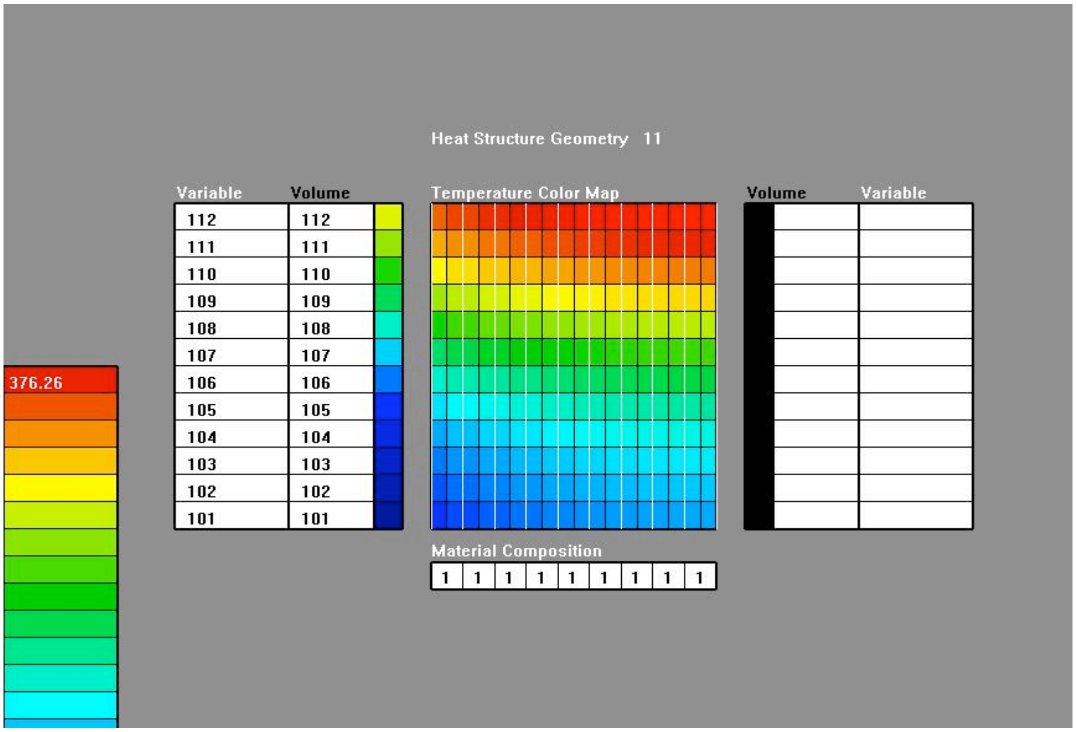


Fig. 22. Temperature distribution inside the inner wall of the VV—coolant left side.

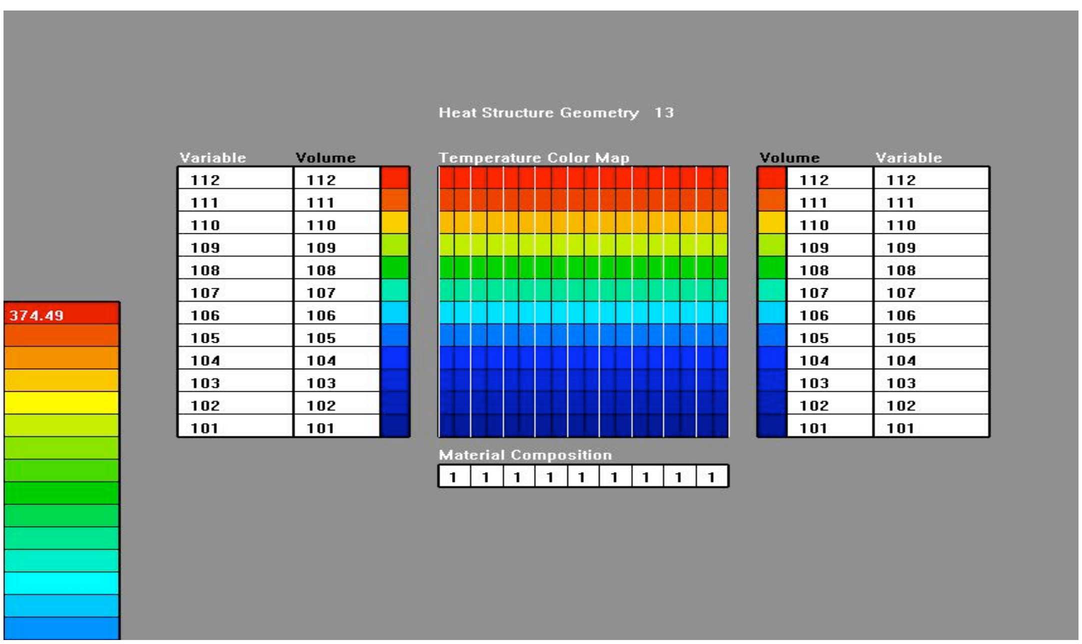


Fig. 23. Temperature distribution inside the ribs of the VV—coolant on both sides.

3.3 DECAY HEAT OPERATION RESULTS

The following results use the heat structure models described in Section 3.1. Decay heat must be removed for 72 h (3 days) with the VV decay heat loop when power to the main loop is not available. A calculation for a total time of 350,000 s (over 4 days, or 1 day more that is required) was completed and the results are presented in this section. The maximum power into the VV from radiation from the attached structures (BLK and DIV added) is 0.509 MW, and when the heat losses to the thermal shield are subtracted, the peak net power into the VV is 0.479 MW, which occurs at 251,000 s (2.9 days) into the transient. Figure 24 shows the calculated radiation powers vs. time, with the contributions from the different structures (BLK and DIV are positive and Thermal Shield is negative). At 350,000 s, the net power input is 0.45 MW. The constant value of 0.5 MW used in the previous calculation is therefore a very conservative estimate of decay heat, which is always below 0.5 MW, with a maximum peak at 0.479 MW.

Figure 25 shows the coolant temperatures entering and leaving the VV during this transient. Temperatures drop (to 365 K inlet to VV and to 367.5 K outlet) during the first 140,000 s, then increase slightly up to 250,000 s, and decrease again afterwards (to 363 K inlet and 366 outlet). This is because at first the HX is removing more heat than is deposited into the coolant, then the HX is removing less heat between 140,000 s and 250,000 s, and then it removes more heat again after 250,000 s, as shown in Fig. 26. A coolant flow of 6 kg/s was used in the secondary side of the HX without any temperature controls. A difference between the maximum hot and the minimum cold temperatures across the VV of only 11 K is indicated by the calculation. Temperatures for the heat structures of the FW/BLK are shown in Fig. 27 and for the heat structures of the DIV are in Fig. 28.

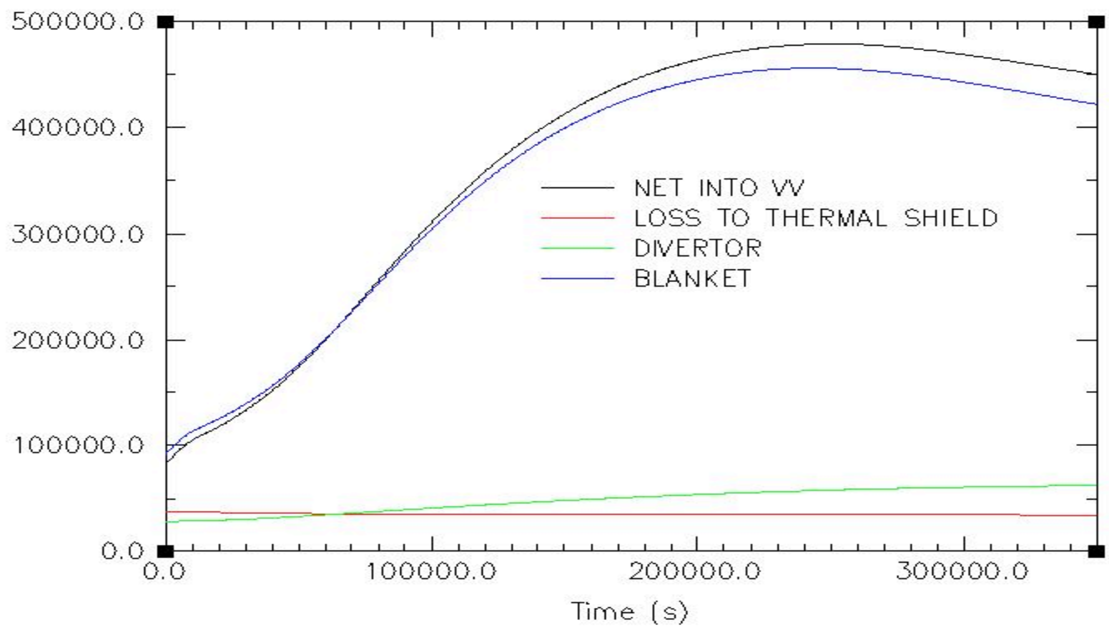


Fig. 24. Power into the vacuum vessel (in W) from radiation sources.

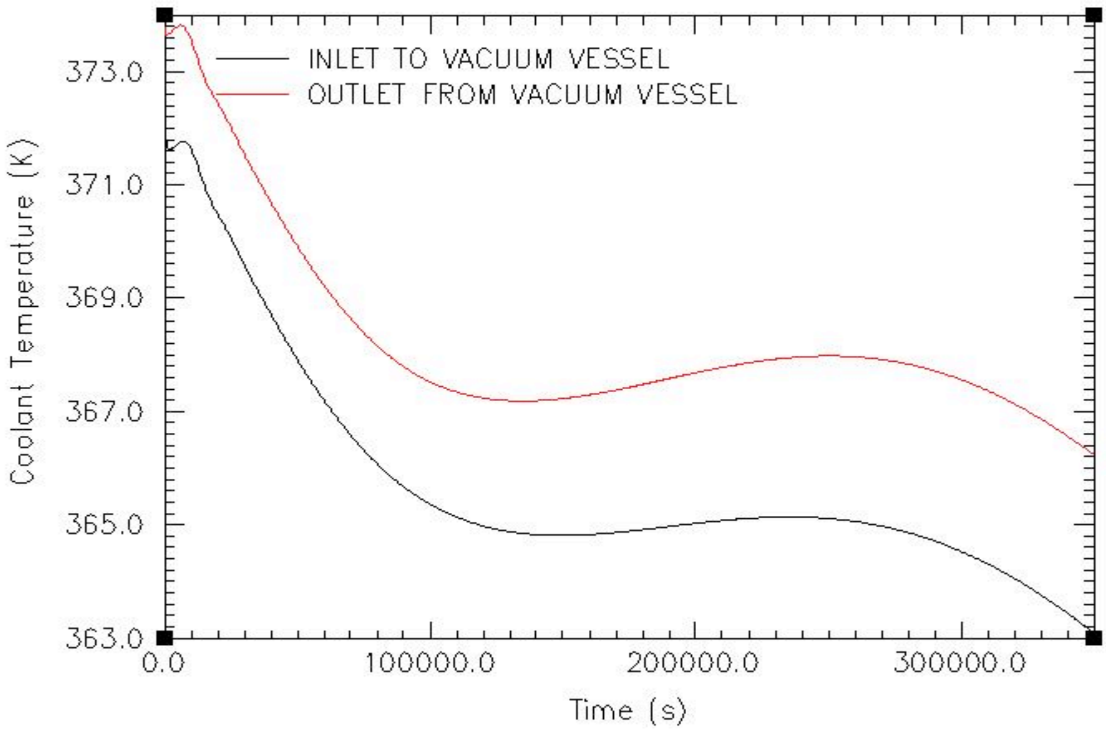


Fig. 25. Temperatures in and out of the vacuum vessel.

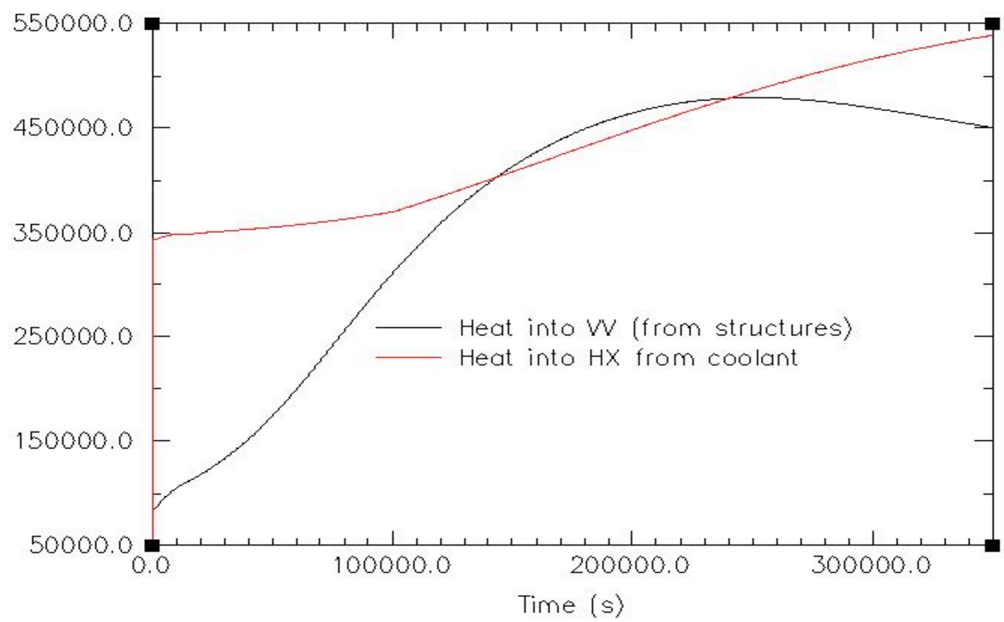


Fig. 26. Heat into the vacuum vessel from structures and removed by the main heat exchanger.

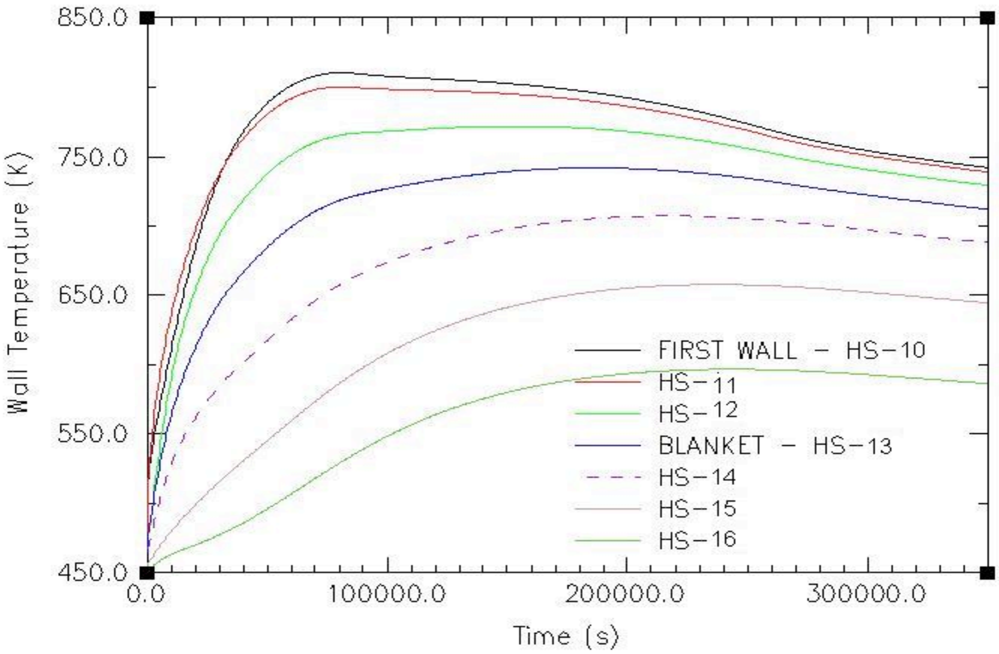


Fig. 27. Temperatures of the first wall and blanket structures.

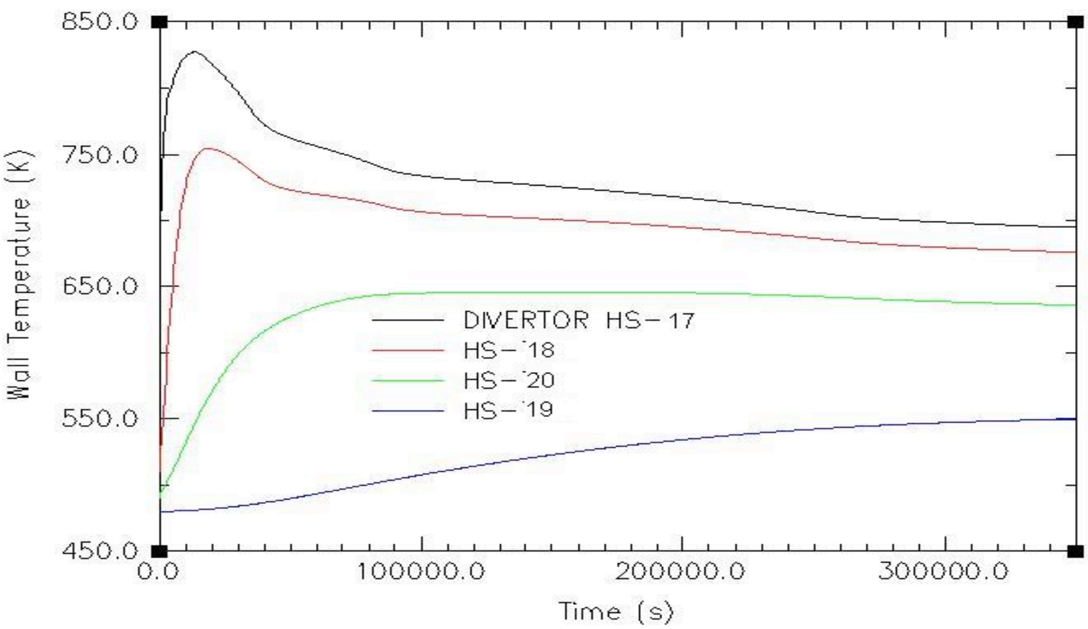


Fig. 28. Temperature of the divertor structures.

4. CONCLUSIONS

These RELAP5 calculations of the VV PHTS have demonstrated that the design is feasible, it performs its functions satisfactorily, and the calculated results are acceptable under both normal and abnormal (decay heat) conditions. The requirement of removing decay heat with the decay heat loop for 72 h (3 days) is met; decay heat can be removed for 4 days as well without power in the main loop using only emergency backup power.

The decay heat HX is designed for the peak high decay source of ~0.5 MW. A smaller HX (for ~0.3 MW) can be used and still can accomplish the safety function and remove decay heat satisfactorily.

The coolant temperature rise across the vacuum vessel remains less than 10°C (a requirement for normal operation), and maximum temperatures are significantly less than the baking temperature for both normal operation and decay heat operation. Additionally, under normal pulsed mode operation, no control of the heat exchanger would be required to meet the temperature requirements of the VV.

Since RELAP5 only models radiation between heat structures (conduction is not considered), actual heat transfer values between structures are expected to be larger than the values calculated by RELAP5.

5. REFERENCES

1. System Requirements Document (SRD) Tokamak Cooling Water System (TCWS) PBS 26-TC, Report ITER_D_2823A2 v1.5, December 2008.
2. *RELAP5-3D Code Manual*, INEEL-EXT-98-00834, Rev. 2.4, Idaho National Laboratory (2006).
3. L. Topilski, "Thermal-hydraulic Models used for the ITER Safety Analysis," Report ITER_D_277XZG, Version 1.2, June 2008.
4. *Shell and Tube Heat Exchanger Design,* http://webbusterz.com, 2009.

APPENDIX A
MAIN LOOP HEAT EXCHANGER DESIGN

A.1 SUMMARY OF PROPOSED DESIGN

Project Name:
Company:
By:
Date:
++
++
SUMMARY OF PROPOSED DESIGN
++
++
SHELL SIDE DATA
++
CCWS Cooling Water
Temperature From: 28 'C
To: 38 'C
Shell passes: 1
Shell Diameter: 678 mm
Shell Side Coefficient: 6037.3121 W/m2'C
Shell side Pressure drop: 35041.3767 Pascal
++
TUBE SIDE DATA
++
VV cooling water system
Temperature From: 100.788 'C
To: 100 'C
Tube passes: 1
Number of Tubes: 260
Tube Outer Diameter: 31.75 mm BWG 16
Tube Internal Diameter: 28.448 mm
Tube Pitch: 39.68 mm
Tube Arrangement: Triangular
Tube Side Coefficient: 26083.9567 W/m2'C
Tube side Pressure drop: 52297.6798 Pascal
++
BAFFLES
++
Baffle Cut: 25%
Baffle Type: Segmental
Number of Baffles: 3
Baffle Spacing: 350 mm
++
Tie Rods
++
Recommended Number of Tie Rods: 0
Tie Rod Diameter: 0 mm
++
Exchanger Type: Split-ring Floating Head
Material of Construction: Stainless steel
Length: 1. m
Heat Transfer Area: 25.922 m2
Duty: Q = 3470.4722
Design Overall Coefficient: 2207.0815 W/m2'C
Assumed Overall Coefficient: 2000 W/m2'C
Clean Overall Coefficient: 3493.5837 W/m2'C
Effectiveness: 0.1648
Number of Transfer Units: 0.18

Shell and Tube Heat Exchanger Design v1.6
http://www.webbusterz.com
http://www.webbusterz.net
http://www.webbusterz.co.uk

A.2 BASIC SUMMARY OF PROPOSED DESIGN

Below is a basic drawing for illustration purpose

Split-ring Floating Head

Shell Side	CCWS Cooling Water	In at = 28	'C	Out at = 38	'C
Tube Side	VV cooling water system	In at = 100.788		Out at = 100	

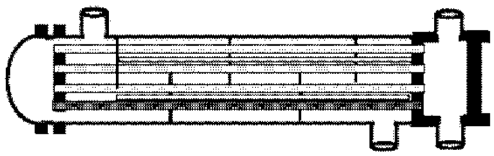
Shell Ds = 678 mm

Shell Thickness = 0 mm

Carbon Steel

No. of Tie Rods = 0

Tie Rod Diameter = 0 mm



BWG = 16

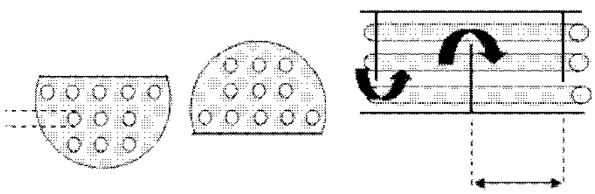
Tube OD = 31.75 mm

Tube Thickness = 1.651 mm

Number of Tubes = 260

Tube Length = 1. m

Area = 25.922 m2

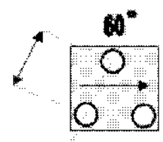


No. of Tube Passes = 1

No. of Shell Passes = 1

Pitch = 39.68 mm

Triangular



Buffle Type	Segmental		Buffle Hole Diameter =	0	mm
Baffle Cut =	169.5	mm	Baffle Spacing =	350	mm
No. of Baffles =	3		Baffle Diameter	673.2	mm

Overall Heat Transfer Coefficient (Calculated) 2207.0815 W/m2'C

You Can add Any Comments Here
up to 428 characters

WeBBusterZ Engineering Software
WeBBusterZ.CoM - WeBBusterZ.Net

APPENDIX B
DECAY HEAT LOOP HEAT EXCHANGER DESIGN

B.1 SUMMARY OF PROPOSED DESIGN

Project Name:
Company:
By:
Date:
++
++
SUMMARY OF PROPOSED DESIGN
++
++
SHELL SIDE DATA
++
CCWS Cooling Water
Temperature From: 28 'C
To: 38 'C
Shell passes: 1
Shell Diameter: 309 mm
Shell Side Coefficient: 5005.873 W/m2'C
Shell side Pressure drop: 4470.6974 Pascal
++
TUBE SIDE DATA
++
VV cooling water system
Temperature From: 95 'C
To: 92.15 'C
Tube passes: 2
Number of Tubes: 146
Tube Outer Diameter: 19.05 mm BWG 16
Tube Internal Diameter: 15.748 mm
Tube Pitch: 23.81 mm
Tube Arrangement: Triangular
Tube Side Coefficient: 15970.3137 W/m2'C
Tube side Pressure drop: 29256.9282 Pascal
++
BAFFLES
++
Baffle Cut: 25%
Baffle Type: Segmental and Strip
Number of Baffles: 3
Baffle Spacing: 250 mm
++
Tie Rods
++
Recommended Number of Tie Rods: 0
Tie Rod Diameter: 0 mm
++
Exchanger Type: U-tube
Material of Construction: Stainless steel
Length: 00.5 m
Heat Transfer Area: 4.3654 m2
Duty: Q = 528.4983
Design Overall Coefficient: 2066.2435 W/m2'C
Assumed Overall Coefficient: 2000 W/m2'C
Clean Overall Coefficient: 3093.8355 W/m2'C
Effectiveness: 0.1679
Number of Transfer Units: 0.19

Shell and Tube Heat Exchanger Design v1.6
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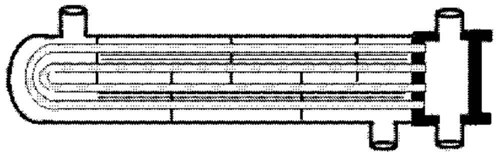
http://www.webbusterz.net
http://www.webbusterz.co.uk

B.2 BASIC SUMMARY OF PROPOSED DESIGN

Below is a basic drawing for illustration purpose **U-tube**

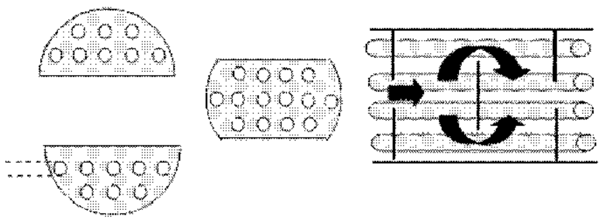
Shell Side	CCWS Cooling Water	In at =	28	'C	Out at =	38 'C
Tube Side	VV cooling water system	In at =	95		Out at =	92.15

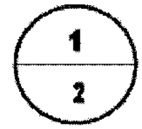
Shell Ds = 309 mm
Shell Thickness = 0 mm
Carbon Steel
No. of Tie Rods = 0
Tie Rod Diameter = 0 mm



BWG = 16
Tube OD = 19.05 mm
Tube Thickness = 1.651 mm
Number of Tubes = 146

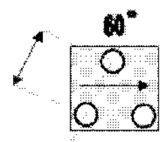
Tube Length = 00.5 m   Area = 4.3654 m2





No. of Tube Passes = 2
No. of Shell Passes = 1

Pitch = 23.81 mm
Triangular



Buffle Type	Segmental and Strip	Buffle Hole Diameter =	0	mm
Baffle Cut =	77.25 mm	Baffle Spacing =	250	mm
No. of Baffles =	3	Baffle Diameter	307.4	mm

Overall Heat Transfer Coefficient (Calculated) 2066.2435 W/m2'C

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APPENDIX C

PIPING DIMENSIONS AND RELAP5 NUMBERING SYSTEM

Piping numbers are labeled starting from the pump outlet.

C.1 PUMP OUTLET TO DISTRIBUTOR PIPING

Figures C.1 through C.3 show the main piping near the pump outlet and heat exchanger, while Figure C.4 shows piping from the pump station to the VV distribution header. Table C.1 lists piping dimensions and the RELAP5 designation for this piping.

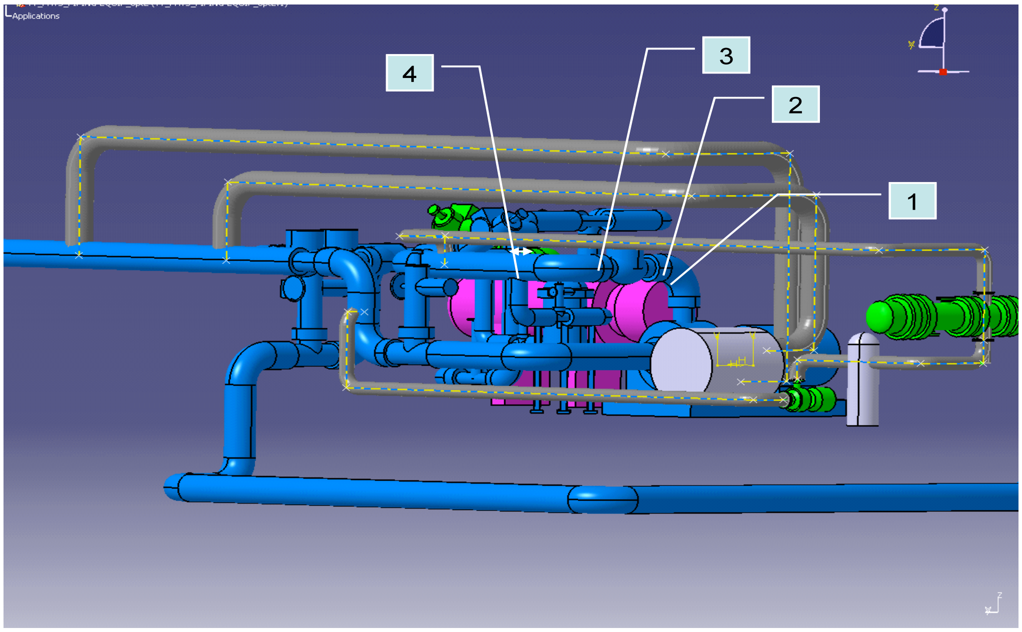

Fig. C.1. Pump outlet piping.

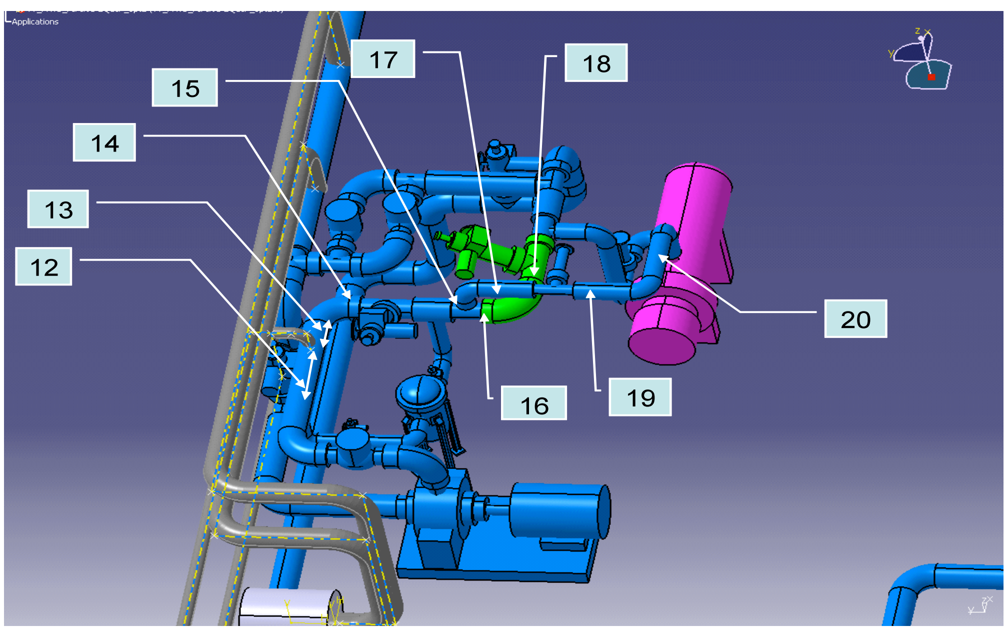

Fig. C.2. Pump outlet piping view #2.

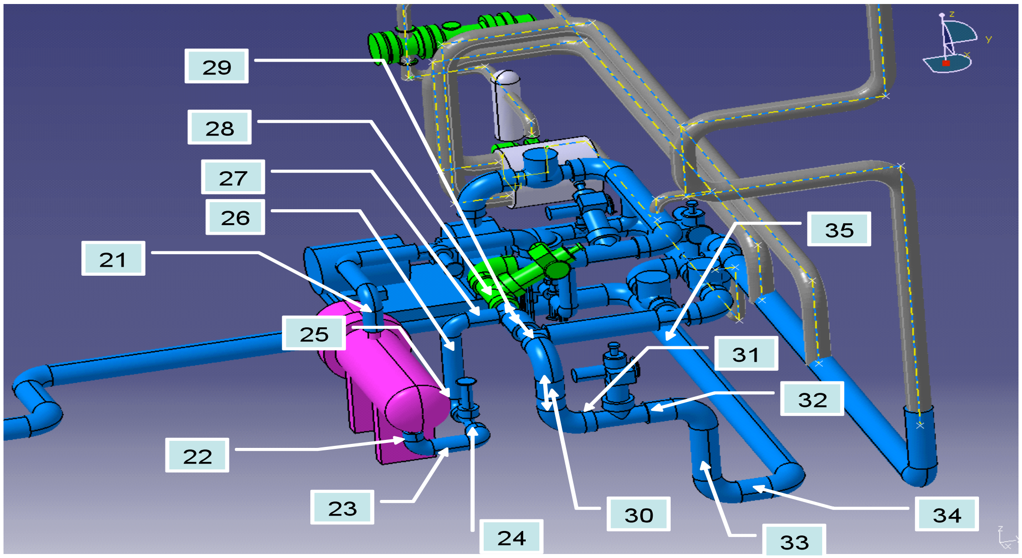

Fig. C.3. Pump outlet piping view #3.

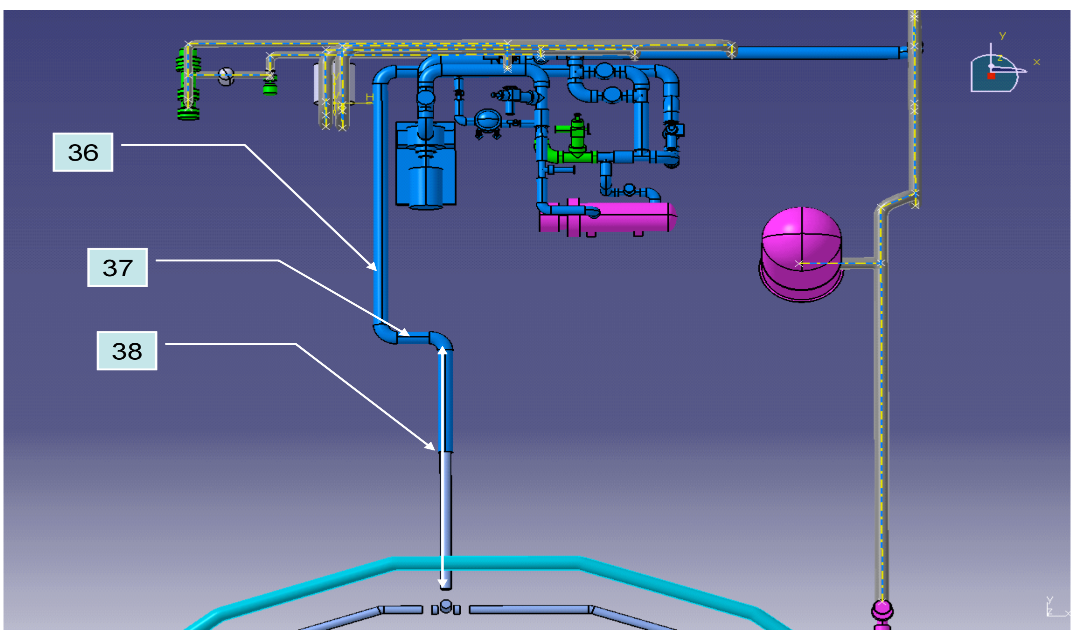

Fig. C.4. Pump station to distributor piping.

Table C.1. Pump to distributor piping

Pipe Number	RELAP5 Designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
1	100	400	0.1178	733	1
2	101	400	0.1178	809	1
3	103	400	0.1178	733	1
4	104	400	0.1178	954	1
12	105	400	0.1178	1422	0
13	105	400	0.1178	998	1
14	106	400	0.1178	733	1
16	107	400	0.1178	733	1
18	108	400	0.1178	733	1
28	108	400	0.1178	200	0
29	108	400	0.1178	1951	1
30	110	400	0.1178	1819	2
31	111	400	0.1178	733	1
32	111	400	0.1178	1033	1
33	112	400	0.1178	2412	2
34	113	400	0.1178	1629	2
35	114	400	0.1178	9858	2
36	115	400	0.1178	11228	2
37	116	400	0.1178	2166	2
38	117	400	0.1178	11134	2
39	118	400	0.1178	1661	1

C.2 DISTRIBUTOR

The distributor is pictured in Fig. C.5. In the RELAP5 model, the distributor is represented by a single pipe that is half the total distributor length, with twice the flow area. The branch piping is located at the end of the distributor. Table C.2 shows the piping geometry used in the RELAP5 model.

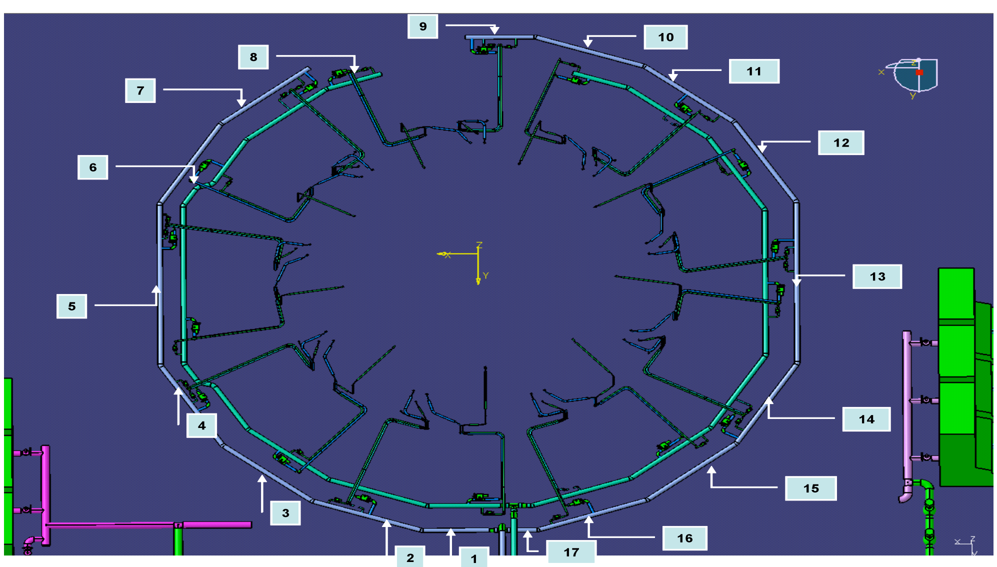

Fig. C.5. Distributor piping.

Table C.2. Assumed RELAP5 distributor geometry

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
–	120	336	0.1779	54000	15

C.3 BRANCH PIPING

The branch piping from the distributor to the VV and that from the VV to the collector have all been lumped together in the RELAP5 model. An example of branch piping from the distributor to the VV is shown in Fig. C.6. Figures C.7 and C.8 show examples of one set of branch piping from the VV to the collector. Table C.3 shows the geometry used for the lumped branch piping running from the distributor to the VV, while Table C.4 shows the lumped representation for the VV to collector.

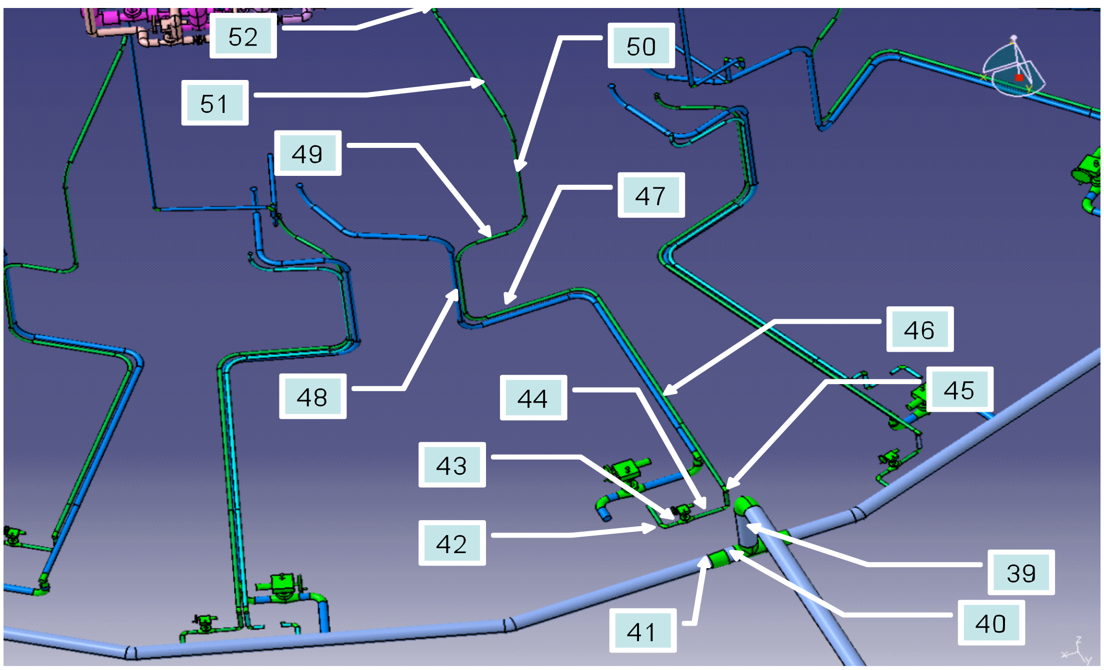

Fig. C.6. Example of distributor to VV branch piping.

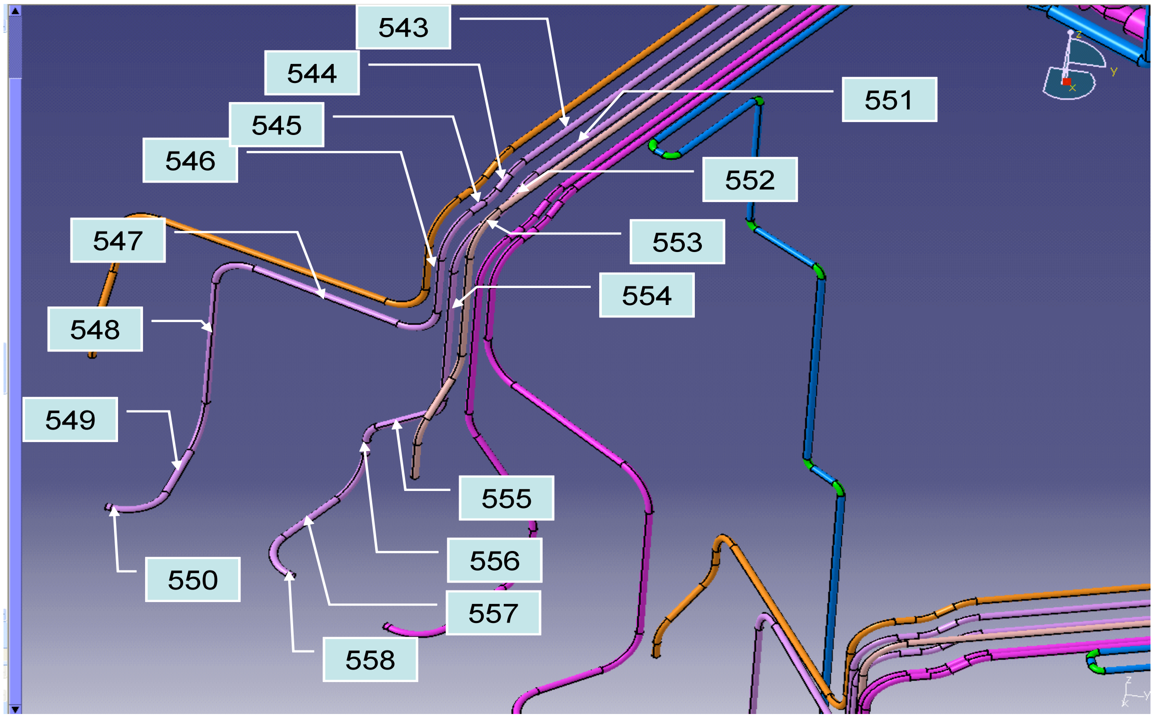

Fig. C.7. Example of branch piping to collector.

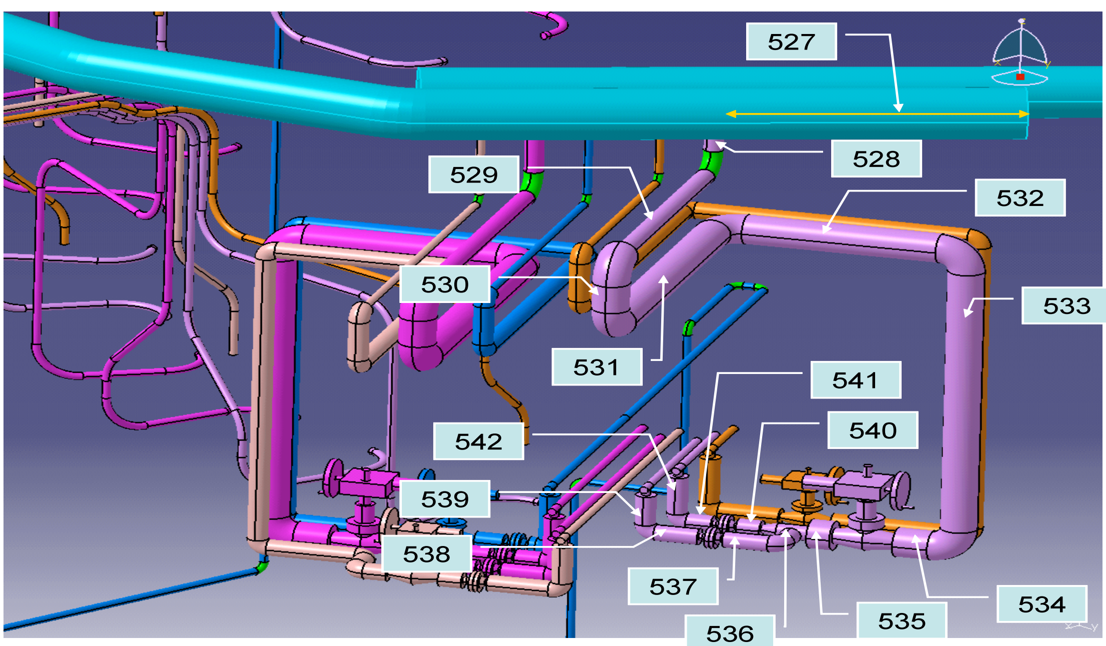

Fig. C.8. Example of branch piping to collector #2.

Table C.3. Inlet branch piping geometry assumed in the RELAP5 model

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
–	121-Br	82.3	0.2404	2813	2
–	122-Br	82.3	0.2404	8297	2
–	123-Br	82.3	0.2404	5700	2
–	124-Br	82.3	0.2404	1000	5

Table C.4. Outlet branch piping VV to collector

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
–	200-out	117.1	0.428	1000	2
–	201-out	117.1	0.428	19982	2
–	202-out	117.1	0.428	7858	4

C.4 COLLECTOR

The collector is shown in Fig. C.9. In the RELAP5 model, the collector is represented by a single pipe that is half the total collector length, with twice the flow area. The lumped branch piping is located at the end of the collector. Table C.5 shows the piping geometry used in the RELAP5 model.

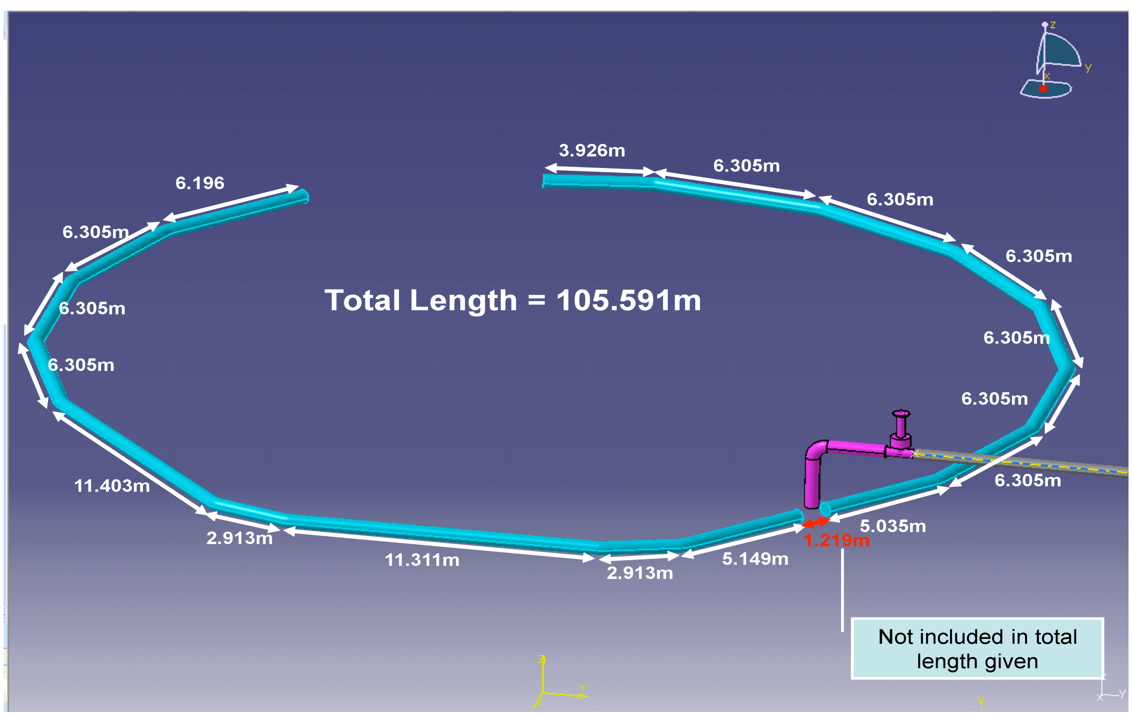

Fig. C.9. Collector dimensions.

Table C.5. Assumed RELAP5 collector geometry

Pipe Number	RELAP5 Designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
–	204	336	0.1779	53400	15

C.5 HOT LEG PIPING

The hot leg piping is shown in Figs. C.10 and C.11, while the hot leg piping dimensions used in RELAP5 are shown in Table C.6.

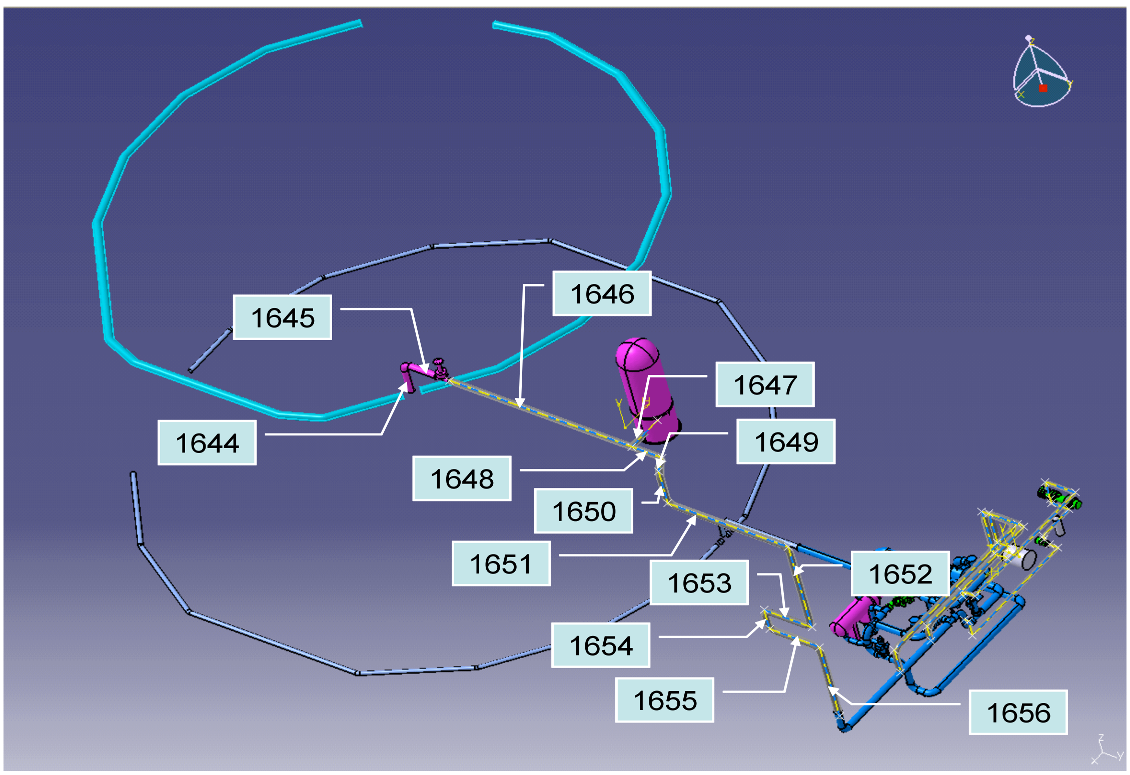

Fig. C.10. Hot leg piping.

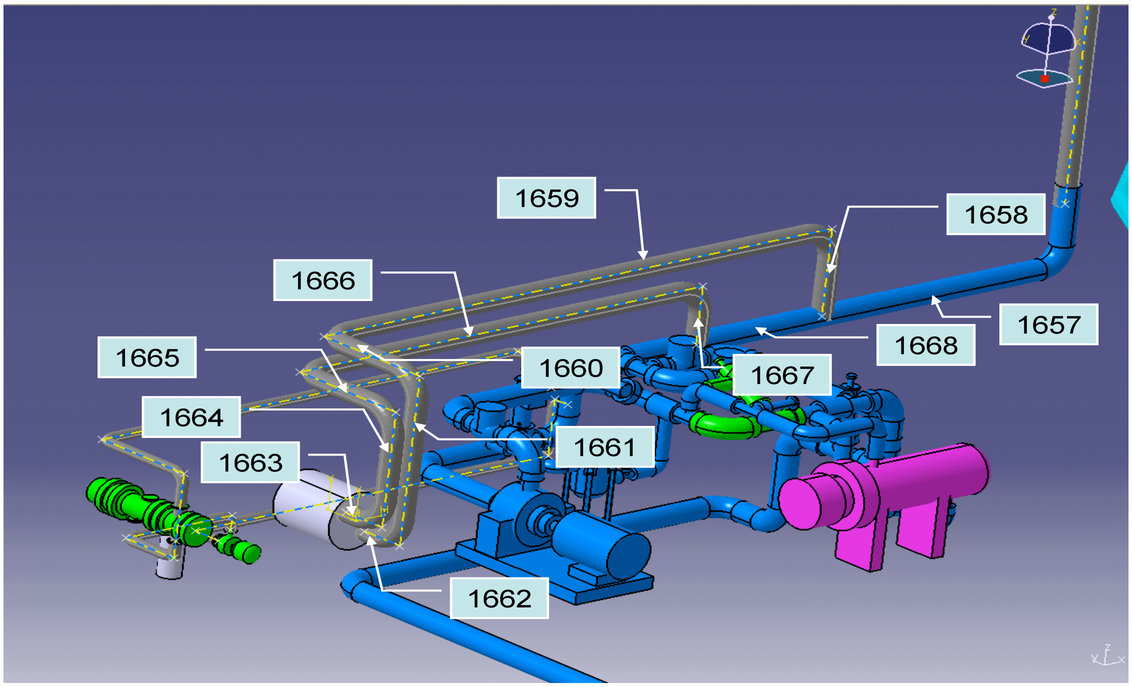

Fig. C.11. Hot leg piping and main heat exchanger bypass.

Table C.6. Hot leg piping dimensions

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
1644	205	408	0.1178	2635	1
1645	206	400	0.1178	2609	1
1646	206	400	0.1178	13898	0
1648	206	400	0.1178	2172	1
1649	206	400	0.1178	1425	2
1650	207	400	0.1178	3131	2
1651	208	400	0.1178	9435	2
1652	209	400	0.1178	7999	2
1653	210	400	0.1178	3743	2
1654	211	400	0.1178	1893	2
1655	212	400	0.1178	3918	2
1656	213	400	0.1178	8374	2
1657	214	400	0.1178	5954	1
1668	260, 262	400	0.1178	603	0

C.6 PUMP INLET PIPING

The pump suction piping configuration is shown in Fig. C.12, and the piping geometry is presented in Table C.7.

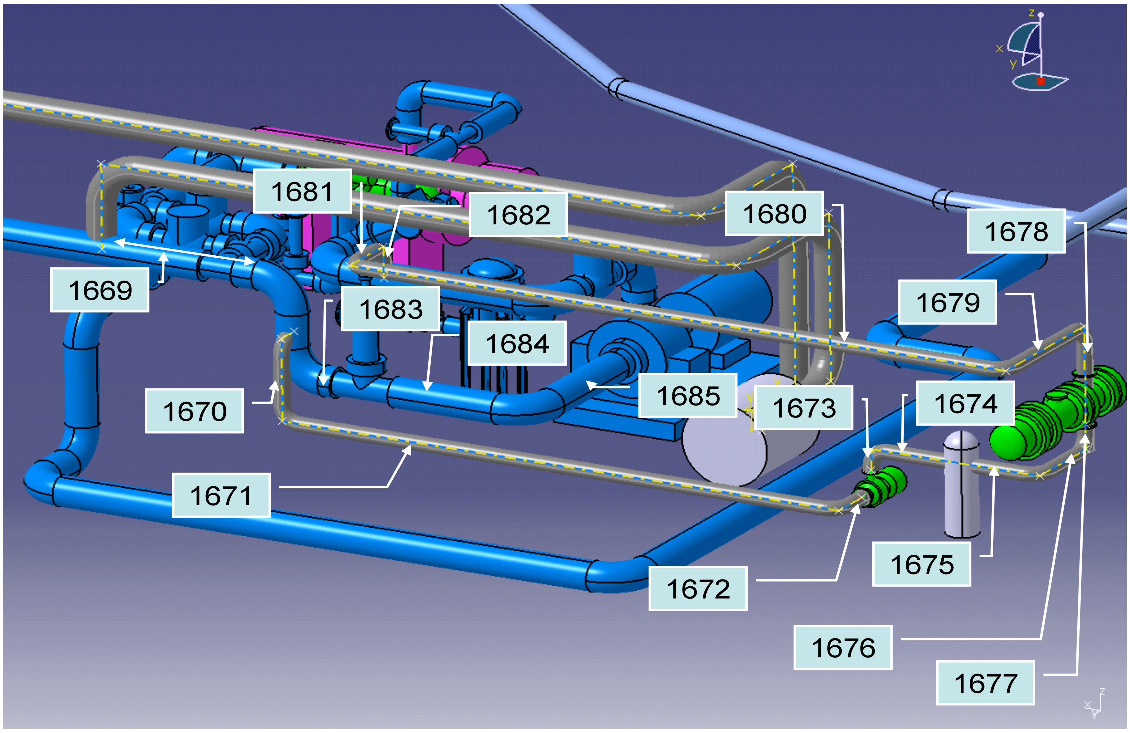

Fig. C.12. Pump suction piping.

Table C.7. Pump suction piping dimensions

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
1669	233	400	0.1178	3553	1
1683	234, 235, 236	400	0.1178	733	1
1684	238	400	0.1178	2233	1
1685	239	400	0.1178	2459	1

C.7 MAIN HEAT EXCHANGER PIPING

The piping for the main HX is shown in Fig. C.11 (large pipe with dashed lines). Dimensions for this piping is shown in Table C.8.

Table C.8. Main heat exchanger piping dimensions

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
1658	215	400	0.1178	1252	1
1659	216, 218	400	0.1178	13224	2
1660	219	400	0.1178	2768	2
1661	220	400	0.1178	4191	2
1662	221	400	0.1178	1015	1
1663	223, 224	400	0.1178	1041	1
1664	225	400	0.1178	2864	2
1665	226	400	0.1178	2772	2
1667	227, 229, 231	400	0.1178	10492	2
1068	232	400	0.1178	603	0

C.8 FILTER BYPASS PIPING

A bypass in the vacuum vessel piping for filtering a few percent of the coolant is located immediately after the pump outlet. This bypass includes filter isolation valves and is shown in Fig. C.13. Dimensions for this piping are shown in Table C.9.

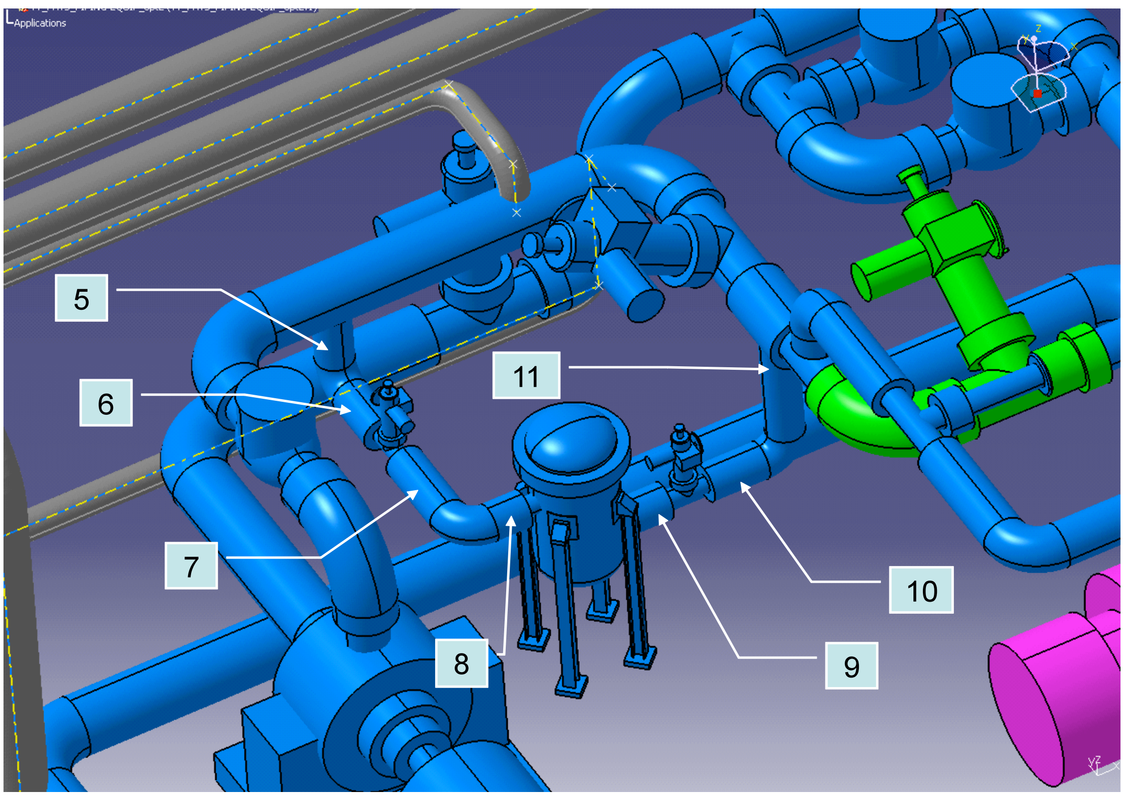

Fig. C.13. Filter bypass piping.

Table C.9. Filter bypass piping dimensions

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (mm)	Number of elbows
5	330	150	0.0186	734	1
6	331	150	0.0186	728	1
7	333	150	0.0186	928	1
8	334	150	0.0186	528	1
9	336	150	0.0186	300	0
10	336	150	0.0186	711	1
11	337	150	0.0186	1284	1

C.9 DECAY HEAT PUMP AND HEAT EXCHANGER BYPASS

A decay heat pump and HX system is incorporated into a bypass around the main pump and HX. The piping for this system is included in Fig. C.12. The dimensions for this piping are shown in Table C.10.

Table C.10. Decay heat pump and heat exchanger bypass piping

Pipe number	RELAP5 designation	Pipe diameter (mm)	Flow area (m^2)	Pipe length (m)	Number of elbows
1670	300,301	150	0.0186	2882	2
1671	302,304	150	0.0186	9184	2
1672	305	150	0.0186	677	1
1673	307	150	0.0186	356	1
1674	308	150	0.0186	1277	1
1675	308	150	0.0186	1069	1
1676	309,311	150	0.0186	1942	2
1677	313	150	0.0186	382	1
1678	313	150	0.0186	777	1
1679	314,316	150	0.0186	2891	2
1680	317,319,321	150	0.0186	11428	2
1681	322	150	0.0186	1533	2
1682	323	150	0.0186	287	1

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